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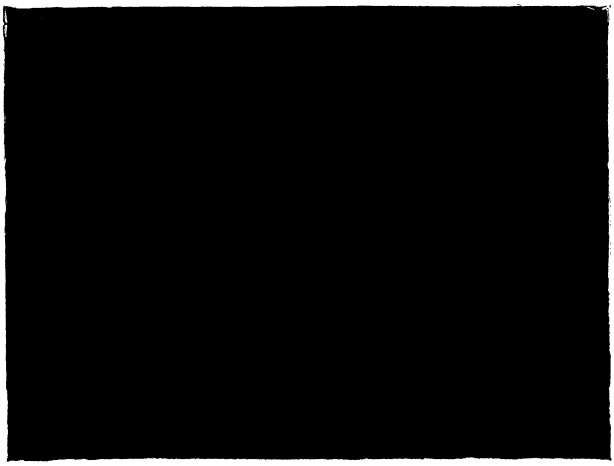

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USE OF HEMISPHERICAL PHOTOGRAPHS IN FOREST ECOLOGY: CALCULATION OF ABSOLUTE AMOUNT OF RADIATION BENEATH THE CANOPY

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1993

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Foreword

In 1924 Robin Hill, the Cambridge biochemist, devised a hemispherical lens for photographing clouds over the whole sky and had it built by Beck, the scientific instrument maker (Hill 1924). In the late 1950s and 1960s use of the Robin Hill hemispherical lens was brought into forest ecology by a group of Cambridge botanists working with G.C.Evans, to photograph forest canopies from below and hence aid the characterization of the forest interior light climate (e.g. Evans & Coombe 1959, Anderson 1964). T.C.Whitmore was a minor participant (Grubb & Whitmore 1967). The manual analysis of hemispherical photographs was tedious and slow and the method languished. From the mid-1970s onwards forest regeneration in gaps, so-called 'gap-phase dynamics', has grown to become a major focus for both temperate and tropical forest ecology, building on insights of another Cambridge botanist, A.S.Watt (Watt 1947).

In 1984 The Royal Society launched a programme of studies on the recovery of tropical rain forests after disturbance in southeast Asia. One project under this programme was funded by a Natural Environment Research Council (NERC) research grant (no. GR3/6246) to Whitmore at Oxford and M.D.Swaine at Aberdeen. This was to investigate the nature of forest regeneration in artificially created canopy gaps of different sizes ranging from 10 to 1500 m^2 in a lowland dipterocarp forest in Sabah.

This project needed the precise measurement of canopy gap size and the characterization of gap light climate. In this remote rain forest hemispherical photography was the obvious tool to use. Advice was received from P.L.Mitchell, then also at Oxford. The work was partly done within the NERC project but much of it was supported by the Oxford Forestry Institute's (OFI) core tropical forest programme, which provided the time of Whitmore, C.I.Goodwin-Bailey and C.M.Brotherton, as well as use of a dedicated Joyce Loebl Image Analyser which the British Overseas Development Administration (ODA) had purchased for another purpose. Dr Gong W.-K., of Universiti Sains, Malaysia, spent part of a Royal Society Commonwealth Visiting Fellowship in Oxford working on this analysis during 1988. Problems arose in equating photosynthetically active radiation (PAR) computed from hemispherical photographs (hemiphots) with actual measurements. Mitchell was brought back in, and he and Whitmore (both by that time in Cambridge) and Goodwin-Bailey progressively discovered a series of problems and limitations in the use of hemispherical photography in forest ecology, some of them going back to the original Cambridge work. The problems were eventually resolved and the power and utility of hemiphots for the characterization of gap size and gap radiation climate is discussed in Whitmore *et al.* (in press).

Hemispherical lenses for use with 35 mm cameras are now commercially available. As part of the intense interest in forest gap-phase dynamics, and over the period 1987–1992 while this research was under way, other groups have continued to publish forest ecological studies using hemiphots. These have been analysed by the computer-based image-analysis systems also now available. Undergraduate and graduate researchers have begun to take such photographs with little awareness of the pitfalls in their interpretation. Hemiphots are an important tool for forest ecology and are especially useful at remote sites. The wide interest in the method is evidence of this. The radiation climate can also be characterized by direct measurement but hemispherical photography is cheap, the camera is robust, and the method has the potential to allow integration over long periods from just one photograph.

In 1990 the ODA revised its research priorities and included a focus on the ecology, silviculture and management of natural tropical forests as one of its strategic interests (ODA 1990). The ODA is now funding publication of the present report. This will make known the results of the work at OFI which it has supported. Also, the meaningful use of hemispherical photography in these forest ecological studies which lie within current ODA research priorities necessitates that the limitations are understood and that suitable precautions are taken.

Acknowledgements

We are grateful to P.J. Bellingham, N.D. Brown, R.L. Chazdon, J.R. Healey, M.D. Swaine, W.P. Sweetenham, I.M. Turner and F.I. Woodward for discussion of various points and for commenting on drafts, and to several anonymous reviewers. We also thank ABW Associates Ltd for very considerable secretarial support. Ehime University, Japan, kindly provided T.C.W. with facilities for the last stage of preparation of this report, and the assistance of Monbusho and the British Council is gratefully acknowledged.

Contents

I Summary

Hemispherical photographs (hemiphots) taken from the ground looking up at the forest canopy provide a record of the canopy. They can be analysed to compute either relative or, more usefully, absolute measures of solar radiation for the sample point, taking account of the contributions of direct (beam or sun) and indirect (diffuse or sky) radiation. Hemiphots can be obtained more easily and cheaply than instrumental measurements especially in remote areas. After explaining the geometry and terminology of hemiphots and solar radiation this paper describes the methods of computing absolute amounts of radiation, dealing with direct and indirect radiation separately and summing for the total as a final step.

The first method uses the product of measured radiation incident above the canopy and site factors computed from the hemiphot. Site factors are a relative measure of radiation defined as the fraction of incident radiation that reaches the ground. Direct and indirect site factors must each be calculated with appropriate weighting for the angular distribution of radiation. The second method is based on the known, constant amount of solar radiation available above the earth's atmosphere (the solar constant) and its attenuation by the atmosphere. Unfortunately, only direct radiation can be computed in this way. Neither method of computing solar radiation from hemiphots is completely independent of instrumental measurements or estimates of incident radiation for the site.

The use of hemiphots (or instrumental measurements) for mapping radiation on the ground is discussed. Interpolation between sample points is a sound procedure only for long-term average radiation and where the canopy is homogeneous, having small holes uniformly distributed. In other circumstances there are unpredictable discontinuities in the amount of radiation which make mapping unreliable.

Hemiphots are an invaluable tool in forest ecology but they require some instrumental measurements to be able to compute absolute amounts of radiation. Checklists of steps in computation and sources of error are given. Because of the relatively low precision of field measurements of radiation close agreement is not to be expected between computed and measured values. Attention is drawn to the assumptions that must be made in computing radiation from hemiphots as these should always be clearly stated, and tested where possible.

Key words: forest ecology, hemispherical photographs, light, photosynthetically active radiation, solar radiation.

1 Introduction

The dominant role of solar radiation in physiological ecology hardly needs to be stressed. It is the ultimate energy source for all organisms and is a large term in heat and water balances. Solar radiation varies widely in time and space at a range of scales and thereby contributes to the diversity of climates and habitats throughout the world. This variability accounts for the difficulty in its quantification. Measuring instruments are expensive as they must be carefully constructed and calibrated, and limited funds usually restrict the number that can be deployed to sample the variation. Consequently a technique such as hemispherical photography, for which the fieldwork is comparatively quick and cheap, is invaluable, provided that absolute measures of radiation can be calculated from the photographs. In this paper we explore the potential and limitations of hemispherical photography for the recording of radiation in forests.

Hemispherical photographs (hemiphots) were introduced to ecology about thirty years ago (Evans & Coombe 1959). They have proved to be a useful method of recording obstructions to light in the hemisphere overhead caused by vegetation (e.g. Anderson 1966), or by slopes and cliffs that raise the local horizon (e.g. Pope & Lloyd 1975, Proctor 1980), or by the structure itself of glasshouses or growth chambers. Beyond a photographic record, hemiphots have been utilized for indirect measurement of canopy structure (Anderson 1971, Norman & Campbell 1989) and to compute relative and absolute measures of solar radiation reaching the sample point (e.g. Anderson 1964; Chazdon & Field 1987; Becker *et al.* 1989, Rich 1990). Although relative measures of solar radiation, such as the Gap Light Index of Canham (1988) and Canham *et al.* (1990) or site factors (see below), are often adequate for use *within* sites, for many purposes absolute measures are necessary. This is because biological processes and microclimate are driven by absolute amounts, not percentages; for example, plant growth depends primarily on the amount of radiation intercepted (Russell, Jarvis & Monteith 1989). It is only when radiation is expressed in absolute units that sites differing in latitude, climate or time of year can be compared (Anderson 1964).

