HEMIPHOT, a programme to analyze light, light quality and vegetation indices from hemispherical photographs

Cover photo (inset): Hemispherical photograph of a large gap in Guyana.

HEMIPHOT, A PROGRAMME TO ANALYZE VEGETATION INDICES, LIGHT AND LIGHT QUALITY FROM HEMISPHERICAL PHOTOGRAPHS

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FOREWORD

During a five-year stay in Guyana I conducted several long term experiments in the forest. Light measurements were an important factor in some, or gave additional information in others. A problem with long lasting experiments is that the light conditions will vary. One answer is to use dataloggers with several sensors. However, if year data are required for something like 40 sites this becomes either very time consuming or very costly. I therefore decided to use hemispherical photography. We acquired SOLARCALC from Robin Chazdon and did our first analyses with this programme. However, we had problems running SOLARCALC properly. This added to the fact that no Mac's were available in our TROPENBOS Programme in Guyana made me write a DOS based programme, PPFDCALC (1991), which enabled us to use 'video-grabbed' images produced with a hand-held scanner. A later version PPFD2 (ter Steege 1992) included a few more options plus a completely new object-oriented user interface. The final version HEMIPHOT (1993), again with an updated user interface, includes more ways to calculate light and does it faster in most cases through faster (often assembler) routines. This was encouraged by the new built in assembler (BASM) of Turbo 6 & 7 of Borland. The last version of HEMIPHOT was made with Borland Pascal and compiled in 80286 mode. Therefore it requires at least a 80286 machine with a VGA 640*480 compatible monitor, preferably with a co-processor.

Several people have been of assistance in developing PPFDCALC and HEMIPHOT. Miranda Boland and Ivo Verburg made the first set of photographs, Robin Chazdon kindly provided an executable copy of SOLARCALC plus the source code and Marcel Kramer conducted the first analysis on a Macintosh in Utrecht. The source code of SOLARCALC proved useful in an other way: the algorithm to calculate the equation of time is borrowed from it. Victor Jetten introduced me to Pascal 5.5, provided the meteo data of 1991 and 1992 and the icons of the OK and Esc buttons, plus a 'polygon area calculating' algorithm. David Hammond made me write an option to calculate gap size and provided gap photographs and corresponding ground data. Leo Brouwer supplied ground data of two very precisely measured gaps, Peter van de Meer provided gap photographs and ground data for gaps from French Guiana. John Pulles supplied a fast circle drawing routine and the C source code to read and write PCX files. Thijs Pons supplied red and far red measuring sensors. I would also like to thank Mitchell & Whitmore for providing a copy of their treatment of hemispherical photography.

Furthermore I would like to thank Feike Schieving and Niels Anten for fruitful discussions on leaf area index, light extinction and solar geometry and Thijs Pons, Dorinne Raaimakers and Wanda Tammens-de Rooij for critically reading the manuscript.

During the course of improving PPFD through PPFD2 into HEMIPHOT and writing several hand-outs, much more information on hemispherical photograph analysis has become available. Therefore this manual has become smaller than first intended. Nowadays several programmes are available that can analyze hemispherical photographs (e.g. CANOPY, Rich 1989; SYLVA, Becker *et al.* 1989 and

SOLARCALC, Chazdon & Field 1987). All of these programmes are based upon the same principles of solar geometry and atmospheric physics, combined with the geometry of hemispherical lenses. All methods and programmes to calculate LAI are based upon the exponential extinction of light through a canopy. HEMIPHOT, as such, is a variation on a well known theme. It is different compared to the other programmes in that it combines most analyses, that may be of interest to ecologists, such as photosynthetic photon flux density (PPFD), leaf area index (LAI,) red-farred ratio (R/FR) and gap size, into one programme. Furthermore it includes the use of grey scales to estimate penumbral effects. Finally by accepting a standard graphics file format (PCX) it has become independent of the scanning source.

1 INTRODUCTION

Light measurements pose problems in forest ecology. It either involves a lot of equipment or a huge amount of time. Neither of these two are usually available in excess. For daily courses of photosynthetically-active photon flux density (PPFD) data loggers with quantum sensors are ideal. They can also be used to obtain instantaneous values. PPFD measured inside a forest and e.g. above the canopy of the same site or in a nearby clearing provide an estimate of the percentage of PPFD available inside the forest. Sunflecks may create problems with these measurements as they have a much higher intensity than the surrounding diffuse light but are very patchy in their distribution, both in place and time (e.g. Raich 1989, Smith *et al.* 1992). Furthermore, measurements taken outside and inside the forest should be taken at the same time, as skylight conditions can change very quickly.

Another method of estimation of PPFD makes use of hemispherical photographs. Hemispherical (or fish-eye) photographs are made using a lens with a 180° view, which produces a circular projection of the sky hemisphere. This type of lens was first described by Hill (1924) and used in cloud cover and cloud height estimation. Evans and Coombe (1959) developed the first theory and methodology to use these photographs in forest light estimation. Anderson (1964) further quantified the technique, including the estimation of diffuse and direct light separately. She also showed that light estimation with photographs yields results very comparable to those made with light sensors. Apart from light a number of other parameters can be estimated from hemispherical photographs, such as, leaf area index (LAI) and leaf angle distribution (Anderson 1981, Bonhomme & Chartier 1972).

Since then a number of methods have been described, ranging from manual analysis which was very time consuming (Anderson 1964, 1966, Madgwick & Brumfield 1969), to semi-automated analysis (Bonhomme & Chartier 1972, Bonhomme *et al.* 1974) and computerized techniques (Becker *et al.* 1989, Chan *et al.* 1986, Chazdon & Field 1987, Rich 1990). Several of these require a substantial initial investment and/or make use of very specific scanning devices.

HEMIPHOT was developed with three main goals; 1) to provide a simple-to-use, menu driven programme running under the MS-DOS environment, 2) to make use of standard input files as to be independent of the scanning device and 3) to include as many possible applications for the use of hemispherical photographs. Thus the programme will run on any IBM or clone, with at least a 80286 on board, will accept PCX files generated by flat-bed scanners, hand-held scanners, video frame grabbers, digital cameras, or graphical software. The programme calculates cover, direct and diffuse light on horizontal and inclined surfaces, with black and white as well as with grey scale images, leaf area index, mean leaf angle, red to far-red ratio, gap size and a number of other graphical analyses.

In the following the methodology of taking photographs, scanning and the theory of the analysis is described. A brief methodology of field measurements is given. In the results section, theory and practice are compared. A full account on the program and how to use it is given in chapter 5.

2 METHODS

2.1 Photography

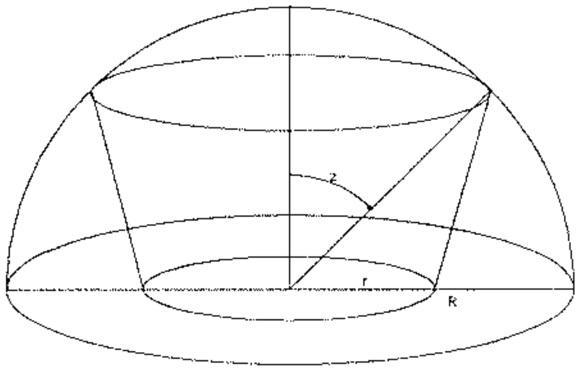

Figure 1. Hill or equidistant projection of the sky hemisphere: z/90 = r/R.

Hemispherical photographs are made with a fish eye lens (available from a number of companies, including Canon, Nikon, Olympus, Soligor etc.). We used a Sigma 8mm f 2.8. The lens should have a lens view of 180° and ideally an equiangular or polar projection (Hill 1924, Herbert 1987). This projection is characterized by a direct relationship between radial distance and zenith angle (Figure 1). Fish eye converters usually give less angle of view and produce more distortion (Anderson 1971, Evans *et al.* 1974, pers. obs.) and hence should not be used. Despite the higher costs, a true equiangular 180° fish eye lens is preferable The photographs are made with pan-chromatic black and white film. Kodak and Ilford both produced good, clear photographs in our work. The film speed can be anything from 25-100 (200) ASA. For good separation of sky and canopy a hard film will probably give the best results.

The camera is mounted horizontally on a stable tripod and levelled with a bubble or bulls-eye level, one side is directed to either the magnetic to the true north (note that the metal in the camera may influence the compass). For easy alignment in processing it is recommended that either the top or side of the picture represents the north.

As in normal photography a trade off exists between exposure time and depth of focus. Exposure times should be short, around 1/125s in the forest, shutter speeds lower than 1/60 may produce unsharp images due to leaf flutter and branch movement. Focus can be increased by decreasing the diaphragm but at the cost of shutter speed. In high forest a diaphragm of 3.5 or 5.6 gives good results but for lower canopies this may not be sufficient. I made most photographs with a diaphragm chosen in such a way that shutter speed would be around 1/125s. This was achieved with an Olympus OM 10 in semi-automatic mode. Others prefer to spot the exposure of the sky outside the forest and use this combination of shutter speed and diaphragm in the forest to lower the effect of sparkling of small openings. This results in 'under-exposure' in the forest and slight over exposure outside. Under-exposure may also limit the 'hindering' halos that appear otherwise around small canopy openings and make them appear larger (Hutchinson *et al.* 1980) This procedure may give sharp results but no great differences were detected with pictures made with semi-automatic exposure. In any case, making several exposures with different combinations will usually include the desired result.

Pictures should be taken during a grey/regularly overcast sky or early in the morning or late in the afternoon, a fact which has been stressed by all working with this technique. During bright days a sun near zenith will always produce scattering of light

through small holes in the canopy. Days with medium cloud cover but well defined clouds produce an irregularly lighted sky, even if the sun is behind a big cloud. Especially when working with grey scales this may give problems later, when classifying light canopy and dark sky.
Developing the film and producing prints are two steps in which large errors may occur. Within a study the procedure should be standardised as much as possible.

2.2 Scanning and image processing

Once proper photographs have been produced the next step is to convert the photograph into an image that can be handled by a computer. Several scanners are available ranging in resolution from 100 to 1200 dots per inch (DPI). The two most common types are flat-bed scanners (e.g. Cutie, Hewlett Packard, Thunderscan) and hand-held scanners (e.g. Cutie, Genius, Logitech). Hand-held scanning may require some skills and training, but they are far cheaper. Suitable images can also be made with video transducers (see e.g. Becker *et al.* 1989, Mitchell & Whitmore 1993), but these devices are more expensive. Storing an image in a standard format, such as TIF, GIF or PCX format reduces storage size required and enables the editing by several commercially available packages.
Most scanners allow some adjusting of the darkness level, that is the cut off level between white and black. To enhance resolution scanning may be done with 16, 32 or 256 grey scale levels. Alternatively a 400 DPI b/w image can be resampled to produce a 100 DPI image with grey scales.