Hemiphots, like most instruments, provide a point measure of radiation. However, the record of the canopy can be analysed for a range of time scales and it is particularly useful for long-term averages. Hemiphots provide a record of the directions from which radiation is received. As the movement of the sun across the sky is predictable, it is possible to analyse the temporal variation in the contribution of direct sunlight within a day and during the year. Thus, hemiphots can be used to compute radiation at a variety of time scales, from a continuous, instantaneous record to an average for the year.

The original method of hemiphot analysis described by Anderson (1964) was manual. It was slow and tedious and is not accurately repeatable between observers (personal communication, D.A.Clark, Organization for Tropical Studies, Universidad de Costa Rica, Ciudad Universitaria, San José, Costa Rica). Nowadays, modern image analysis equipment and microcomputers make it comparatively easy to quantify hemiphots and there are several independently developed systems which make various analyses (Ducrey 1975; Chazdon & Field 1987; Becker *et al.* 1989; Rich 1989; Barrie *et al.* 1990; Whitmore *et al.* in press). In every system there are errors that the authors consider (see e.g. Rich 1990), but what has received less critical attention are the methods to calculate absolute amounts of radiation received at the sample point. We do not describe here an analytical system. Instead the reader is referred to one of the published systems mentioned above. The main technical terminology involved in analysis is included in the Glossary to this report.

Here we attempt a complete treatment of the assumptions and errors involved in the analysis of hemiphots for the calculation of absolute amounts of radiation received. This is based partly on experience of trying to reconcile measured and computed radiation for sites in Borneo (Whitmore *et al.* in press). Difficulties can be identified and solved only by careful analysis of the steps in the calculation and clear statements of assumptions. Compensating errors may lead any particular study to yield the correct answer from an imperfect method but this does not guarantee the method for general use and it obscures the causes of future problems. As far as possible each stage of calculation should be tested against actual radiation measurements.

From our experience in writing this account and explaining the ideas to others we conclude that this subject is inherently complex: not so much in the individual concepts as in the number of points which need to be understood and related to each other. Most biologists find radiation and three-dimensional geometry difficult subjects, especially when expressed concisely in mathematical form. Here we use words and the minimum of mathematics. Inevitably this increases the length of the account and requires care in the precise use of terms. Most terms are defined when first used and all are collected together in the Glossary.

2 Geometry of hemispherical photographs

There are several methods of projecting a hemisphere on to a plane (Hill 1924, Herbert 1987), but the one which has been used in ecology is the equidistant (or equiangular or polar) projection. Angles from the zenith to the horizon of the hemisphere are transformed linearly into distance from the centre to the edge of the hemiphot. The extent to which this is not precisely true for a particular lens can be measured and a small correction made (Evans, Freeman & Rackham 1975, Rich

1989). A vertical cylinder in the field of view of the lens appears on a hemiphot tapered towards the zenith because successive points up from the base are farther from the camera and subtend smaller angles. This is the main reason for the distorted view of objects in a hemiphot. The cylinder appears at the correct azimuth and points on it appear at the correct zenith angles as linearly transformed to the radius on the photograph. However, equal areas on the hemisphere are not represented by equal areas on the hemiphot. This point has been overlooked by most of the ecologists who have worked with hemiphots. The magnitude of the distortion can be measured (Herbert 1987, and see Appendix) and if it is necessary a correction can be made.

Lenses that give an equal area projection are also available but because they do not have the equidistant projection the conversion of radial distance on the hemiphot to zenith angle is more complicated. Clark & Follin (1988) gave a calibration procedure for such lenses.

The advantage of the equidistant projection is that objects on the hemiphot can easily be located by their zenith and azimuth angles. This means, for example, that the path taken by the sun for any day of the year at any latitude can be drawn on the hemiphot from the equations of apparent solar movement (Evans & Coombe 1959, Gates 1980, Jones 1983 and any astronomy textbook). From our experience, it is worth pointing out what the books do not say: that equations for sine (azimuth) apply up to azimuth of 90° only. The sine function in this context is ambiguous because inverse sine may be positive or negative; if assumed positive beyond 90° the sun appears to move backwards! Alternative formulæ for cosine (azimuth) do not have this problem because the cosine function changes sign as it moves through 90° (cos 0° = 1, cos 90° = 0, cos 180° = -1).

The daily solar tracks form a band across the hemiphot whose edges are defined by the tracks for the summer and winter solstices (Fig. 1). The central track for the equinoxes connects due east and due west. On the equator the band lies across the diameter of the hemiphot, Fig. 1a. On each tropic the band is curved and displaced (to the south in the northern hemisphere and vice versa) so that the edge of the band reaches the zenith when the sun is directly overhead at noon on the day of the summer solstice. As latitude increases the band becomes lower in the sky and increasingly curved because summer sunrises and sunsets are well north (or south) of due east and west. The band for 50° north is shown on Fig. 1b. Examples for various other latitudes can be seen in Gates (1980, Appendix 4), Evans & Coombe (1959), Anderson (1964, 1971), Pope & Lloyd (1975), Chazdon & Field (1987), Rich (1989), Pearcy (1989) and Whitmore *et al.* (in press).

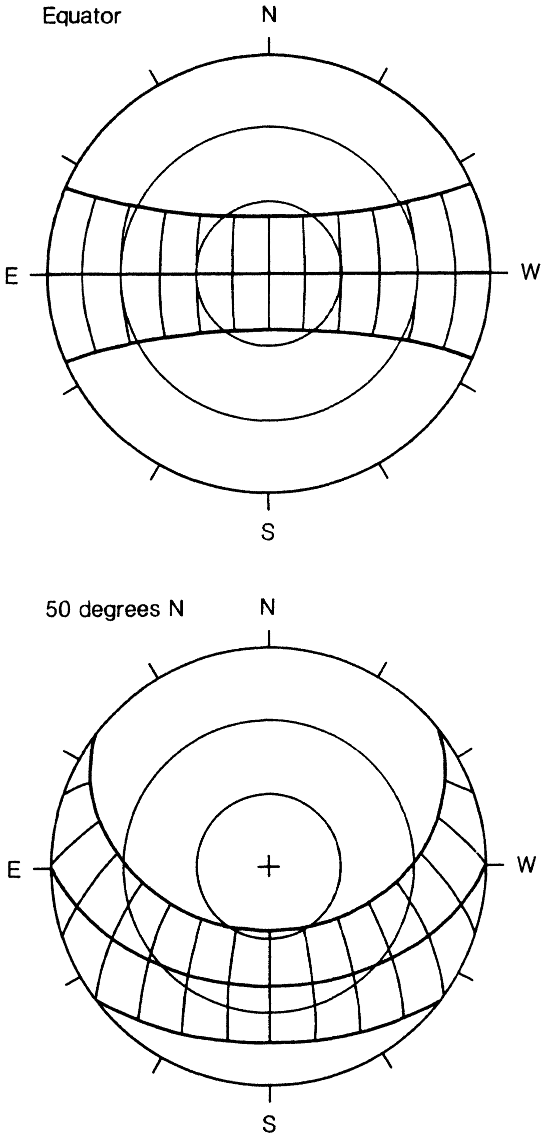

Figure 1. Examples of solar tracks for the equinoxes and solstices for latitudes 0° and 50°N as they would appear on hemispherical photographs (based on Gates 1980). Note that east and west are reversed from the compass arrangement because hemiphots look up at the sky. The two inner circles are for 30° and 60° zenith angles. The slightly curved lines across the band of solar tracks are for hours in the day, solar time.

3 Sampling on hemispherical photographs

3.1 Direct radiation from the sun

Once the solar tracks have been overlaid on the hemiphot sample positions of the sun are equivalent to samples in time, first in a day and then within the year. The resolutions of the hemiphot and the image analysis system need to be considered to assess the useful intensity of sampling.

On a hemiphot the shortest track through the zenith represents 12 hours between sunrise and sunset and 180° of travel, as at the equinoxes on the equator (Fig.1a). The sun has an apparent diameter of half a degree so that along this track its apparent width corresponds to two minutes in time. This means that, for example, 100 sample points (pixels on the digitized image) are 3.6 sun widths or 7.2 minutes apart. On a longer track, e.g. 16.1 hours at midsummer at latitude 50° (Fig.1b), 100 sample points would be 9.7 minutes apart.