Newer possibilities are scanning (and inversion) of negatives with film scanners or video transducers. This eliminates the step from negative to photo-print. Digital reflex-cameras with portable disk units eliminate even the processing of film to negative and may produce instant computer-images. At present the price tag of these devices (10,000 US$) will restrict their use.

2.3 Picture analysis

2.3.1 Canopy cover

The projection of the sky hemisphere can be thought to consist of 89 concentric rings, dividing the main radius (R, Figure 1) in 89 parts. Each ring corresponds to a circular sphere segment in the sky hemisphere with a arc of 1 degree. The area of all segments is different and will be smaller on those segment nearer to the sky zenith. To obtain canopy cover from a hemispherical photograph we can calculate cover for each of the 89 rings, but have to correct for the actual area of that segment on the sky hemisphere. The area on a sphere segment defined by a lower angle α_1 and an upper angle α_2 is given by

$$A_{\alpha 1\,-\,\alpha 2} = 2\pi \cdot R^2 \cdot (\sin\alpha 2 - \sin\alpha 1) \qquad (1)$$

In the forest this relation can be used to estimate the approximate canopy cover in gaps (see Appendix 1).

Since the total hemisphere has an area of $2\pi R^2$, the fraction of the sky given by each of the 89 rings is given by

$$A_\alpha = \sin(\alpha + 0.5) - \sin(\alpha - 0.5) \tag{2}$$

With α from 0.5 to 89.5. Thus to obtain the total canopy cover of a site we have to obtain the sum of the cover fractions (C_α) per circle multiplied by their part in the sky fraction

$$canopy\ cover = \sum_{\alpha=0.5}^{\alpha=89.5} [T_\alpha \cdot A_\alpha \,/\, A_{tot}] \tag{3}$$

Canopy cover calculated as such is a measure of total cover of the sky hemisphere and not identical to vegetation cover as used in syn-ecology, which is a horizontal projection of cover. Canopy cover is an independent powerful canopy characteristic, not influenced by location of study site. Proper alignment with respect to the geographic north is unimportant for calculation of canopy cover.

2.3.2 Leaf area index

The leaf area index (LAI) of a vegetation may be important in a number of studies, including photosynthesis modelling, rain interception, evaporation. The LAI of a vegetation is defined as: the amount of leaf area per unit of ground area. LAI is difficult to measure precisely, particularly in forests. Several methods exist (Norman & Campbell 1989). Direct measurements such as the clipping of all foliage include undoubtedly the most precise but can be very laborious in agricultural crops or even nearly impractical in tropical forests.

Many indirect measurement methods are based upon the determination of gap fractions in the foliage. Light has a chance to be intercepted by leaves as it passes through the vegetation. The chance of being intercepted depends on the path length through the vegetation, the foliage density and foliage orientation. With the assumptions that leaves are small, randomly distributed, have no azimuthal preference and do not transmit light, the gap fraction in the zenithal view angle z can be related to LAI. However, the gap fraction at a given angle is highly dependent of the leaf angle distribution. For instance a vegetation with nearly vertically arranged leaves will show a high gap fraction at z = 0°, whereas a vegetation with horizontally arranged leaves and similar LAI will show a much lower gap fraction at this angle. The gap fraction (T) at z = 67.5° is little affected by leaf angle (Bonhomme & Chartier 1972, Norman & Campbell 1989, Welles & Norman 1991) and is related to LAI (Bonhomme & Chartier 1972) as

$$LAI = 1.1 \cdot -\ln(T_{67.5}) \tag{4}$$

On hemispherical photographs this is by far the simplest way to estimate LAI. However, errors at 67.5° will affect the LAI estimated for the total vegetation as seen by the lens. It is also possible to include more viewing angles to get a more accurate estimate of LAI and also be able to estimate mean leaf angle. A method described by Welles & Norman (1991), which is used by the LI-2000 Plant Canopy Analyzer is implemented in HEMIPHOT. As in the Plant Canopy Analyzer five viewing angles are used: 7, 23, 38, 53, 68. The gap fraction (openness, T) around each viewing angle, in bands of 15°, is calculated with similar methods as total openness for the hemisphere (formulae 13 to 15) and total LAI is then calculated as (Welles and Norman 1991)

$$LAI = 2 \cdot \sum_{z=7}^{z=68} [-\ln(T_z) \cdot W_z / S_z] \qquad (5)$$

where z takes the five values mentioned above, W_z are weights to account for area correction and S_z are the reciprocal path length corrections $1/\cos\theta_z$. For restrictions using this method see Welles & Norman (1991).

HEMIPHOT includes two more methods to estimate LAI with the openness of five view angles. One method uses an inversion of a matrix for three leaf angle classes and the last method uses a matrix inversion with an ellipsoid leaf angle distribution. Both methods are described in detail by Norman & Campbell (1989). HEMIPHOT uses Pascal translations of the BASIC listings given in their treatment of canopy structure.

2.3.3 Light

Solar geometry

Solar tracks are calculated with standard spherical trigonometry (Figure 2, e.g. List 1984, Gates 1980). solar altitude (α), the angle of the sun with the horizontal, is calculated as

$$\sin\alpha = \sin\psi \cdot \sin\delta + \cos\psi \cdot \cos\delta \cdot \cos\eta \qquad (6)$$

where ψ is latitude, δ is the declination of the sun and η is the hour angle. Note that solar altitude, sometimes referred to as angular elevation or solar angle, equals $\frac{1}{2}\pi$ - z (z = zenithal angle) and thus $\sin\alpha = \cos z$. Sine and cosine (both are required) of solar azimuth (β), the angle of the sun with the north-south axis, are calculated as (Campbell 1981)

$$\sin\beta = -\cos\delta \cdot (\sin\eta \,/\, \cos\alpha)$$
$$\cos\beta = -(\sin\delta - \sin\psi \cdot \sin\alpha) \,/\, (\cos\psi \cdot \cos\alpha) \qquad (7)$$

Solar declination is a function of the day in the year and is calculated according to Campbell (1981, 1985)

$$\delta = 0.39785 \cdot \sin[4.869 + 0.0172 \cdot day + 0.03345 \cdot \sin(6.224 + 0.0172 \cdot day)] \qquad (8)$$

where day is the Julian day number, 0.0172 is a constant ($2\pi/365$) to convert the Julian day to the day angle. The declination ranges from 23.5° at June 21, the summer solstice, to -23.5° at December 21, the winter solstice. Except for the solstices each declination occurs twice a year. A declination of zero, equinox, occurs on March and September 21.

Direct light

The estimation of direct light requires several steps. First of all an estimate of the amount of radiation on the outer atmosphere is required. This amount, the Solar constant (S_c) is a function of the amount of radiation emitted by the sun and the distance between the sun and the earth and amounts to approximately 1360 W m^{-2} (Gates 1980). However, the orbit of the earth around the sun is elliptical rather than circular and the sun is not directly in the centre of this ellipse Consequently the radiation on the outer part of the atmosphere must be calculated for each day (Kreith & Kreider 1978)

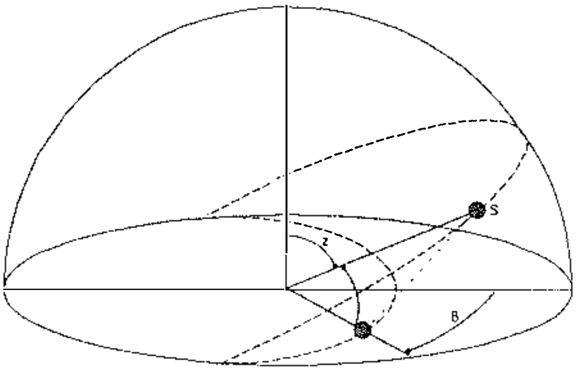

Figure 2. Location of the sun with projections and solar angles.

$$S_{out} = S_c \cdot [1 + 0.034 \cdot \cos(2\pi \cdot day / 365)] \tag{9}$$

Thus the deviation from 1360 W m^{-2} is plus or minus 3.4%. Secondly the loss of radiation due to atmospheric absorbtion and scattering must be estimated. Both transmissivity and path length through the atmosphere influence the amount of direct light on a surface normal to the beam (Gates 1980).

$$S_{no} = S_{out} \cdot \tau^M \tag{10}$$

Where τ is the transmissivity of the shortest atmospheric path length (= 1 optical airmass, sun in zenith). τ is usually between 0.5 and 0.8 (but may be as low as 0.4 in the tropics, Whitmore *et al.* 1993) and mostly taken as 0.6 (Gates 1980), and M is the relative path length in number of optical airmasses, ranging from 1, with the sun in zenith, to around 36 at sunrise and sunset (List 1984). M can be estimated accurately by 1/cos(z) for solar angles over 30° (zenithal angles less than 60°). List (1984, Table 137) gives data for angles under 30° and all others. M can also be calculated accurately for all solar angles (Kreith & Kreider 1978)

$$M = \sqrt{1229 + (614 \cdot \sin\alpha)^2} - 614 \cdot \sin\alpha \tag{11}$$

M can be corrected for altitude (Kreith & Kreider 1978)

$$M_h = M_0 \cdot p_h / p_0 \tag{12}$$

where p_0 is the atmospheric pressure at sea level and p_h is the atmospheric level at altitude h.

p_h/p_0 is calculated according to the International Commission of Air Navigation (ICAN) standard atmosphere (List 1984, Table 64).

$$p_h / p_0 = [(288 - 0.0065 \cdot h) / 288]^{5.256} \tag{13}$$

The airmass is obviously also affected by atmospheric pressure but this effect is neglected in HEMIPHOT. Finally the amount of direct light (S_{dir}) on a horizontal surface should be cosine corrected and is calculated as

$$S_{dir} = S_{no} \cdot \sin\alpha \tag{14}$$

All values are short wave radiation in W m^{-2} (300-3000 nm). At tropical latitudes approximately 51% of the incoming radiation is PAR (400-700 nm, Stigter & Musabilha 1982), but can be as high as 61% under full cloud cover. A factor 4.6 is used to convert W m^{-2} to μmol m^{-2} s^{-1} (McKree 1981).
Calculation of the amount of direct light at the site of exposure involves the calculation of the amount of direct light as above and the location of the sun on the projection of a solar track on a particular day usually in steps of 1 to 3 min and determining if a pixel on that location identifies open sky (white) or obstructed sky (black). The assumption is made that there is direct light as calculated above if the sun is not obstructed and there is no direct light if the sun is obstructed by canopy structures. This is an obvious simplification as it ignores cloudiness, penumbral effects and scattering within the canopy. As the solar disc is 0.5° degrees, which corresponds to approximately 1 pixel at an image diameter of 360 pixels this works fairly well as an estimate (Chazdon & Field 1987, but see below for penumbral effects).