The solar tracks for any given period of time cover a band across the hemiphot. A choice has to be made of how intensively to sample the population of daily solar tracks. Adjacent tracks are never far apart, even at the equinoxes. A sensitivity test can be carried out before a long run of hemiphots is analysed (e.g. Whitmore *et al.* in press) and analysis of tracks for every 5, 10 or 15 days may be sufficient.

3.2 Indirect radiation from the sky

For the manual method of analysis developed by Anderson (1964) and to assess the whole hemiphot (without sampling) it is convenient to divide it by a combination of azimuth and angular altitude. These appear on the hemiphot respectively as radii and concentric circles in a spider's web grid. A similar approach has been used by Rich (1989) as part of his computer program *CANOPY*. It should be noted that if equal intervals of altitude are used then each cell in the grid cannot have the same area. Cells of equal area can be arranged by computing a varying width of annulus along the radii (Fig. 2b). Anderson (1964) went one step further by designing cells of equal contribution of indirect radiation - see Fig. 2d and section 6.2 below. The choice of number of annuli and radii to be used is a compromise between too few, which give coarse resolution over the hemisphere, and too many, which take a long time to process. The resolution of the image analysis system may also be a relevant consideration.

An alternative procedure is to sample individual pixels with a scheme that weights the sample for the relative area of hemisphere it represents (e.g. Chazdon & Field 1987). An allowance for area distortion can be included at this stage as well if desired.

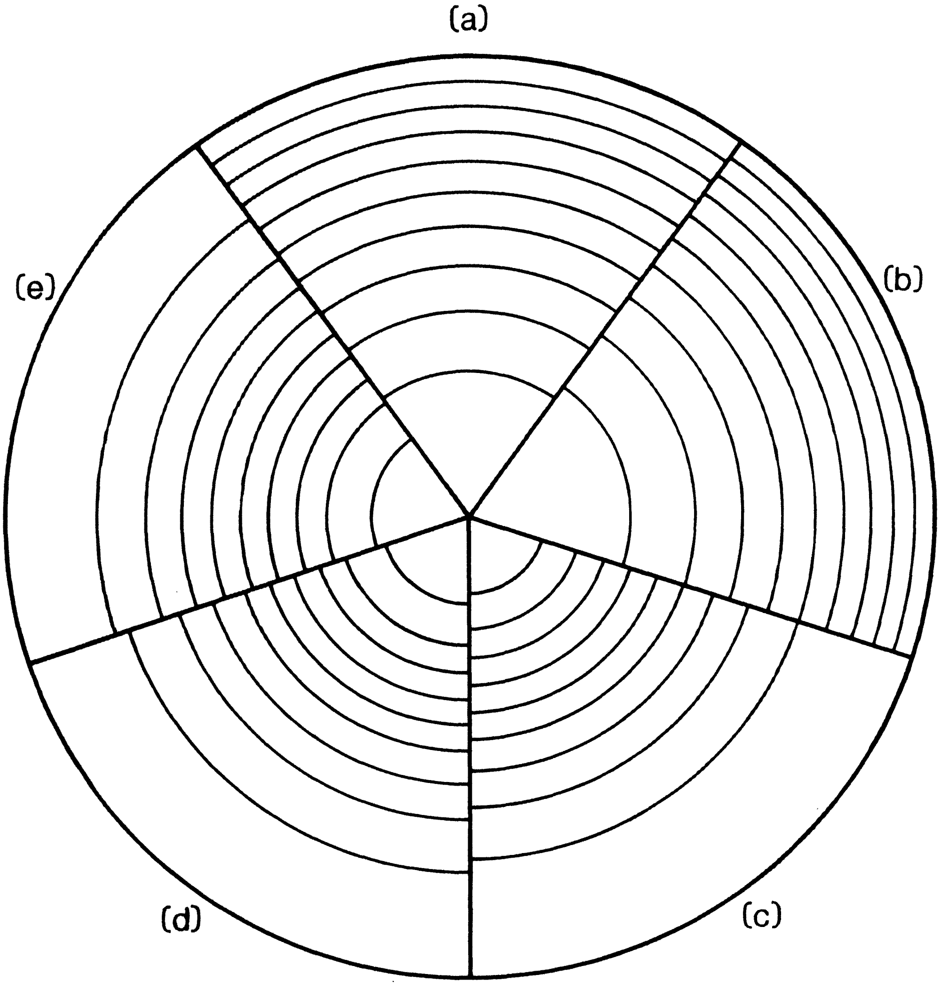

Figure 2. Examples of ten annuli for calculation of indirect radiation received from the hemisphere.

- **(a)** Annuli of equal area on the hemiphot, for reference only.
- **(b)** Annuli of equal area on the hemisphere, taking into account the area distortion of the equidistant projection.
- **(c)** Annuli of equal contribution from the hemisphere on to a horizontal surface allowing for area distortion (b), plus cosine correction.
- **(d)** Annuli of equal contribution of indirect radiation, assuming a Standard Overcast Sky and including cosine correction but ignoring area distortion (viz. the computation of Anderson 1964).
- **(e)** As (d) but allowing for area distortion (b).

4 Terminology and conventions for radiation

Solar radiation reaches the earth's surface in two forms (Fig. 3a). Some radiation arrives as a direct solar beam (and this includes a small component of forward scattered radiation). The rest, indirect or diffuse radiation, comes from the whole hemisphere of blue sky and clouds and originates as the fraction of solar radiation which is scattered by the molecules and dust particles in the atmosphere and by water droplets in clouds. When the sun is overhead in a clear sky the direct component can be up to 89% of the total (Gates 1980). At the other extreme, for any sky where the sun is obscured there is no direct component and the total is comprised of indirect radiation only. Inside vegetation (Fig. 3b) only a proportion of the direct or indirect radiation penetrates between leaves and branches. For a full understanding, direct and indirect components must be dealt with separately and summed to reach the total as the last step, as has been fully described by Evans (1956) and Anderson (1966).

Under a leaf canopy there is a third component about which hemiphots can give no information. This is the radiation which has been scattered within the canopy by either reflection or transmission by plant parts (Fig. 3b). Computations from hemiphots can provide only the penetrated radiation but the canopy-scattered component may sometimes be a substantial fraction of the total. The only figures we know of that were obtained in the field are 43% and 25% below closed canopy in tropical rain forest in Singapore and Nigeria respectively (Whitmore & Wong 1959; Evans 1956), estimated for the waveband 400–700 nm by indirect means. It is the scattered component that provides the altered spectral composition - light quality - of radiation beneath a canopy (Coombe 1957, Holmes & Smith 1975, Smith 1982).

Measurements and calculations can be of solar radiation (wavelengths of 300–3000 nm) or, for general relevance to plant growth, of photosynthetically active radiation (PAR, wavelengths of 400–700 nm). We follow meteorological practice and distinguish irradiance (the instantaneous rate of receipt of radiation, e.g. J m^{-2} s^{-1}, that is, W m^{-2}) from irradiation (the total amount received over some time period, e.g. MJ m^{-2} day^{-1}). Each of these terms can also be used with quantum units (e.g. μmol m^{-2} s^{-1}, mol m^{-2} day^{-1}). Whether to think about and measure electromagnetic radiation as propagating waves or a stream of discrete particles is a choice of the observer and not a property of the radiation itself.

As far as possible measurements and computations should be made for the same waveband and in the same terms to facilitate comparison. Nevertheless it is sometimes necessary to convert between solar radiation and PAR, and between energy and quantum units. As a long-term average in energy terms, the PAR fraction of incident solar radiation is 0.50 in temperate latitudes (Szeicz 1974). The

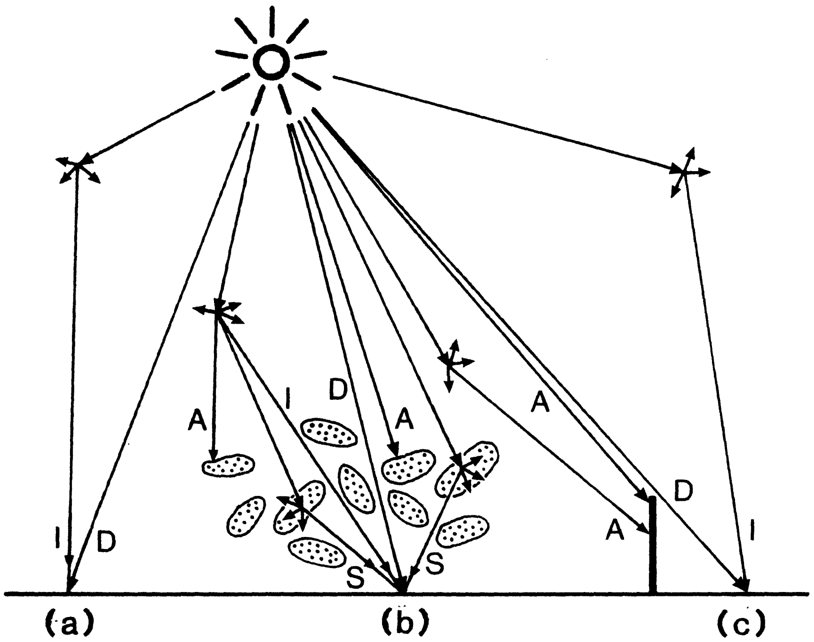

Figure 3. Diagram to show the components of radiation received (a) in the open, (b) under a leaf canopy (leaves stippled), and (c) with an absorbing, non-scattering obstruction (e.g. a wall) above the horizon. Scattering is shown as groups of diverging rays in the atmosphere and in a leaf. Rays are labelled as follows:

D direct beam from sun

I indirect or diffuse radiation from the sky

S scattered by a leaf

A absorbed by a leaf or non-scattering obstruction.

Under a leaf canopy all the radiation has been transmitted by the canopy and consists of penetrated radiation (direct and indirect) and scattered radiation. Hemiphot analysis can provide an estimate of the penetrated component only.

fraction for indirect radiation is above this, up to 0.70; and for direct a little below, down to 0.40 when the sun is low and in clear, dry air. Stigter & Musabilha (1982) confirmed these results for a tropical climate where the overall fraction was 0.51. For conversion of PAR (not solar radiation as a whole) from energy to quantum terms the figure of 4.6 μmol J^{-1} is widely accepted (McCree 1981). These ratios are, of course, unaltered for penetrated radiation, which is the component computed from hemiphots.

The fraction of PAR in solar radiation measured by sensors under a canopy is not 0.50 because scattered radiation is included, and the canopy scatters the PAR and solar radiation wavebands to different extents. For example, Baldocchi *et al.* (1984) measured PAR as 0.25 of solar radiation beneath a canopy of leaf area index 5. Somewhat surprisingly, however, the ratio of 4.6 μmol J^{-1} for conversion of PAR from energy to quantum units is hardly altered beneath a canopy (P.L.Mitchell, unpublished results). This is because the spectral composition is changed symmetrically about the central wavelength of 550 nm when PAR passes through a canopy. This is very useful for the forest ecologist who may have instruments for the PAR waveband that record energy, but needs to express his results in quanta, or vice versa.

It is conventional in most botanical work to measure radiation on a horizontal surface, for simplicity and for comparability with standard meteorological measurements. Therefore measurements or computations have to be cosine-corrected so that each ray is weighted for receipt on a horizontal surface by the cosine of its angle from normal, i.e. from the perpendicular to the surface.

5 The two methods to compute PAR

Let us consider the use of hemiphots to compute the amount of PAR beneath a forest canopy. This will be useful particularly in remote sites where making instrumental measurements is logistically as well as technically difficult. It is the simplest quantitative use of hemiphots which are a record of the effect of the opaque leaves and twigs on the radiation from the sky and sun, and from which therefore the penetrated radiation can be computed. Other uses of hemiphots include the deduction of canopy structure, leaf area index and amounts of radiation within and below canopies from complex models of scattering. The values of parameters in these models are rarely known for the vegetation in many places where ecologists are likely to use hemiphots.

There are two approaches to the use of hemiphots to compute the amount of PAR which penetrates the canopy. In both approaches direct and indirect radiation must be treated separately. The first approach is for the fraction transmitted (the site factor, see below) to be computed from the hemiphot and multiplied by the amount of PAR incident on the canopy. This necessitates measurements of incident PAR. The alternative approach is to compute the amount of penetrated PAR directly from the hemiphot, without the expense, difficulty and time needed for instrumental measurements. The second approach relies on the fact that the amount of solar radiation reaching the top of the atmosphere hardly varies, hence the term 'solar constant', see section 7.1 below. If simple, well understood allowances are made for attenuation of the radiation as it traverses the atmosphere down to the top of the canopy, then all that remains for the computation of penetrated radiation is to allow for the screening by leaves and twigs recorded on the hemiphot. This is the Holy Grail of hemiphot analyses which, if attainable, would be of great ecological utility.

6 Computation of PAR from site factors

6.1 Site factors and openness

Anderson (1964, p.28) defined the site factor as the radiation received beneath a canopy as a fraction of that incident above the canopy, all measurement conditions being identical. (She did this to avoid the connotations of transmission or penetration, and we and Rich (1990) continue to find it a useful term.) A site factor must be qualified by the source or component of radiation, the waveband, the orientation of the receiving surface and the period of time to which it refers. If the site factor is known then the transmitted radiation can be calculated as the product of the site factor and the incident radiation, which may be measured or estimated (e.g. from meteorological network observations). The site factors from hemiphots are solely for penetrated radiation and so differ from those obtained by instruments which include the canopy-scattered component.

The ratio recorded on the hemiphot of unobstructed sky to the whole hemisphere is (canopy) openness and is easy to comprehend and to measure on an image analyser. But canopy openness is inadequate for computation of radiation under the canopy because patches of unobstructed sky of the same area on the image but in different places on the hemisphere are not equivalent in the amount or timing of radiation admitted to the sample point. For indirect radiation it depends on the altitude and azimuth of the part of the sky involved. For direct radiation it depends on whether the sun crosses that patch and when, and on the probability of the sun being obscured by cloud at that time. In both cases cosine-correction is needed for receipt on a horizontal surface.

The problem with this method of computing radiation is how to give appropriate weighting to site factors derived from hemiphots.

6.2 Indirect site factor

The indirect site factor (ISF) is the ratio of the indirect radiation which has penetrated the vegetation canopy to that of the unobscured sky. Several computer programs which work out ISF from hemiphots have been developed. Their main weakness is the lack of knowledge of the distribution of indirect radiation across the hemisphere. The distribution of radiance varies with the position of the sun and of any clouds. Only the two extreme cases of a clear or of a completely overcast sky have been well studied.

In a clear sky the radiance of any patch of sky depends on its altitude and its azimuth, with reference to the position of the sun. The area near the sun is much the brightest: 4–10 times brighter than the minimum at 90° to the sun in the vertical plane containing the sun and the zenith. The edge of the hemisphere near the horizon is generally brighter than the upper parts, except near the sun, because of the geometry of scattering (Steven 1977; Gates 1980). The angular distribution of indirect radiation in a clear sky shows a consistent pattern independent of the actual total of indirect radiation from the whole hemisphere and this enabled Steven (1977) to tabulate standardized distributions for four 10° bands of solar altitude. Using a model of clear sky brightness and for their site at 36° N latitude and at the summer solstice, Hutchison *et al.* (1980) found that the weighted mean indirect radiation for a day from a clear sky was close to the SOC distribution described below.

Under a completely overcast sky one conventional measure of the distribution of indirect radiation is the Uniform Overcast Sky (UOC). This measure is only likely to apply in exceptionally heavily clouded weather, especially in the tropics where the sun daily passes near the zenith. An alternative, more realistic, distribution is one where the zenith is brighter than the horizon so that the indirect radiance is uniform with azimuth but increases with altitude according to the general equation (Monteith & Unsworth 1990)

$$R_a = \frac{1}{1+b} R_z((1+b)\sin a) \qquad (1)$$

where R_a is the radiance at angle a from the horizon and R_z is the radiance at the zenith. A particular case when $b = 2$ gives radiance from the zenith three times that from the horizon. The equation is then for the Standard Overcast Sky (SOC), adopted by the Commission Internationale de l'Éclairage (Anderson 1971) and based on measurements of luminance (i.e. the radiation between 400 and 700 nm weighted by the relative spectral response of the human eye which peaks at 555 nm). Grace (1971) measured indirect radiance at wavelength 575 nm over the sky and found good agreement with the SOC. However, Monteith & Unsworth (1990, p.43) pointed out that for the zenith relative to the horizon a value of 2.1–2.4 (i.e.

b = 1.1–1.4) is more appropriate for radiance in the 300–3000 nm waveband than 3.0 which was found for luminance.