Diffuse light
Diffuse light originates from direct light, scattered by the atmosphere. Clear skies scatter differently from clouded skies, due to different properties of both sky types (see Gates 1980). For most purposes, under clear sky conditions, the amount of diffuse light on a horizontal surface can be estimated as being 15% of the amount of direct light added to the amount of direct light on that same surface (Gates 1980). However, at low solar altitudes the amount of diffuse light may be much larger (over 50%). Thus a more accurate (empirical) estimation for diffuse light in a clear not dust-free sky is given by (Liu & Jordan in Gates 1980)

$$S_{dif} = S_{out} \cdot (0.271 - 0.294 \cdot \tau^{M}) \cdot \sin\alpha \tag{15}$$

Similar observations were made by Goudriaan (1977). The amount of diffuse light is not distributed equally over the sky hemisphere (Gates 1980). However, it can be simplified without much loss of accuracy by the Standard Overcast Sky (SOC) in which the illumination (I_z) of an point at zenithal angle z is given by (Anderson 1971)

$$I_z = I_Z \cdot (1 + 2 \cdot sinz) / 3 \tag{16}$$

SOC estimates the sky at zenith (Z) three times as bright as compared to the sky near the horizon. The Uniform Overcast Sky (UOC, Monsi & Saeki 1953) assumes that each part of the sky is equally bright. When gaps are mainly overhead and only diffuse light is present at zenith (often at high latitudes) both sky estimations may result in quite different estimations of the total amounts of light (cf. Madgwick & Brumfield 1969). In reality most diffuse light originates from 10° around the solar disc and both SOC and UOC are poor estimators of instantaneous diffuse light as they neglect the solar angle (Hutchinson *et al.* 1980), but differences are small when averaged over a longer period.

In hemispherical photograph analysis often the terms indirect (diffuse) site factor (ISF), direct site factor (DSF) and total site factor (TSF) are used as introduced by Anderson (1964). The factors are the fractions of direct, indirect or total radiation that will penetrate at a particular site relative to the amount of radiation above the canopy. DSF, ISF and TSF are often strongly correlated (Turner 1990, Whitmore *et al.* 1993, ter Steege 1993, ter Steege *et al.* 1993). The indirect site factor is important in the calculation of diffuse light.

The indirect site factor and finally the amount of diffuse light (D_u) at the site of exposure is calculated for the UOC as

$$D_u = S_{dif} \cdot \sum_{\alpha=0.5}^{\alpha=89.5} [C_\alpha \cdot (A_\alpha / A_{tot}) \cdot \sin\alpha] \tag{17}$$

and for the SOC as

$$D_u = S_{dif} \cdot \sum_{\alpha=0.5}^{\alpha=89.5} [C_\alpha \cdot (A_\alpha / A_{tot}) \cdot (1 + 2 \sin z) \cdot \sin\alpha] \tag{18}$$

Under leaf canopies diffuse light may also originate from scattering (reflection and transmission) by leaves. Scattered light may represent a large quantity under closed canopies (up to 43%, see Mitchell & Whitmore 1993). Multi-layered canopies models which include scattered light do exist (e.g. Goudriaan 1977) but such models are not included in HEMIPHOT. HEMIPHOT can estimate transmitted light with a simple extinction model (see below).

Finally direct and diffuse light are added to result in a total amount. Daily totals can be found by summing all instantaneous values per two minutes and multiplying those by 2 times 60 (2 minutes of 60 seconds).

Penumbra

The sun is not a perfect point light source. In fact with a radius of 696 $\cdot 10^6$ m at a distance of 149.6 $\cdot 10^9$ m it forms a disk at the sky hemisphere of approximately 0.5°. The fact that the sun is not a perfect point light source is causes penumbral effects (e.g. Anderson & Miller 1974, Miller & Norman 1971). Ignoring penumbral effects the light intensity can only be direct or direct plus diffuse light. With an image diameter of 300 to 400 pixels the size of one pixel is approximately equal to the image size of the solar disk. As the sun hops from one pixel to the next it will either be totally visible or totally obscured by vegetation. Daily courses of PPFD may compare relatively well with data from data loggers (Chazdon & Field 1987) but the procedure neglects the gradual changes caused by the size of the solar disc. Furthermore, low resolution scanning in black and white may result in a loss of tiny holes in dense canopies.

Sunflecks on the forest floor consist of an area of full sunlight (umbra), which at the edges gradually changes into full shade. In the area where the gradual change takes place, the actual penumbra, the light intensity (Dir_{pen}) is a function of the amount of solar disk 'seen' by the exposure site (Miller & Norman 1971)

$$Dir_{pen} = Dir \cdot [1 - (U \cdot \sqrt{1 - U^2} - \arccos(U)) / \pi] \tag{19}$$

It can be shown that the size of the penumbral area depends on canopy height but is independent of the canopy opening (Appendix 2). The size of the area with full light intensity (numbra) depends both on the size of the canopy hole and the height of the canopy. A 'sunfleck' consists solely of penumbral area if the ratio between the diameter of the hole and height of the canopy, D:H, is 0.01 (Appendix 2, Smith *et al.* 1989).

To allow for the inclusion of penumbra in the photo analysis, photographs can be scanned at 400 DPI (b/w) and resampled at 100 DPI with 256 grey scales. These 256 grey scales are truncated by HEMIPHOT into 16 scales (0-15) for calculations. It is assumed that if a pixel has a value of 5 that 5/15th part of the sun is visible at that point. It is possible to relate the amount of the solar disc seen with the amount of light received (Equation 19, Figure 3). This function, which relates light intensity to the amount of solar disc cut off by a straight leaf edge, is not linear (Equation 19) but approximation by a straight line will not cause too large overall errors. Furthermore edges will not always be straight and may be caused by more leaves. Thus if a pixel has value x ($0 \leq x \leq 15$) then the amount of light passing through the canopy at that time and place is approximately $S_{dir} \cdot x/15$.

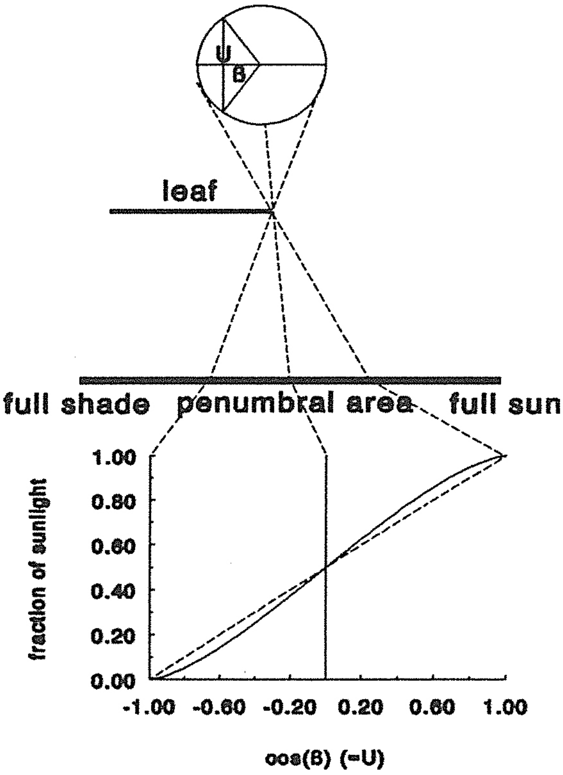

Figure 3. Light intensities in solar penumbra as a function of the position within the penumbral area.

2.3.4 Light quality

The light quality under a closed canopy is notably different from that above the canopy or in gaps (e.g. Schulz 1960, Lee 1987, Brown 1993). The most commonly used parameter in this respect is the ratio between red (655-665 nm) and far-red

(725-735 nm) photon flux, the R/FR. The change in quality has profound effects on the morphology of plants (Smith 1982) and seed germination (Vasques-Yánes & Orozgo-Segovia 1984), especially in pioneer species.

When light passes through a vegetation it is intercepted by foliage. If we consider the vegetation to consist of many (n) small layers of horizontal leaves, all of which with an equal part of the total LAI, then each layer will have a partial leaf area of L =LAI/n. The chance of a light beam of not being intercepted in such a layer is then 1-L. After n layers the chance of still not being intercepted becomes $(1-L)^n$ or the total light intensity relative to that of above the canopy after n layers becomes

$$I_n = I_0 \cdot (1 - L)^n \qquad (20)$$

or in exponential form

$$I_i = I_0 \cdot e^{n \cdot \ln(1 - L)} \qquad (21)$$

Usually this formula is given in the form of (e.g. Monsi & Saeki 1953)

$$I_i = e^{-K \cdot LAI} \qquad (22)$$

Thus light diminishes exponentially in a vegetation with respect to LAI and there is no change in quality if we assume that leaves do not transmit any radiation. The last is obviously not correct. Leaves do transmit some light (and reflect some as well). Moreover, transmission and reflection are wavelength dependent. Red and blue light are absorbed much more than is green or far-red light (e.g. Gates 1980, Lee 1987). The light in the understorey is, apart from being green, rich in far-red light, compared to that of above the canopy. The transmittance of leaves in the red and blue part of the spectrum is approximately 2-5% and in the far-red part up to 55% (e.g. Goudriaan 1977, Gates 1980, Lee 1987). Thus after each successive leaf layer there is a relative enrichment of far-red light. If we assume a canopy with small, randomly placed leaves then the changes of light beam passing through x leaves (n from 0 to 10 or more) should follow a Poisson series, where the chance of being intercepted by x leaves is

$$p_x = e^{-\mu} \cdot \mu^x / x! \qquad (23)$$

and the amount of total transmission

$$T = \sum_{x=1}^{x=n} [e^{-\mu} \cdot (\tau \cdot \mu^x) / x!] \qquad (24)$$

A similar conclusion was made by Alexandre (1982). μ depends on the LAI as seen above. Alexandre argued that τ would be different for each successive layer, as the leaves do not have equal transmittance over the range of light studied. Furthermore, Alexandre used μ = -kF and calibrated the summation for use under a forest canopy with a given LAI. When using hemispherical photographs, however, we know the chance of a light beam touching no leaves, which is equal to the canopy openness, θ. Thus

$$\theta = e^{-\mu} \rightarrow \mu = -\ln(\theta) \qquad (25)$$

From T_0 all next terms can be calculated. HEMIPHOT calculates the summation up to 10 leaves, after which the transmitted fraction is considered negligible. For red light a transmission of 5% is used, for far-red light a transmission of 45%. But these can be changed to fit other circumstances. In calculations of diffuse light summation (Equation 24) of zero up to ten leaves is used. In calculations of direct light the information of solar geometry and canopy structure is used. If the sun is not obstructed by foliage R/FR has a similar value as above the canopy, if the sun is obstructed by foliage equation 24 is used from one to ten leaves, with p_0 similar to the diffuse calculations.