The SOC (Equation 1 with $b = 2$) was used by Anderson (1964) for indirect radiation. For receipt on a horizontal surface she made the cosine-correction and integrated the equation with respect to solar altitude to produce:

$$I = \frac{1}{3}\sin^2 a + \frac{4}{9}\sin^3 a \tag{2}$$

where I is the irradiance received from the annulus of sky from the horizon up to angle a. From this she calculated the relative widths of annuli for equal amounts of radiation (Fig. 2d) which together with 50 radii produced the spider's web overlay described above for manual scoring of hemiphots. Barrie *et al.* (1990) used Anderson's equation so that their method calculates an indirect site factor (ISF), not in fact canopy openness as they state.

Often the sky is neither wholly clear nor wholly cloudy. The general problem with indirect radiation is to choose an appropriate distribution of sky radiance which takes into account the amount, type and distribution of cloud, either for particular moments or as long-term averages, for instantaneous or long-term average computations respectively. The SOC appears to be the most generally applicable distribution for periods of a day or more (Hutchison *et al.* 1980) because it is appropriate for overcast skies and offers a distribution weighted in the right direction for clear or partially cloudy skies, especially in the tropics where the sun passes near the zenith. For shorter periods with a clear sky a more realistic distribution can be derived either from measurements (Steven 1977) or from models (Hutchison *et al.* 1980). Hooper, Brunger & Chan (1987) gave a model for clear sky radiance and Brunger, Hooper & Wardle (1985), cited therein but not seen by us, may provide suitable angular distributions for hemiphot analysis.

6.3 Direct site factor

The direct site factor (DSF) is the ratio of direct radiation which has penetrated the canopy to that of the unobscured sky. By similar reasoning to that given for ISF, the DSF must be weighted because the amount of radiation received when the sun appears in a particular hole in the canopy depends on the position of that hole. Only holes along a solar track are relevant, of course, but the 'value' of a hole depends on its altitude since direct radiation is attenuated in proportion to the length of its path through the atmosphere. For a receiving surface facing the sun (subscript prefix p), the solar constant (${}_pS$), (discussed further in section 7.1), is attenuated by a weighting factor to give the direct radiation component on the ground (${}_pS_d$) as in the following equation (Gates 1980, p.107):

$$ {}_pS_d = {}_pST^m \tag{3}$$

In this equation the transmittance of the atmosphere (averaged over all wavelengths) is T, for the shortest path at the zenith. It is raised to the power m, the relative optical path length, i.e. relative to that from the zenith. For a given angle of the sun (z for zenith angle, a for angle from the horizon):

$$m = \sec z = \frac{1}{\cos z} = \frac{1}{\sin a} \tag{4}$$

The curvature of the earth and refraction through the atmosphere decrease the accuracy of this relationship for solar altitudes less than 30° until at 10° or less resort must be made to tabulated values of m (Monteith & Unsworth 1990, p.40), or to empirical equations as in Iqbal (1983) and Pearcy (1989) where, for example, $m = 35$ instead of infinity on the horizon. Values of m can be corrected for site altitude by p/p_o where p is the atmospheric pressure for the site and p_o is standard pressure for sea level, 1013.25 mbar (Gates 1980). The correction factor is 0.95 at 1400 m altitude and 0.69 at 3000 m.

The appropriate weighting factor to the solar constant for direct radiation on the ground is, therefore, instantaneously, T^m which must have the cosine-correction made. Substituting m from Equation 4 and including the cosine correction:

$$\text{weighting factor} = (cos z)T^{(1/\cos z)} \tag{5}$$

for $z = 0$–80°. A long-term weighting factor has to be integrated over a day and over a year. It can be seen that the weighting factor is not independent of T which means that a suitable value for the site must be measured or estimated. Note that the weighting factor depends on solar altitude but not azimuth.

The DSF is the ratio of the direct radiation for the sum of the periods for which the sun is opposite a canopy hole to the total direct radiation for the day. The DSF for a day can be calculated, given a value for T, by numerical integration along that day's solar track. Long-term values can be calculated by averaging the appropriate daily solar tracks. Direct radiation below the canopy is then DSF multiplied by measured direct radiation in the open. Note that no correction for cloudiness (cf. section 7.1) is necessary since the measured radiation is an actual value and includes the effects of cloud.

7 Computation of PAR from first principles

7.1 Direct PAR

Equation 3 provides a fundamental method of computing the amount of direct radiation at the earth's surface. The solar constant is the flux of solar radiation on a surface perpendicular (normal) to the sun's rays outside the atmosphere at the mean distance of the earth from the sun, and is currently taken as 1373 W m^{-2} (Monteith & Unsworth 1990). The solar constant is a conservative rather than a constant quantity but fluctuates by only a few percent. If necessary the fluctuation of about 3.4% owing to the elliptical orbit of the earth can be calculated (e.g. equations in Pearcy (1989), but note that the factor 0.34 he uses should be 0.034, and in Iqbal (1983)).

The attenuation of solar radiation by constituents of the atmosphere has been much studied (see e.g. Iqbal 1983). Here the simplest possible model has been chosen in which absorption and scattering by molecules and by aerosols (dust, smoke, etc.) are accounted for in the single parameter T, modified by the path length m discussed in the previous section. (The equation can also be written in a form based on Beer's Law where the attenuation is exponential (e^{-km}) and k is the extinction (turbidity) coefficient.) More elaborate models are given in Iqbal (1983). For us there is little to be gained from more detailed models of attenuation because for the remote sites where hemiphots are most useful details of atmospheric conditions needed to use the models are poorly known, especially as a weighted average for the year.

A value must be given to transmittance T and for a clear sky the range 0.4 to 0.8 covers all probable values (Gates 1980, p.107). The highest values occur on mountains with very clear, dry skies and the lowest at low altitude sites with high atmospheric turbidity. Gates suggested that 0.6–0.7 is a realistic range. The value of T is independent of cloudiness in so far as cloud that obscures the direct beam means that no direct radiation is recorded, a simple on/off effect. But haze, which can reduce markedly the amount of direct radiation, is not mentioned in textbooks as a factor decreasing the value of T. However, haze is a well-known although unquantified phenomenon in the humid tropics (cf. Evans, Whitmore & Wong 1960). It appears to be necessary for some tropical sites to reduce the value of T for haziness to balance Equation 3, when integrated over time and taking into account good estimates of cloudiness. This was done by Whitmore *et al.* (in press) who computed $T = 0.4$ for their site in Borneo. This demonstrates the importance of haze, for unless haze is invoked 0.4 is unrealistically low for tropical sites remote from industrial activity and when free of volcanic dust.

Equation 3 is for potential direct radiation and the actual amount is reduced because of clouds in front of the sun. For a particular day, the record from a

Campbell-Stokes sunshine recorder can be used to apply a cloudiness correction, point by point along a solar track. The limitations of a sunshine recorder should be borne in mind (Painter 1981): principally overburning of the card because the burn does not stop immediately when clouds pass rapidly across the sun, and the dependence of burning on the state of the card and sphere, especially with dew or frost. For long-term computations it is possible to use a collection of daily sunshine records to provide cloudiness correction factors for different periods of the day and of the year, corresponding to segments along the band of solar tracks on the hemiphot (Whitmore *et al.* in press).

Chazdon & Field (1987, p.527) used Equation 3 to obtain the potential direct radiation (no correction for cloudiness) but multiplied ${}_pS_d$ by 0.85 to represent the fraction of total radiation that is direct, under clear skies and for sun angles above 40° from the horizon. Such a correction is unnecessary because this calculation already concerns direct radiation alone, so what fraction it is of the total is irrelevant. Their computed potential direct radiation is therefore only 85% of the correct value. However, the error is in the right direction to allow for cloudiness and the good agreement they got between measured actual and computed potential PAR can be attributed partly to compensating errors.

7.2 Indirect PAR

There seems to be no way of computing indirect radiation that is equivalent to the fundamental method for computing direct radiation. It is, in fact, possible to calculate the amount of indirect radiation from the solar constant and a weighted mean transmittance factor for the whole hemisphere. However, this factor must be obtained empirically, as the ratio between measured indirect radiation and the solar constant, computed for receiving surfaces with the same orientation and totalled over the same period of time. Moreover, the amount of indirect radiation obtained this way is for the whole hemisphere, and there is no information on its angular distribution, which is what hemiphot analysis requires. Thus we are forced to use the site factor method described above.