The same procedure can also be used to calculate the amount of transmitted total PPFD to allow for estimation of at least a part of the scattered light component. Re-reflected light can be accounted for in canopies (Goudriaan 1977). Light directly reflected from lightly coloured trunks is not easily implemented in a model.

2.3.5 Gap size

Gap size is a frequently used term in ecology. Gap sizes are difficult to measure in the forest and a few definitions have been put forward. The first standardization was made by Brokaw (1982): *'A gap is a "hole" in the forest extending through all levels down to an average height of two m above ground'*. The size is estimated by locating the edge of the gap in eight compass directions and calculating the size of the octagon formed by these eight points. Brokaw suggested that *'Irregularities of outline tend to cancel out'*. Popma *et al.* (1988) showed that the area affected by a tree-fall was normally much larger than as estimated with Brokaw's method. A similar manner to estimate gap size was described by Runkle (1981), who defined the gap as the area surrounded by the bases of the large trees forming the edge. Minimum size of the trees used is 20 cm DBH. Estimates made with the different methods may yield very different results (van der Meer *et al.* in prep.) and thus will produce completely different turn over times of the forest if data are gathered for this purpose.

Plants are obviously more affected by changes in micro-climatic parameters associated with gap size than by gap size per sé. With increasing gap size light levels, soil temperature and air temperatures tend to increase and humidity tends to decrease (Schulz 1960, Chazdon & Fetcher 1984, Whitmore *et al.* 1993, Brown 1993). Physical gap size is a much poorer predictor of these micro-climatic variables than canopy openness or site factors (Whitmore *et al.* 1993). Thus an 'ecological gap size' may better be estimated through the calculation of canopy openness. Moreover, structural gap size estimations do not take the height of the canopy into account. If one is interested in the effect of gap size on the increase of light levels this is an important flaw (van der Meer *et al* in prep., Whitmore *et al.* 1993).

Still structural gap size gives a general idea of the size of the disturbed area and may thus be important for comparison between studies. An estimate of gap size in m^2 can also be obtained with hemispherical photographs.

Assuming a relatively homogeneous gap edge height (note that this is often not the case!) we can calculate the gap size using the equiangular projection of the fish eye lens. If the height of the canopy is H and the edge of the canopy is located on the projection at distance r/R, R being the total radius, then the horizontal distance of that canopy point from the location of the photograph in the field is

$$D = H \cdot \tan(r \cdot 90 / R) \tag{26}$$

Note that r · 90/R gives the zenith angle. Since the compass directions of the points are given by the azimuth (β) of the points at the photo projection, the coordinate of a point in the field can be given as ($D \cdot \cos\beta$, $D \cdot \sin\beta$). HEMIPHOT allows two methods 1) estimating the gap size in Brokaw's manner, defining eight canopy heights and locating those points on eight compass lines or 2) giving one average canopy height and selecting as many gap edge points as are wanted. Total gap area is then calculated as

$$Gap\ Area = \left| \sum_{i=1}^{i=n} [(x_{i+1} - x_i) \cdot (y_{i+1} + y_i)] / 2 \right| \tag{27}$$

where the last point (n+1) is equal to the first point.

2.4 Methods used to test the programme

2.4.1 Light measurements

Data logging and instantaneous measurements
To test the accuracy of HEMIPHOT several measurements of the light climate were made in the rain forest of the TROPENBOS Ecological Reserve, Mabura Hill, Guyana. Light on a site was measured each minute with two quantum sensors (Li-Cor inc., LI-191SB) attached to a LI-1000 (Li-Cor Inc.) data logger. R/FR was measured each minute with custom made R/FR sensors connected to the LI-1000 in current mode (Pons 1983). Data were logged on several days in the forest understorey, in small gaps and in large gaps. On a few bright days, light levels and R/FR were measured manually, with the above equipment, in the shade in the understorey, in light flecks of different size, small gaps and large gaps, in shade and in full sun.

Year round radiation measurements
At the northern edge of the Ecological Reserve a small meteo-station was set up in 1990. Among several parameters, radiation was measured for more than two years in hourly averages (Jetten 1993a,b). These measurements (W m^{-2}) were converted to PAR as above. A hemispherical photograph was taken at the exact site of the radiation sensor and PPFD was calculated with HEMIPHOT for each day in the year for that site.

Radiation and hours of sunshine
Radiation has been measured for a long time by the meteorological service in Guyana. More recently a sunshine recorder network was set up (Persaud 1982). Four

stations are relatively near and surrounding Mabura Hill. The average amount of sunshine hours per month and per year was used to correct the amount of direct light, with the assumption that no sunshine recorded meant no direct light. Thus the direct light calculated could be multiplied by [possible sunhours/actual sunhours]. Furthermore data from Georgetown included both radiation and sunshine hours per day. These data were used to find a relation between sunshine hours and the amount of radiation.

2.4.2 Leaf area index and light quality

Leaf area index

Artificial canopy images were made with LAI's from 1 to 10, assuming spherical leaf angle distribution. Each point on the image was randomly assigned a black or a white pixel depending of its view angle and the average theoretical openness (T_z) of that view angle ($T_z = e^{[(-LAI/2)/\cos(z)]}$). The four methods included in HEMIPHOT were compared on a number of different images. No attempt was made to estimate the LAI of the forest around Mabura, other than with photographs.

Leaf transmittance and red:farred ratio

Leaves of dominant canopy tree species were collected and the transmittance to PAR, red and far-red light was measured. Light generated by a 12V Quartz halogen lamp was directed on a LI-191SB sensor through a small tube, which was bright white inside and black on the outside. The round sensor fitted neatly in the opening of the tube. The output of the sensor was measured and a leaf was placed on top of the sensor and the output was recorded again. Transmittance was calculated as the output with leaf divided by the unobstructed output. Similarly transmittance was measured for red and farred with the subsequent sensors. Data obtained for these leaves were used to test HEMIPHOT against the R/FR measurements made with the data loggers and the instantaneous measurements.

2.4.3 Gap size

Comparison of true and calculated gap sizes

Hemispherical photographs were made in several gaps of which ground data was available. A first set of gaps (courtesy David Hammond) was measured with Brokaw's method. Distance to the centre and height of the gap edge were measured on eight lines. Two other artificial gaps, created for nutrient balance studies were measured very carefully with a grid (courtesy Leo Brouwer) and photographs were taken in the centre of them. These gaps were also used as data logging sites (see above). Finally photographs of gaps with ground data from French Guiana were supplied by Peter van de Meer, Wageningen. Gap sizes measured in the field were compared with gap sizes computed by HEMIPHOT. Calculations were also made with artificial circular gap images with increasing gap size.

3 RESULTS AND DISCUSSION

3.1 Light

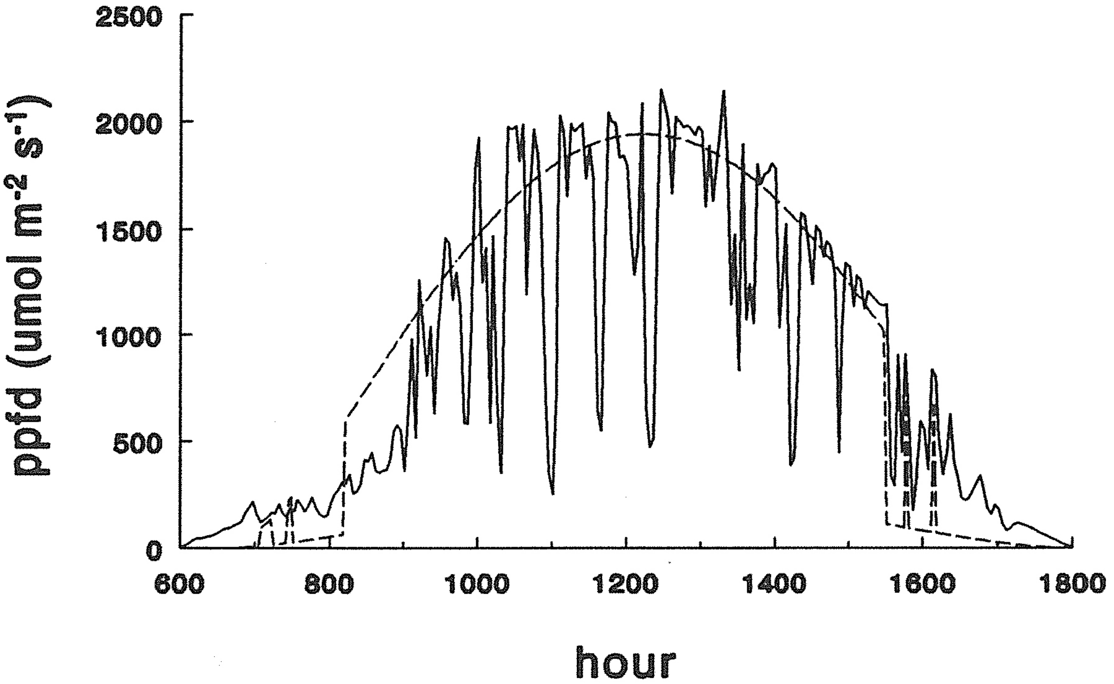

Figure 4. Measured (solid line) and predicted (broken line) PPFD from 6. to 18. h in a large gap in Guyana.

Values for PPFD calculated for large open sites compare very well those measured. Figure 4 shows calculated and measured values for a large open site (cover 44%). Some persistent cloud cover was present between 800 and 900 hours and clouds obscured the sky various times of the day. Between 1500 and 1615 hours two tree canopies obscure the track of the sun and this is interpreted well by HEMIPHOT. It is obvious that due to irregular cloud cover total daily calculated and measured PPFD do not match (measured 37.5 and calculated 40.9 mol m^{-2} d^{-1}). Furthermore measured peak intensities are higher than the calculated values. This could in part be explained by high light intensities as a result of reflection of direct light on clouds (Gates 1980) but especially in the morning by a higher atmospheric transmittance (τ) than 0.6, as the measured peak values are consistently higher than the calculated ones.

Figure 5 shows the results for an understorey plot. Analysis with 16 grey scales gives results that are in closer resemblance to output of data loggers than using b/w images. The small peaks between 1200 and 1400 hours are better interpreted by the 16 grey scale analysis. As for the former site, total PPFDs for the day do not match due to unpredictable cloud cover.

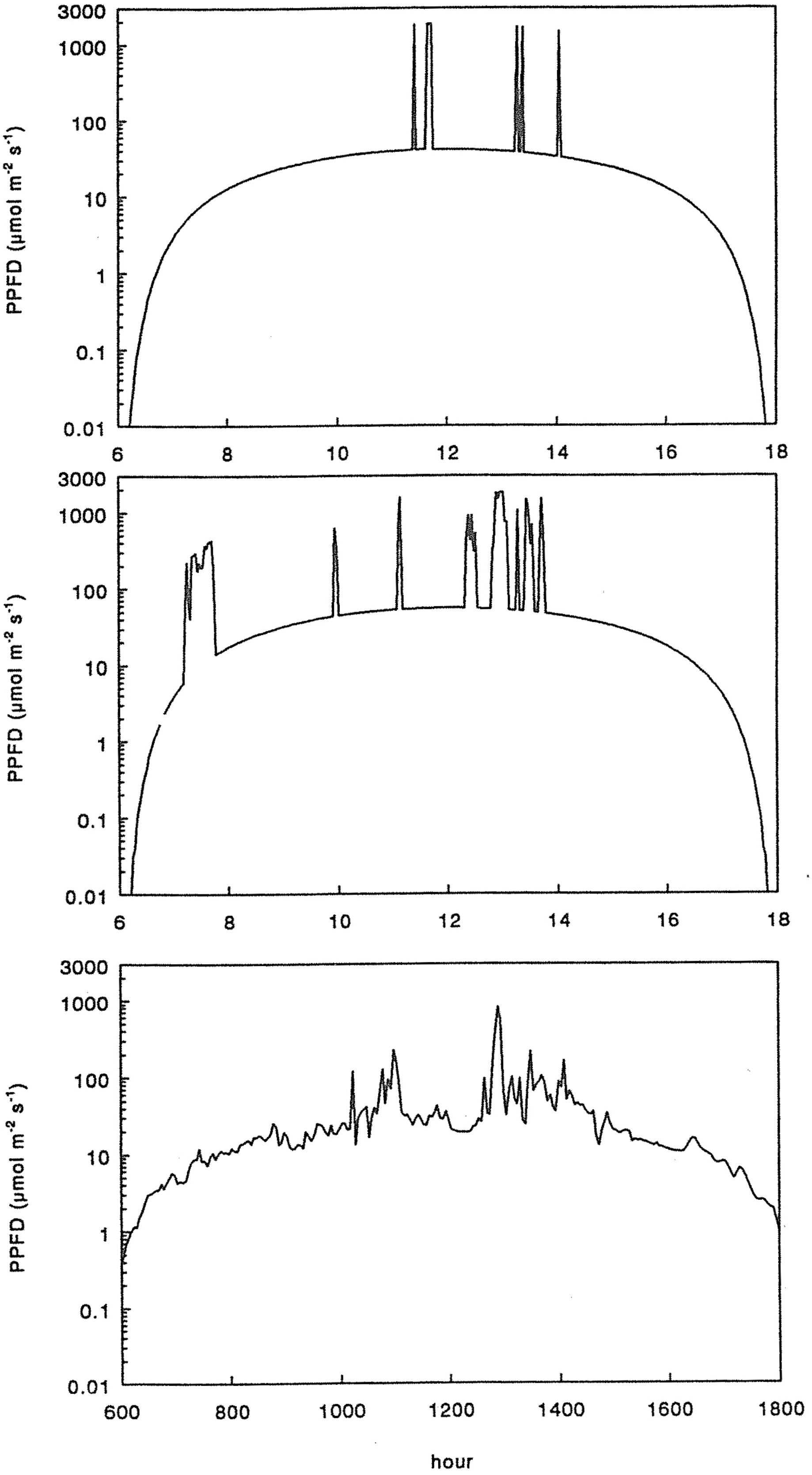

Figure 5. Daily courses of PPFD on 17/8/1993 for an understorey site, calculated with b/w image (top), grey scale image (centre) and measured with a datalogger.

Generally year averages compare well to values found in literature (Chazdon & Fetcher 1984, Oberbauer & Strain 1985, Raich 1989). However, due to the lack of precise estimation of timing of cloud cover, the lack of precise diffuse sky modelling and difficulties in exact aligning, daily courses of PPFD are instructive but unreliable.

Daily values for the large meteo-station gap in Figure 6 show the lack of precise correspondence between calculated daily values and daily measurements for 1991 and 1992. Measured values never exceed the calculated ones but are mostly substantially lower. Several factors contribute to the large differences. Firstly HEMIPHOT makes no *a priori* corrections for cloud cover. Secondly, the amount of diffuse light may not be a 15% of direct light and thirdly, τ may not be 0.6 for tropical latitudes (see Whitmore *et al.* 1993). A simple correction would be to multiply the ratio of actual and potential sunshine hours with direct light (both averaged per month), as suggested by ter Steege *et al.* (1994).

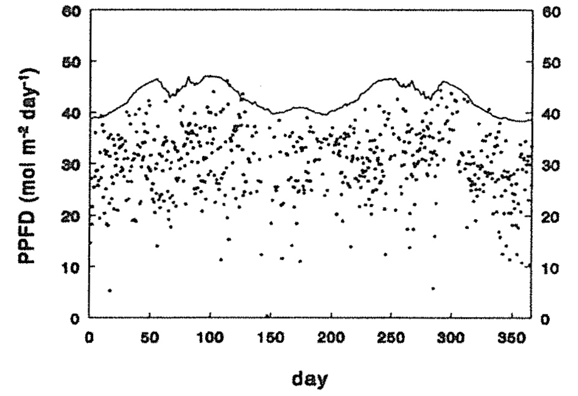

Figure 6. PPFD measured in a large gap in 1991 and 1992 (after Jetten 1993a,b). Top line: calculated PPFD for this site.

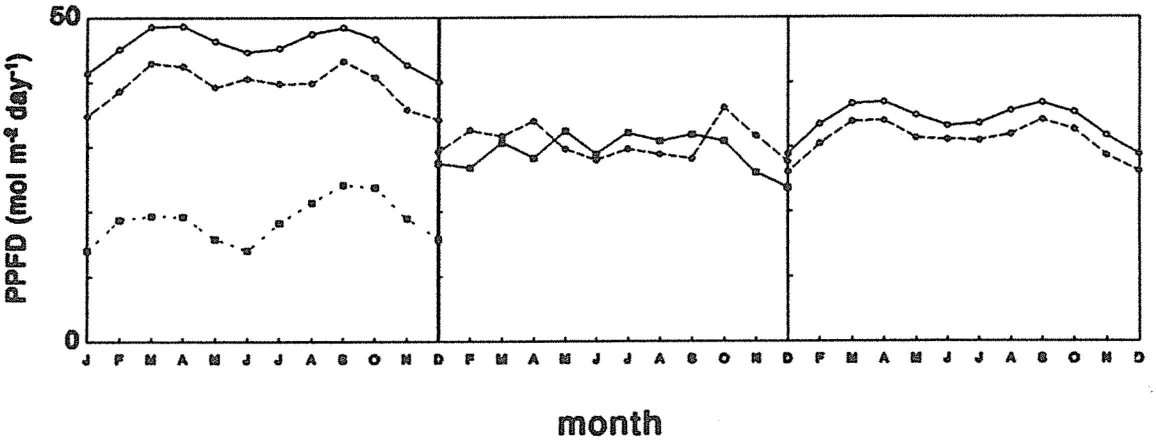

Figure 7. Average monthly PPFD per day for a large gap in Guyana. Left: top line total PPFD above canopy with atmospheric transmission at 0.6 and diffuse as 15% of direct, middle line total in the gap, bottom total in gap with correction for cloud cover. Centre: measured average daily totals for 1991 and 1992 (Jetten 1993a,b). Right: top line total PPFD above canopy with atmospheric transmission set at 0.4 and diffuse as 40% of direct.

This is shown in Figure 7 (left). Values obtained with this correction are far too low compared to the actually measured monthly averages (Figure 7, middle). Note that the average amount of PPFD per day is rather constant throughout the year at roughly 30 mol m^{-2} day^{-1}. A similar observation was made by Raich (1989). Periods with thin cloud cover may not be recorded as sunshine periods, but light penetrating through these clouds may be much higher than ambient diffuse light (pers. obs.). Thus, in periods with sunshine too low to be recorded by the Campbell-Stokes sunshine recorders, there is some direct light but τ is much lower than 0.6. Whitmore *et al.* (1993) made similar observations under what they called 'hazy sky' and calculated an average τ for their Bornean site (4° 54' N) of 0.4. Furthermore diffuse light may be more than 15% of direct light (Whitmore *et al.* 1993, Brown 1993, and below).

Due to the irregular pattern in cloud cover reliable estimates are hard to make with a computerized method, unless for non-overcast days. Values obtained by setting a standard diffuse percentage and a standard atmospheric transmission will therefore only be comparable for sites that are nearby. To be able to compare sites at different latitudes straightforward analysis with hemispherical photographs alone is insufficient (Whitmore *et al.* 1993). Mitchell & Whitmore (1993) and Whitmore *et al.* (1993) suggested two methods to estimate absolute light quantities from hemispherical photographs. For the first method absolute direct and diffuse amounts above the canopy are necessary. Both can be multiplied by their respective site factor to obtain a more reliable total estimate of PPFD. Errors in this method still include a lack of knowledge of timing of cloud cover. Thus in the particular case when the solar track passes holes only in the morning and not in the afternoon, while at the same time cloud cover is present at one interval and absent in the other, some error occurs. Averaged over a year Whitmore *et al.* (1993) considered this to be of small importance. If no separate values for direct and diffuse light are available, average total PPFD of above the canopy may be multiplied by the total site factor. The second method requires the precise knowledge of sunshine hours for fixed parts of the day (e.g. in one or two hour periods), and reduce direct light with the fraction of cloud cover for that period. Diffuse light is then calculated as a percentage of direct, using either the UOC or SOC.