8 Penumbral effects in direct PAR

When working at the fine scale necessary to compute instantaneous direct irradiance, the discrete size of the sun in relation to holes in the canopy gives rise to penumbral effects (Anderson & Miller 1974; Smith *et al.* 1989). That is to say, if the hole is about the same size as the sun appears to be, the same total of radiation as from an unobstructed view of the sun at that angle is spread over a larger area on the ground and appears as a bright central spot (at lower irradiance than the unobstructed view) plus an annulus of penumbra. The dimensions of the penumbra can be calculated from the geometry of the case. Smith *et al.* (1989) used the width of the canopy hole and its distance from the ground (which can be difficult to calculate in a deep forest canopy), but it could equally well be formulated as angles, for incorporation into hemiphot analysis. For a realistic computation of direct instantaneous irradiances, for example to analyse the frequency distribution of irradiance, the penumbral effect must be taken into account using the exact size and position of holes of the solar track for the day in question. However, when long-term averages (irradiation) are required, it is reasonable to assume that for each sample point the occurrence of the penumbræ from holes near to but not on a solar track are an uncomputed addition to the radiation total which balances the uncomputed loss from small holes on the track where the bright spot actually has less than the computed irradiance. The assumption here is that holes small enough to give penumbral effects are not clustered around particular solar tracks but occur randomly across the band of tracks.

9 Precision of measurements

It remains to consider how close an agreement can be expected between computed and measured PAR. This is a particularly difficult problem with the low absolute values found under complete leaf canopies, typically down to one or two percent, i.e. 20 μmol m^{-2} s^{-1} (or 0.5 mol m^{-2} day^{-1}) compared with up to 2000 μmol m^{-2} s^{-1} (or 50 mol m^{-2} day^{-1}) in the open.

The resolution of computed PAR depends on many factors including the properties of the photograph and the image analysis system. From the discussion so far it will be clear that there are numerous assumptions and approximations (see also Rich 1990). The effect of some assumptions, e.g. the sampling procedures for direct radiation along and among solar tracks, can be assessed by sensitivity analysis (see Whitmore *et al.* in press).

We think that a cautious view should be taken of measurements of radiation in the field. Biggs (1986) suggested that 10–25 percent error under non-ideal conditions is to be expected. Quantum sensors and integrators for PAR are expected to measure correctly over at least four orders of magnitude for irradiance (< 0.2 to > 2000 μmol m^{-2} s^{-1}), to follow the cosine rule exactly, to integrate in time irradiance that may fluctuate rapidly, and to reject radiation outside the limits of the 400–700 nm waveband (Biggs 1986). This last quality is severely tested under deep vegetation shade where there will be a much higher ratio of infra-red beyond 700 nm to PAR (400–700 nm) than in the open. Manufacturers take pains to show that their products are accurate and precise when calibrated and operated in well-controlled laboratory conditions or when carefully set up and regularly maintained in meteorological stations. But ecologists subject them to rough use in harsh environments with infrequent cleaning and calibration. We believe that a good rule of thumb is to accept only two significant figures in final results, although more figures should be carried in chains of calculations. Without photomultipliers or very careful calibration and operation it is difficult to have much confidence in more than one significant figure (thus ± 0.5 units) below 5 μmol m^{-2} s^{-1} or 5 mol m^{-2} day^{-1}. An accuracy of ±10% is the greatest likely to be attainable under field conditions at higher values. Thus it is quite likely that there will be large percentage differences between true and measured PAR in the low radiation regime below a canopy.

Consequently when computed PAR is plotted against measured PAR it is expecting too much for the points to fall on a 1:1 line. Rather, good correspondence is shown if the points fall within an envelope set by the precision of measurement (see Whitmore *et al.* in press). If the points tend to fall above or below the envelope this suggests bias in either the measurements or the calculations.

10 Mapping the distribution of radiation on the ground

Often in forest ecology the amount of radiation reaching the ground is required for a large number of points. These may be individual seedlings whose growth is under study or as a transect across a gap or forest edge. To record radiation at so many points may necessitate more measurements than resources allow. The question arises as to whether the radiation can be mapped by interpolating between a more manageable number of sample points systematically or randomly distributed across the study area. To analyse whether this is a reasonable procedure we need to consider the variations in solar radiation in time and space under a canopy.

Direct radiation contributes much more than indirect radiation to temporal variation because of the great range in irradiance during the day (and in temperate latitudes during the year) from the changes in solar angle, to which must be added the effects of clouds and the canopy. Direct radiation also makes a large contribution to spatial variation under a canopy because its penetration is restricted to holes and gaps and its irradiance is usually much higher than the diffuse background of indirect radiation. Together these effects account for the occurrence and behaviour of sunflecks.

At any given point, variation in radiation through time occurs on scales from minute to minute (the sun moving across canopy holes, clouds moving across the sun), through day to day (sunny and cloudy days), and month to month (change in solar tracks and seasonal changes in the canopy), to year to year (climate variability and changes in the canopy during the forest growth cycle). On the forest floor the variation in space is particularly evident as a pattern of sunflecks. A complete record of the radiation on the floor would require continuous and instantaneous measurement from an infinite number of minute sensors covering the area. As this is unattainable it is usual to make measurements at a small number of points in space and integrate up to the scale of interest. There is an interplay between integration in space and time such that integration in time overcomes lack of integration in space (Gay, Knoerr & Braaten 1971, Reifsnyder, Furnival & Horowitz 1971). Most instruments sample the radiation at a point in space. Tube solarimeters and linear arrays of quantum sensors provide limited spatial integration by sampling an area of up to 1 × 100 cm. Temporal integration depends on how long the sensor is left in position, how the signal is processed and then on further processing of the measurements. Hemiphots are only a point sample in space and time but have the advantage that they can be analysed to provide long-term temporal integration.

The extreme variability of radiation in space on short time scales (seconds - minutes - hours) is visible in the forest in the movement of sunflecks on the ground, as the sun moves across the sky and canopy holes and as wind moves the leaves and re-arranges the holes. This was shown by Chazdon, Williams & Field (1988) who found poor correlation between simultaneous instantaneous readings of sensors only 20 cm apart. The consequence is that interpolation between sample points is unlikely to produce a precise map unless they are only a few centimetres apart. In the long term (weeks - months - years) the effects of individual sunflecks average out, provided that they are uniformly distributed and are small compared with the scale of mapping. This implies that canopy holes must be small and evenly distributed for interpolation to be possible. When the canopy is not homogeneous in this fashion then there are marked discontinuities of long duration in the distribution of radiation on the ground which cannot be mapped unless sample points are very close. These discontinuities are a function of the precise distribution of canopy holes and gaps in relation to the sky and especially the sun. The clearest such example is a canopy that has a gap which gives a large and long-lived sunfleck when direct radiation penetrates it. This is demonstrated by Canham *et al.* (1990, p.625 and Figures 4, 6, 9) for a relative measure of PAR, the Gap Light Index. Canopies of intermediate heterogeneity are those with holes that are variable in size and irregularly distributed across the hemiphot.

We do not know how to quantify the boundary between heterogeneity and a distribution of holes which renders the canopy acceptably homogeneous and hence capable of transmitting a mappable pattern of radiation. However, hemiphots do provide a permanent record of the canopy. The image of a canopy, once captured in a computer memory, is in a form susceptible to general image analysis as practised by geographers and materials scientists. It should be possible to devise methods to quantify canopy heterogeneity and thereby to identify those conditions when mapping would be a reasonable procedure. As far as we know this has not yet been attempted.

Fernández and Fetcher (1991) showed how the temporal and spatial variation changed, in a subtropical montane forest in Puerto Rico (18°20'N) after Hurricane Hugo of 22 September 1989, as the canopy resprouted and, particularly, as pioneer trees grew up. They measured PAR with sensors on posts 60 cm tall at 1 m spacing along a 30 m transect at 2–4 month intervals during 13 months after the hurricane had stripped most leaves and some branches from the tree canopy of 15–20 m in height. Moderate spatial variability, as assessed from plots of semivariance (their Figure 4), was found in the first six months. This was replaced by high variability four months later when the rapidly growing pioneer tree seedlings were approximately the same height as the sensors and shaded them, and the sun was at some of its highest angles for the year (July). After a further four months the seedlings were all taller and casting much more uniform shade. Solar angles were lower (November) and spatial variability was the lowest recorded. We surmise that only on this last occasion would mapping by interpolation of long-term average PAR be reasonable, whether from measurements or computations from hemiphots.

To summarize, hemiphots allow mapping of radiation in so far as they can be used to compute a long-term average from a point record in space and time. Short-term or instantaneous radiation under a canopy cannot be mapped by interpolation because spatial variation is always high. But even long-term average radiation can only be mapped when the canopy is homogeneous because otherwise there are unpredictable discontinuities which make interpolation unreliable.

11 Conclusions

We have shown that the computation of absolute radiation from a hemiphot is far from straightforward, and as far as we can see is impossible without some instrumental records for the incident radiation of the site and of cloudiness. Table 1 gives a checklist of calculations.