There are no separate measurements of diffuse and direct light in Guyana but data from the meteorological station in Georgetown include both sunshine hours and radiation (Hydromet 1976). Radiation for this station from 1974 is displayed in Figure 8. The data appeared unrealistically high. To fit all observations under the maximum theoretical amount (the top line in Figure 8) an average atmospheric transmission of over 0.7 had to be assumed. A correction factor of 0.85 was used to bring most observations under the theoretical maximum (with atmospheric transmission of 0.6). The average is then around 30 mol m^{-2} day^{-1}, which is consistent with the data from the meteo-station in Mabura Hill . As with the daily measurement from the Mabura meteo-station gap actual values are often considerably lower than predicted ones. Still

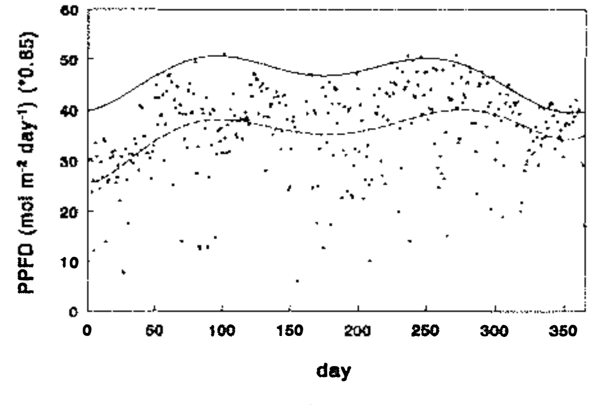

Figure 8. Daily PPFD for Georgetown (after Hydromet 1976), with calculated daily maximum (top line) and fitted 6th order polynomial (lower broken line) to show bi-modality in the data.

the bi-modality, with the peaks at the right place, can be picked up with a 6th order polynomial regression.

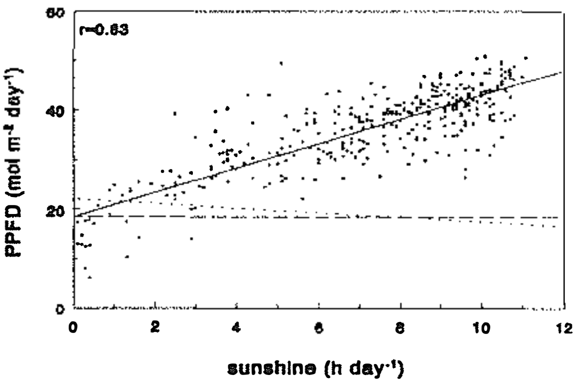

Figure 9. Correlation of daily sunshine hours and PPFD for Georgetown 1972 (after Hydromet 1976). The horizontal line indicates diffuse light, the down sloping broken line diffuse light after Whitmore *et al* 1992.

Actual daily PPFD (monthly average) is strongly related to sunshine hours per day (Figure 9). During totally overcast days the site still receives around 19 mol m^{-2} d^{-1} (21.3 without correction). This is in close correspondence to values obtained by Whitmore *et al.* (1993) and Brown (1993). As the amount of direct light is mainly influenced by the amount of true sunshine hours (though light cloud cover may produce direct light but no recorded sunshine on the Campbell-Stokes recorders), the linear relation predicts that the amount of diffuse light should remain rather constant around 19.3 mol m^{-2} d^{-1} for all days. Data of Whitmore *et al.* (1993) show indeed only a very slight decrease of diffuse sunlight as a function of the amount of total light per day (see Figure 9). As the amount of average daily sunshine hours per month is known for a number of sites around Mabura, these can be used to estimate the amount of diffuse light as a percentage of direct light. The amount of actual sunshine hours in the forestry belt is approximately 47% (5.7 hours, ter Steege 1993, ter Steege *et al.* 1993, here presented as 5.2 per 11 hours) and this would suggest an average PPFD of slightly over 30 mol m^{-2} d^{-1} (read from Figure 8, 35 mol m^{-2} day^{-1} if uncorrected) of which 19 mol is diffuse (66% of the total light). Brown (1993) reports an average of 58% of diffuse light. The average daily amount of 30 mol m^{-2} day^{-1} agrees well with the data of our own meteo station (29.9 mol m^{-2} day^{-1}, Figure 9). The values show striking similarity with those of Whitmore *et al.* (1993, Borneo) and Brown (1993, idem), who report 47% sunshine amounting to 5.7 hours per day, with an average of 35.3 mol m^{-2} day^{-1}, of which 61% is diffuse. Average values reported from other tropical areas amount to: Chazdon & Fetcher (1984, Costa Rica) - 33 mol m^{-2} day^{-1}, Oberbauer & Strain (1985, Costa Rica) - 27 mol m^{-2} day^{-1}, Raich (1989, Borneo) - 31.2 mol m^{-2} day^{-1}.

3.2 Leaf area index

Calculations of LAI on artificial canopy images is shown in Table 1. HEMIPHOT estimates LAI of these artificial images up to a LAI of 4 excellently. Values around 6 are slightly underestimated and values of 8 and higher are not measured very accurately.

As expected measuring LAI with only one small zenith viewing angle of 67.5° results in the largest errors. All other methods are sensitive to small differences in transmission at large zenith angles when cover is high. In such a case slightly better estimates might be calculated by using only the upper three zenith angles. This is not an option in the programme, but the transmission percentages can be viewed when calculating LAI with the ellipsoidal leaf angle distribution (see 5.2.2).

Table 1. Estimations of LAI with HEMIPHOT's four methods and cover percentage on artificial canopy images with random small leaves and fixed LAI. N varies between 3 and 5. LAI Images were made with MAKELAI.EXE.

LAI	theoretical cover	LAI as Licor	LAI at z=67.5	LAI with Inversion	LAI with Ellipsoidal	calculated cover
0.25	31.32	0.26	0.24	0.26	0.25	31.92
0.50	47.62	0.51	0.50	0.51	0.50	47.83
1.00	66.90	1.03	1.05	1.02	1.00	67.13
2.00	84.91	2.04	2.05	2.00	2.00	85.01
4.00	96.17	3.97	3.97	3.90	3.84	96.08
6.00	98.91	5.82	5.83	5.63	5.69	98.80
8.00	99.67	8.38	18.3	8.29	6.77	99.66

standard error of LAI in any repetition less than 0.01 except in LAI 8.
standard error for cover never larger than 0.15.

In these artificial canopies the programme calculates cover very precisely up to a canopy cover of 99.5%. Thus it is expected that the calculation of cover percentage of image analysis at 100 DPI is as accurate as the photography and scanning permit.

LAIs calculated from canopy photographs of the forest in Guyana range from 3.5-7. This is within the range reported for rain forest canopies of Amazonia (Saldarriaga & Luxmoore 1991, McWilliam 1993).

One of the problems in LAI estimation is the amount of trunks and branches on a photograph. In temperate and tropical deciduous forests a correction can be achieved by comparing photographs during the leafless period when LAI is in fact BAI (branch/stem area index) and during the leafy period when 'LAI' is true LAI plus BAI (see Appendix 3). By comparing deciduous forests and tropical forests of similar stand structure at least an estimate of the error in true LAI may be achieved. For further limitations of the technique see (Norman & Campbell 1989, Welles & Norman 1991).

3.2 Light quality

Transmission of red, farred light and PAR of selected species is given in Table 2. All species absorb the red light more strongly than they do farred light. Absorbency of total PAR is high but not as high as red light. These results are in full agreement with the expectations (see e.g. Gates 1980, Lee 1987) and are used further to calculate R/FR from canopy images.

Instantaneous measurements of R/FR on two days in the forest show comparable figures (Table 3). R/FR of full sunlight in Mabura is around 1.2-1.3; R/FR in large gaps in shade is around 0.9-1.1; under cloud cover 1.0; in the forest in sunflecks of 1-2 m^2 from 0.8-1.0; in forest shade depending on the type of forest from 0.1-0.4. Daily averages calculated with HEMIPHOT for a number of different sites correspond better with daily averages achieved with data loggers, than the empirical formulae found by Lee (1987). In a large gap both the 'poisson model' and 'Lee' estimate R/FR to be near 1.2, slowly decreasing with gap size. In the few understorey plots three daily runs were finally achieved with two quantum sensors and the red and far-red sensors. These data are given in Table 3.

Daily PPFD values are overestimated in closed forest plots because (1) no correction is made for cloud cover, and (2) the overestimation of canopy openness in dense

Table 2. Transmittance of red light (670 nm), farred (730 nm) and PAR (400-700 nm) of single leaves of selected Guyanese canopy species, n = 10, se in parentheses. The first five are dominant climax species, the last two are pioneers.

	red (630nm)		farred (730 nm)		PAR (400-700nm)	
climax species						
Eperua falcata	1.2	(0.1)	42.0	(1.0)	3.6	(0.3)
Eperua grandiflora	1.1	(0.1)	42.9	(1.2)	2.8	(0.2)
Mora gonggrijpii	0.7	(0.1)	43.0	(1.8)	3.3	(0.5)
Chlorocardium rodiei	0.7	(0.1)	37.4	(2.0)	2.6	(0.5)
Dicymbe altsonii	1.3	(0.1)	39.7	(0.8)	3.0	(0.2)
pioneers						
Cecropia obtusa	2.2	(0.2)	42.0	(1.2)	4.6	(0.5)
Goupia glabra	4.3	(0.2)	52.7	(1.0)	8.5	(0.3)
all combined	1.6	(0.2)	42.8	(0.7)	4.1	(0.3)

Table 3. Measured daily PPFD and R/FR in six sites in rain forest near Mabura Hill, Guyana, compared with values calculated with HEMIPHOT.

		datalogger		HEMIPHOT			
date	site	PPFD	R/FR	cover	PPFD	$R/FR_{poisson}$	R/FR_{Lee}
09/07/92	meteo gap	37.54	1.23	74	39.33	1.17	1.17
11/07/92	small gap	7.88	1.05	74	36.11	1.15	1.15
14/07/92	large gap	15.21	1.16	58	38.36	1.16	1.16
07/08/92	understorey 1	0.27	0.21	91	6.43	0.61	0.82
17/08/92	understorey 2	1.47	0.22	92	1.40	0.12	0.53
19/08/92	understorey 3	0.20	0.05	91	2.92	0.35	0.67

canopies due to halo effects. The last is notably present in understorey plot 3. As R/FR is in part calculated with the amount of direct light it will likewise be overestimated. However the overestimation is less than with an empirical formula such as Lee (1987) and keeping the limitations in mind the method is useful to get at least an idea of R/FR at a site.

3.3 Gap size

Artificial gaps are handled accurately by HEMIPHOT if only a general idea of gap size is needed. Since artificial gaps are perfectly round an octagon method always underestimates the size by 25%. With decreasing gap size the error of the multi point technique also increases in error. The error is always such that the size is underestimated because lines make short cuts.

This suggests that using an octagon method in the field is likely to underestimate gap size in general. Natural gaps are more difficult to measure with photographs. Estimates of gap area with HEMIPHOT of a large gap of 3440 m^2 ranged from 2800-4000 m^2, those of a smaller of 730m^2 from 800-1000 m^2. Measurements of other gaps for which ground data were available (courtesy David Hammond, Peter van Der

Table 4. Estimates of gap size of circular gaps with eight points or many points and errors produced by both methods.

α (°)	30	45	60	75	97
area (m^2)	11545	3848	1283	276	43
8 points (m^2)	9034	2937	986	209	31
error (%)	-22	-24	-23	-25	-27
multi points (m^2)	11525	3688	1186	226	34
error (%)	-0.1	-4	-8	-18	-20

Meer) showed more variation. The problem, as in the forest, is the decision of what is gap border and what is not. Comparison of an eight point method with a multipoint method showed large differences. Measuring a gap with only eight points may lead to an error of 300% in irregular gaps. It proved impossible to estimate the area of very large gaps with some remaining vegetation free from the gap edge. Thus technically it is possible to measure physical gap size with HEMIPHOT. Problems in defining the gap edge render the method less useful in irregularly shaped gaps.

4 CONCLUSIONS

Canopy cover (or openness), used by most calculations, is estimated well by HEMIPHOT, provided the canopy images are of good quality. Canopy openness is prone to the least ambiguities of all parameters. As light, site factor, LAI, R/FR are all either linearly of logarithmically highly correlated to cover, this may prove to be the best estimator if additional information is lacking.

HEMIPHOT can give good estimates of maximum potential light levels for any site and any day. In order to obtain absolute amounts of PPFD knowledge of diffuse and direct light components from above the canopy are necessary. Light should be monitored for the length of the period of interest. Direct light can be measured directly with dataloggers and sensors (see Pearcy 1989 for methodology). Diffuse light can be obtained by using a band to shade sensors from direct sunlight. Alternatively an estimation of direct light can be made with the relation between recorded sunshine hours and PPFD measured. PPFD under densely covered canopies may not be estimated well by the programme, mainly due to limitations in the photography (halo effects) and/or scanning. Daily courses of PPFD may be instructive, those made with grey scales may seem very plausible, but should never be treated as fully reliable.

LAI may be estimated well up to 6, with a slight underestimation, less well up to 8. LAIs over 8 are not handled well by HEMIPHOT. Some correction should be made for stem and branch area on the photographs.

R/FR can be estimated as an indication. Since it is based partially on direct and diffuse light calculations the same restrictions apply as for the PPFD estimates.

Gap sizes of regular gaps can be measured relatively easily, those of irregular gaps not. As gap size is a poor predictor of microclimate its use is not recommended.

5 HOW TO USE HEMIPHOT?

5.1 Hardware requirements

To be able to run HEMIPHOT a few minimum requirements must be met. Needed are an IBM (compatible) computer with at least a 80286 processor on board and a VGA compatible monitor, HEMIPHOT will select 640 x 480 mode even if a better resolution is available. A 80x87 co-processor is not strictly necessary, but will speed up some calculations by a factor 10. For instance a 80386 25 MHz with 80387 performs much faster than a 80486 SX at 33MHz. HEMIPHOT is written solely for use with a mouse and will not start if a mouse driver is missing. With a mouse driver, but without a mouse, the programme will start up, but that's it (ctrl-alt-del will help to continue). You can use any scanner as long as the scanner or you are able to make PCX files of 1 or 8 bits per pixel with an image size not larger than 400 by 430 pixels. A palette is not strictly necessary, as HEMIPHOT will translate the 256 colour values/grey scales to 16 VGA grey scales.

5.2 Software and installing

You can install HEMIPHOT by inserting the hemiphot diskette in your diskette drive (a:) and logging in to it. Then at the dos prompt type install↵. The installation will make a subdirectory HEMIPHOT on your C drive and transfer all necessary files to it, log in to that directory and show you the PCX files it copied down for you. Now type HEMIPHOT↵, after starting up click the OK button on the logo box with the left mouse key and you are ready to start.

5.2.1 The main menu

With the left mouse button you can select any of the buttons on the top menu bar. Some will only work if a file has been selected. Quit (leave the programme), Mem (show RAM available), Disk (show available free disk space), About (show logo Pop Up) will work. To select a file click the File button, select a file format button, normally PCX (GRB files is the old files type of PPFDCALC). If more than 20 files are present you can page up or down with the triangle buttons on the right. To select a file, just click it with the left mouse button. The photo will appear in the left square and can be edited by selecting the edit button. In B/W mode only black and white can be changed by selecting colour, in grey scale mode you can choose from a palette appearing on the left after selecting colour. Pick up a colour with the left mouse key. To change pixels press the right mouse key to change one pixel at the time, press the left one to change many. In grey scale mode it is also possible to change the darkness level and contrast of the total image or a sub-square. To change only the contrast of a sub square select a corner of the area, press the left mouse key, draw a square and press left mouse key again. To clear the square, click the square button of the top menu and then press escape on the keyboard. Undo will undo all changes made after an 'Accept' action, or all if you have not accepted any 'Edit-action' up till then. An edited file can be saved by the save button in the main menu. HEMIPHOT will prompt for a name on the lower status line and warn if a file with a similar name will be overwritten, esc on the keyboard cancels during typing, other wise click the escape button if a message appears. To check out our addresses try the logos.

To be able to do your calculations the image needs to be aligned. Click the Align button. HEMIPHOT will prompt you to select the north (true or magnetic) on your photo-image. You can select that point by moving to it with the mouse and pressing the left mouse key or moving to it with the arrow keys, pg up (=10 up), pg down, home, end and pressing enter at the right spot. You now need to draw a circle around the image, by moving the mouse (now the south of the picture) or using the same keys as above. The keys U (=up), D (down), L (left) and R (right) will shift the whole circle including the north and the south in the direction wanted. Press the left mouse key or enter to accept the circle. A circle too small or with a part outside the phot square will be rejected, you will be prompted to point at a new north. If you accept the circle the Calculations menu will appear.

5.2.2 The calculations menu

Once a file has been properly aligned you can start the calculations. Before you start you will need to check if the options have been properly set for your ask. Click the Options button and all options will appear. You can change all within preset limits.

-Latitude:	Between -90 (South Pole) and 90 (North Pole). Input as [degrees,minutes].
-Longitude:	between -180 (east) and 180 (west). Input as [degrees,minutes].
-Time zone:	Between -12 and 12. HEMIPHOT will calculate the standard time zone for each longitude, negative values for the west, positive for the east. If your time zone does not correspond to the standard time zone (STZ) find the correct or in an atlas. Beware of changing summertimes. Input as [hours,minutes]
-Altitude:	Altitude above or below mean sea level, between -10 (Dutch polders) and 8848 m (mt Everest, seems to be changing all the time). Input as decimal meters.
-Number of days:	One (1) or (7). Choose 7 if you want a quick year average, choose one for a particular day. Click the appropriate box.
-Day:	Between 1 and 365 if number of days is 1. Input as Julian day. Use JDAY.EXE if you do not know the exact day numbers.
-Sky type:	Either Uniform Overcast Sky (UOC) or Standard Overcast Sky (SOC). Click the appropriate box.
-Trans Red:	Between 0.005 and 0.9. Transmission of one leaf for red light. Input as decimal.
-Trans Farred:	Between 0.005 and 0.9. Transmission of one leaf for farred light. Input as decimal.
-RFR:	Between 1.0 and 2.0. The red-farred ratio above the canopy. Input as decimal.
- Diffuse part:	Between 0.05 and 0.5. The amount of diffuse light added to the amount of direct light. With clear skies a value of 15% is most suitable. Input as decimal.

-Tau:	Between 0.1 and 1.0, default 0.6. The transmission of 1 optical airmass (use 1.0 if you want to know the amount of light on top of the atmosphere). Input as decimal.
-Magn. Corr:	Between -90 and 90. Use this correction if your camera was not aligned at the true (map) North, but at the magnetic North. If the magnetic North is left (anti clock wise) of the true North the value should be negative. Input as [degrees,minutes].
-Leaf Ang:	Between 0 and 90. Inclination angle of leaf. Input as [degrees,minutes].
-Leaf Azim:	Between 0 and 360. Azimuth angle of leaf. Input as [degrees,minutes].

After the right choices have been made calculations can be performed. Click the Calc button.

Cover	is calculated for the total hemisphere, with area corrections, using all pixels on 89 concentric circles (Equation 3).
PPFD	can be calculated according to Gates (1980) where diffuse light is 15% of the direct light. The distribution of the diffuse light over the hemisphere depends on the type of sky chosen (UOC, Equation 17 or SOC, Equation 18). Model calculates diffuse PPFD according to Equation 15, finally extinction calculates diffuse light similar to red and farred light equation 24. The last option should only be used in fairly closed canopies. PPFD is calculated in steps of two minutes.
Year data	calculates PPFD for 365 days and stores day values in a comma-delimited file with extension YRD. The data can be used to make graphs. To convert 365 day values to 12 month values, use YEAR2MON.EXE
LAI	67.5° calculates LAI with the gap fraction at a zenithal view angle of 67.5°, with Equation 4. LiCor calculates LAI with five view angles, equation 5. Inversion of gap fractions with five view angles and three leaf angle classes (see Norman & Campbell 1989). Ellipsoid, with ellipsoidal leaf angle distribution (see Norman & Campbell 1989).
R/FR	Model calculates R/FR with poisson distribution, Equation 24. Sensu Lee uses an empirical formula which relates cover to R/FR (Lee 1987). Both methods calculate R/FR for one day only (the last day of seven if this option is on).
SubCircle	calculates cover for a smaller part of the hemisphere, you are prompted to input the desired zenithal angle at the lower status line.
GapSize	according to Brokaw (1982) or with a free choice of points but fixed gap edge canopy height. You will be requested to input information on the lower status line.