It is always likely that there will be differences between PAR recorded at a point and that computed from a hemiphot. Table 2 lists the reasons from the point of view of the calculation of PAR. It assumes that there are negligible errors in the procedures of image analysis (what these are and how to minimize them is discussed by Rich 1990).

The inescapable error in ignoring scattered radiation turns out to be insignificant as Whitmore *et al.* (in press) discuss in detail. Although in deep shade the scattered

Table 1. Checklist of calculations required to compute PAR from hemispherical photographs.

A For indirect radiation

- **1.1** Choose an angular distribution
- **1.2** Calculate ISF (including cosine-correction) from hemiphot
- **1.3** Obtain measured incident indirect radiation (average for relevant period - day, month, year)
- **1.4** (Penetrated indirect radiation) = ISF × (incident indirect)

B For direct radiation

- **2.1** Choose a value for atmospheric transmittance
- **2.2** Choose sampling intervals along and among solar tracks
- **2.3** On hemiphot point by point along solar tracks

either

- **2.4** Evaluate Equation 3 (making cosine-correction and multiplying by the probability that cloud is not obscuring the sun) and sum for required period to give penetrated direct radiation

or

- **2.5.1** Calculate DSF (including cosine-correction) averaging for required period
- **2.5.2** Obtain measured incident direct radiation (averaged for relevant period - day, month, year)
- **2.5.3** (Penetrated direct radiation) = DSF × (incident direct)

C For total radiation (Total penetrated radiation) = (penetrated indirect) + (penetrated direct)

Table 2. Checklist of possible reasons for differences between PAR as measured and as computed from hemiphots. The reasons are listed from most to least likely, and correspondingly from irremediable to those easily allowed for but this does not indicate the size of the errors: for example (1) is always present although not important quantitatively.

1 Calculated PAR cannot include that scattered by canopy.

2 For indirect radiation.

- (a) Is the angular distribution based on long-term average measurements or good estimates for the site taking into account the range of sky conditions?
- (b) Have good estimates of the amount of incident radiation been made for the site?
- (c) Does the lens used have serious area distortion in the part of the hemisphere where gaps and holes are concentrated (see Appendix and Fig. 6)?

3 For direct radiation.

- (a) Has a reasonable value been chosen for the transmittance through the atmosphere?
- (b) For computation from first principles, have realistic probabilities for the sun being unobscured by cloud been chosen, for the time of year and time of day if these details are available?
- (c) For instantaneous computations, is it a good assumption that small holes in the canopy allow direct penetrated radiation at its full value, or are there penumbral effects?

4 Are any conversion factors between solar radiation and PAR or energy and quantum units untrustworthy for some reason?

component can be up to 43% of the total (Whitmore & Wong 1959) it is a percentage of a very small total. In the open the PAR computed from a hemiphot should equal that measured and in practice may be made to do so since the measurements are needed to estimate a value for atmospheric transmittance (see Whitmore *et al.* in press).

The clearest way to compare computed and measured PAR is to plot the deviation (computed minus measured) against measured PAR which is assumed to be the true value; see Fig.4. Constant errors are shown as horizontal lines above and below zero deviation and percentage errors as lines radiating from zero deviation at zero measured PAR. To allow for scattered radiation two points can be plotted for, say 0.5 mol m^{-2} day^{-1} computed in deep shade (where measured would be 1.0 mol m^{-2} day^{-1} if the scattered component was 50% of the total) and 25 mol m^{-2} day^{-1} in the open, computed and measured: respectively a and b on Fig. 4. With linear interpolation $a-b$ (the new line of agreement allowing for the scattered component) is still close to the line of zero deviation and even for this extreme case lies within the envelope of error based on the precision of field measurements.

For direct radiation, calculation can be based either on a site factor from the hemiphot or on the attenuation of the solar beam passing through the atmosphere at sample points along the solar track. Both methods require an estimate for the transmittance of the atmosphere.

For indirect radiation only the site factor method is feasible, with calculations for sky conditions averaged over a day, a month or a year (except for the two extreme cases of a clear sky and an overcast sky when instantaneous calculation is possible). Measurements of the long-term average angular distribution of indirect radiation have simply not been made as far as we are aware. With modern radiation detectors and data-loggers such measurements would be possible at a comparatively low cost and we suggest that they are important for future progress in the use of hemiphots to estimate absolute amounts of radiation. An alternative would be a method of calculating a weighted average from measured examples of sky conditions whose relative frequency was known.

Even with such information for the angular distribution of indirect radiation we cannot escape from the need for instrumental measurements to compute PAR from hemiphots so we conclude that we have not found the Holy Grail, namely the means to compute PAR from hemiphots with no instrumental readings at all, and if our arguments are correct it does not exist. However, we have identified methods that should work with the minimum of measurements at the hemiphot site and we have also identified a variety of assumptions that need always to be tested and justified to validate the computation of PAR.

In the interest of progress in this complex subject we hope that readers will identify and publish our errors and omissions.

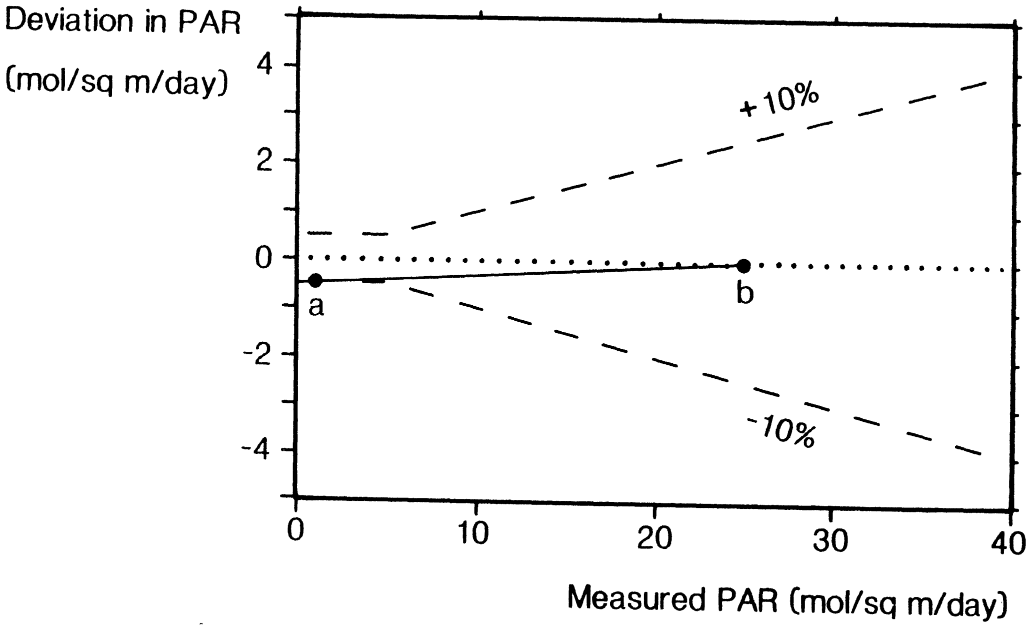

Figure 4. The deviation in PAR (computed minus measured) plotted against measured PAR to show the envelope of error associated with the limits of precision of field measurements (see section 9). The line *a*–*b* shows an allowance made for scattered radiation (see text for details). The two points are (*a*) in deep shade at 1 mol m^{-2} day^{-1} measured, 0.5 mol m^{-2} day^{-1} computed and (*b*) in the open at 25 mol m^{-2} day^{-1}.

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B Appendices

B.1 Representation of area on hemispherical photographs

Although azimuth angle is easily located and zenith angle is linearly transformed on to a hemiphot, equal areas on the hemisphere are not represented by equal areas on the photograph. This is implicit in Hill's paper (1924, p.277) where he mentions that for an equidistant projection a small circle imaged at the zenith as a circle would appear as an ellipse at the horizon with its long diameter $\pi/2$ times the shorter one. But this point was not commented on by Evans & Coombe (1959) nor by anyone else that we know of who has used hemiphots as an ecological tool until Herbert (1987) demonstrated its effect and Chazdon & Field (1987) allowed for it in their sampling scheme for pixels along radii on the hemiphot image. Given the exact correspondence of azimuth angles and the linear transformation of zenith angle, the area distortion is not intuitively obvious to us so we demonstrate here with minimum mathematics that it exists, and its magnitude. The reasoning is similar to that in Chazdon & Field (1987). The general problem is the same for cartographers projecting the globe on to a flat map: projections can be for equal linear distances or for equal area but not both.