The Show button offers several graphical options:

Grayscales	Histogram of the number of pixels per grey scale. B/W images will only contain 0 and 15.
Suntracks	Shows the suntracks for the day or number of days and latitude chosen.
PPFD site	Shows the PPFD of the day last calculated, or the last day of the seven days.
PPFD leaf	Same for a leaf with defined inclination and azimuth.
Sunflecks	Shows a histogram of the number of sunflecks in 2 minute classes, calculated for 11 days in the year.
Gap frac	Shows the gap fraction per zenithal angle.
Year data	Shows the total daily PPFD of above and below the canopy if the data have been calculated for that site i.e. if the YRD file exist.
Circles	Shows all circles sampled for cover and diffuse light calculations.
All tracks	Shows all pixels used by 365 days calculations.

The Append button offers to save most of the data shown with the show option and under the same names to comma delimited files. Also PCX files can be created of suntracks overlain on the hemispherical images. Datafile appends all calculated data to a standard file name HEMIPHOT.DAT. The data are identified by the filename. With the print option several graphs and suntracks can be printed but only on an Epson matrix printer. It is far better to save the data into comma delimited files and use a programme more appropriate for making and editing graphs. PCX files of suntracks can of course also be edited and printed by most DOS or WINDOWS based drawing programmes or directly imported into e.g. Word Perfect (see Figure 10).

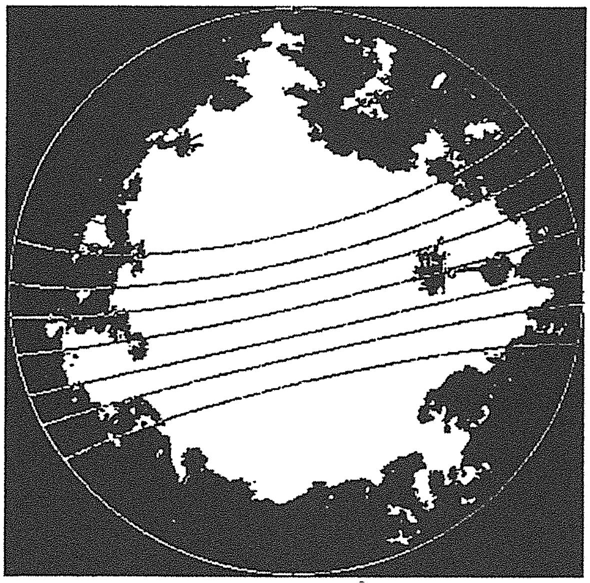

Figure 10. Solar tracks with 13° magnetic correction, for a large gap (meteo station) in Guyana.

Finally Return brings you back to the main menu, if you want to select and align a new file. The old alignment will be cleared.

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7 ABBREVIATIONS

A_α	area of sphere segment at angle α
A_{tot}	area of total hemisphere
D_u	diffuse (indirect) site factor
Dir	direct light
Dir_{pen}	direct light in penumbral area
DSF	direct site factor
day	julian day
ISF	indirect (diffuse) site factor
I_0	light intensity above canopy
I_n	light intensity after n layers of foliage
I_z	diffuse illumination of sky at zenithal angle z
I_Z	diffuse illumination of sky at zenith
L	partial leaf area of a leaf layer
LAI	leaf area index
M	(optical) airmass
p_h	atmospheric pressure at altitude h
PPFD	photosynthetic photon flux density
R/FR	red to farred ratio
S_c	solar constant (1360 W m^{-2})
S_{dir}	direct light
S_{no}	direct light on a surface normal to the beam
S_{out}	actual radiation at the outer atmosphere
S_z	path length correction in LAI calculations
SOC	standard overcast sky
STZ	standard time zone
T_α	canopy openness (gap fraction) at angle α
T_{tot}	total canopy openness
TSF	total site factor
U	area of solar disc obstructed by foliage
UOC	uniform overcast sky
W_z	weight factor (for area) at angle z in LAI calculations
z	zenithal angle
Z	zenith
α	solar altitude
β	solar azimuth
δ	solar declination
η	hour hangle
τ	atmospheric transmission (of one airmass)
ψ	latitude

APPENDIX 1 Estimation of cover in a gap

With the aid of equation 2 a quick estimation of the canopy cover in a 'semi-circular' gaps can be made. Since the lower angle is zero, equation 13 simplifies to

$$\text{cover} = A_\alpha = \sin\alpha$$

(see Figure 11). The Table below gives canopy cover and gap size of gaps in steps of canopy cover of 5%.

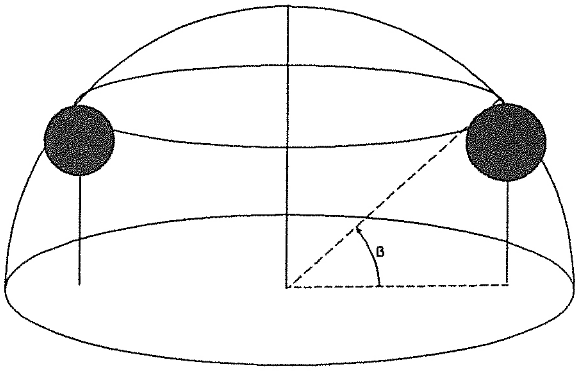

Figure 11. Estimation of canopy openness in a large gap.

Table 5. Canopy cover, openness and gap size of circular gaps with gap edge angles at 5° intervals and canopy height of 30 m as afunction of the viewing angle to the top gap edge (α).

angle (°)	cover (%)	openness (%)	size (m^2)
α	100 · sin(α)		$\cos(\alpha)^2 \cdot 30$
2.87	5	95	2820
5.74	10	90	2799
8.63	15	85	2764
11.54	20	80	2714
14.48	25	75	2651
17.46	30	70	2573
20.49	35	65	2481
23.58	40	60	2375
26.74	45	55	2255
30.00	50	50	2121
33.37	55	45	1972
36.87	60	40	1810
40.54	65	35	1633
44.43	70	30	1442
48.59	75	25	1237
53.13	80	20	1018
58.21	85	15	785
64.16	90	10	537
71.81	95	5	276

APPENDIX 2 Geometry of penumbra

From Figure 12 it follows that

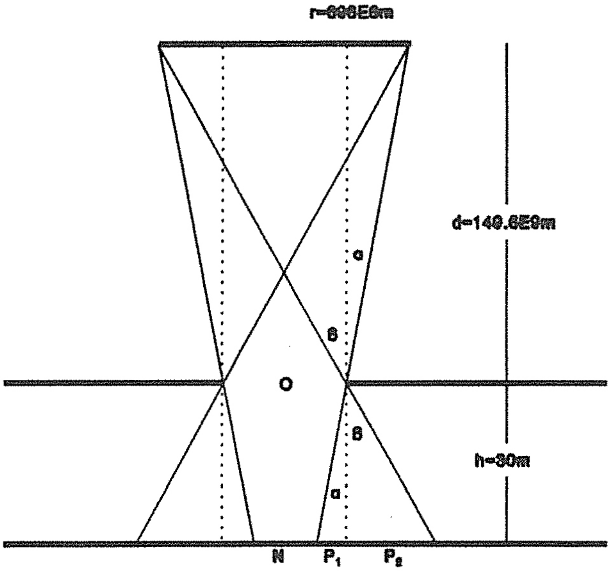

Figure 12. Geometry of penumbra.

$$\sin\alpha = (r - \tfrac{1}{2}O) / d = P_1 / h$$

so

$$P_1 = h \cdot (r - \tfrac{1}{2}O) / d$$

and

$$\sin\beta = (r + \tfrac{1}{2}O) / d = P_2 / h$$

so

$$P_2 = h \cdot (r + \tfrac{1}{2}O) / d$$

the total penumbral area is

$$P = P_1 + P_2$$

so

$$P = 2 \cdot h \cdot r / d$$

Thus the size of the penumbral area is independent of the size of the canopy opening, but is a function of h. The size of the umbra is related to the gap opening as

$$U = O - 2P_1$$

There is no umbra (or full sunlight) when $N = 0$ and then

$$O = 2 \cdot h \cdot r / (d + h)$$

if $h = 30$m then $O = 0.28$ m or more generally $O : h \approx 0.01$. This results is similar to Smith *et al.* 1989. In a canopy of 30 m high an opening of 0.3 m is roughly 0.3° or slightly less than the solar angle and one pixel at an image diameter of 360 pixels. In this canopy gaps smaller than 0.25m will not be recognised when scanning at 100 DPI, as the amount of sky is less than half a pixel. Scanning at 400 DPI will ideally recognize gaps of 0.06 cm in a 30m high canopy.

APPENDIX 3 Estimation of LAI, from TAI and BAI

Assume a canopy with of total area index of TAI, a leaf area index of LAI and a branch area index of BAI. The following can be reasoned with the basis of Equation 5. If we have two photographs, one with leaves and branches (TAI) and one with stems and branches only (BAI):

for our canopy it should hold that

$$TAI = LAI + BAI$$

from Equation 19 it follows that

$$TAI = 2 \cdot \Sigma[-\ln(T_{i,TAI}) \cdot W_i / S_i]$$

and

$$BAI = 2 \cdot \Sigma[-\ln(T_{i,BAI}) \cdot W_i / S_i]$$

$$LAI = TAI - BAI = 2 \cdot \Sigma[-\ln(T_{i,TAI}) \cdot W_i / S_i] - 2 \cdot \Sigma[-\ln(T_{i,BAI}) \cdot W_i / S_i]$$

as W_i and S_i are similar for each i for both BAI and TAI and LAI the following holds

$$LAI = 2 \cdot \Sigma[-\ln(T_{i,TAI}) - \{-\ln(T_{i,BAI})\} \cdot W_i / S_i]$$

or

$$LAI = 2 \cdot \Sigma[-\ln(T_{i,TAI} / T_{i,BAI}) \cdot W_i / S_i]$$

T_i for the five view angles can be obtained by calculating LAI for each of both photographs with the ellipsoidal leaf angle option. W_1 to W_5 are 0.034, 0.104, 0.160, 0.218, 0.494, S_1 to S_5, 1.007, 1.086, 1.269, 1.661, 2.670.