To start we need accept only the equidistant projection (zenith angles linearly represented on the radius of the hemiphot) and the geometry of a sphere proved by Archimedes (Stroud 1981). This states that the surface area of a sphere is the same as the area of the curved surface of a cylinder which exactly encloses the sphere, like a ball in a tube as long as the diameter, i.e. $4\pi r^2$. Now consider a horizontal slice of thickness h through the cylinder and sphere. The area of curved surface of the slice of sphere (a zone) is equal to the area of curved surface of the slice of cylinder, i.e. $2\pi rh$. The extra length along the curved surface of the zone, viewed from the side (Fig. 5), compared to the height of the slice is exactly compensated by the smaller circumferences of the zone compared to the cylinder. This means that we can easily calculate the areas of zones by reference to their thickness. We can also calculate the angle from the centre of the sphere to the upper and lower circumferences of the zone. These angles can then be projected as on to a hemiphot and the areas of the annuli enclosed calculated.

For n slices of equal surface area of hemisphere the thickness of each slice, h_i, is r/n where r is the radius of the hemisphere (Fig. 5). The area is $(r/n)\ 2\pi r$ which is $2\pi/n$ for unit radius. Counting slices up from the horizontal plane, so that the upper circumference of the ith slice is ir/n up from this plane we have:

$$\sin a = \frac{ir/n}{r}$$

where angle a is above the plane (Fig. 5). To convert this angle to distance from

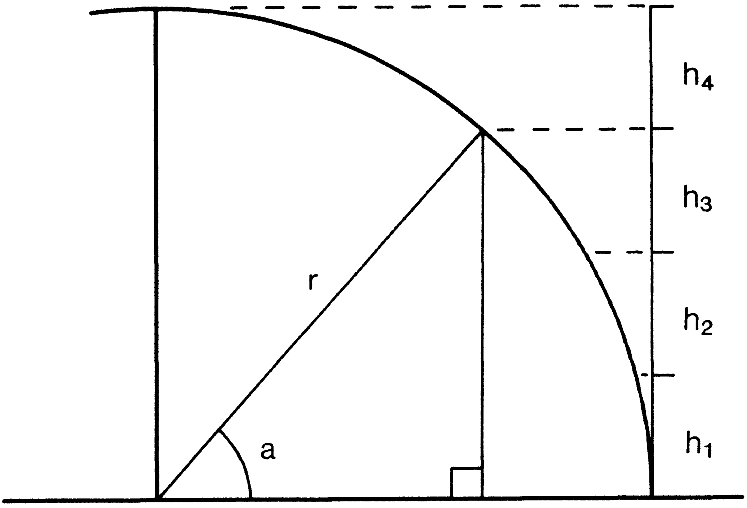

Figure 5. Part of a vertical section through a hemisphere to show division into four zones of equal height and so of equal area of curved surface, and the triangle from which can be calculated the angle from the horizon to the upper circumference of the third zone ($\sin a = (3r/4)/r = 0.75$, so $a = 48.6°$).

the centre of the hemiphot we take its complement to get the zenith angle and then scale for unit radius by dividing by 90. The area on the hemiphot of annulus i, now counting from the centre, is A_i and r_i is its outer radius so that:

$$A_i = \pi(r_i^2 - r_{i-1}^2)$$

where r_0 is zero, the centre point. The area of a hemisphere is $2\pi r^2$ but this is represented by πr^2 on the hemiphot so each annulus area must be doubled before comparison with the area of its zone.

The results of calculations for 20 equal area zones are shown in Fig. 6. The deviation (as a ratio) of the area of annuli from the true area of the zones is plotted against average zenith angle for the zone. It can be seen that there is exact correspondence at a zenith angle of about 63°. Closer to the zenith the hemiphot under-records the true area, closer to the horizon it over-records. Here we have scaled the calculation so that the total area out to a horizon at 90° to the zenith is represented correctly. This demonstration by a numerical method of course gives the same results as analytical solutions. Herbert (1987, Fig. 2) plots the deviation from true area relative to the zenith to show that the recorded area is greater by $\pi/2$ or 57% at the horizon. Pearcy (1989, Equation 6.14) calculated a weighting factor (90 sin z/z in degrees, $\pi \sin z/2z$ in radians) which is unity at the horizon and tends to $\pi/2$ as zenith angle, z, tends to zero.

What implications does area distortion have for previous work with hemiphots wherein it was not recognized? Calculations of solar tracks are unaffected since zenith and azimuth angles are not in question. For most work the sun is treated simply as a point to be located on the hemiphot to see whether it would be visible or not. However, where the apparent size of the sun is important, as when allowing for penumbral effects for example, area distortion needs to be taken into account since away from the zenith the sun would appear as an ellipse, notably so near the horizon.

Area distortion does affect computations of percentage canopy openness and indirect site factor (and hence the absolute amount of indirect radiation). It has probably not been apparent in previous studies because the effect (see Fig. 2a, b, and d, e) is small relative to other approximations made, especially the choice between a Uniform or Standard Overcast Sky. (The SOC involves a three-fold reduction in radiation from zenith to horizon which we have argued above is a better long-term approximation to real skies.) Where most gaps or holes are within 45° of the zenith, as is common under forest canopies, the area distortion could bias the results downwards by around 15% (Fig. 6). Another situation liable to significant errors is where large areas of sky near the horizon contribute to the indirect radiation received, as at forest edges (in which there is current research interest, e.g. Williams-Linera 1990), on steep slopes, or where hemiphots are used

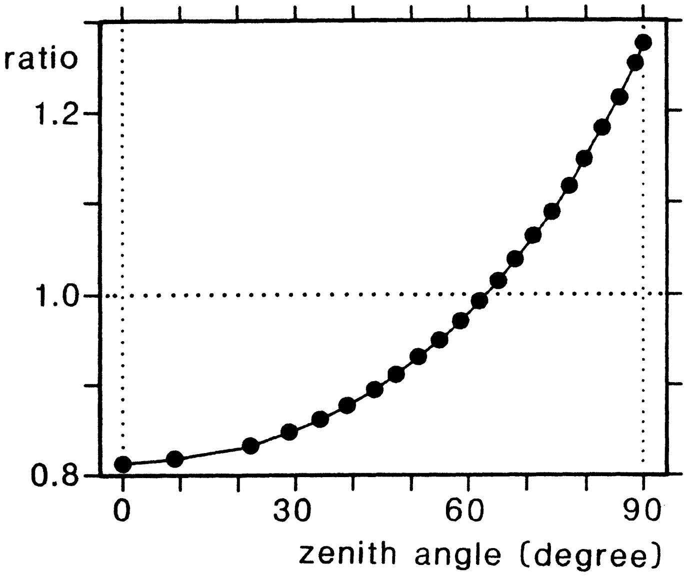

Figure 6. Graph to show how the ratio of the area of an annulus on a hemiphot to the area of the corresponding zone on a hemisphere varies across the hemiphot from the centre (zenith angle 0°) to the edge (90°). The points were calculated for 20 zones of equal area except at 0° and 90° which are for zones with areas one millionth of the hemisphere.

to investigate the effects of site aspect (Pope & Lloyd 1975). Holes within 20° of the horizon will be overestimated by about 20% (Fig. 6). The error may be noticeable for indirect radiation but will be diluted when direct radiation is added to obtain the total. In forests where the holes occur above and below 63°, at which deviation is zero (Fig. 6), the positive and negative errors will tend to cancel out.

Herbert (1987) found that one lens tested had remarkably little area distortion: at worst up to 1.07 at a zenith angle of 85° instead of the expected 1.49 relative to 1.0 at the zenith. This appeared to be the result of small deviations from the perfect equidistant projection. Clearly lenses can vary from their designed specification so they should be checked for both their projection and area distortion as Herbert recommends. Correction factors can then be applied in computer programs that analyse hemiphots.

B.2 Glossary

angular altitude The height of the sun measured as an angle from the horizon.

azimuth The direction in a horizontal plane in which the sun lies. Note that the reference point may be either due south or north.

beam radiation = direct radiation.

cosine-correction The implementation of Lambert's cosine law which states that the irradiance (q.v.) on a horizontal surface of a beam of radiation is proportional to the cosine of the angle from normal (i.e. perpendicular to the surface). Thus as cos 0° = 1.0, a vertical beam is received at full effect but at 90°, cos 90° = 0, a horizontal beam passes over the surface without being received.

diffuse radiation = indirect radiation.

direct radiation Radiation reaching the earth in a beam from the sun without being scattered in the atmosphere. In fact there is a very small component of forward scattered radiation (q.v.) which cannot be separated by measuring instruments. See Fig. 3.

direct site factor (DSF) The site factor (q.v.) for direct radiation.

equiangular projection = equidistant projection.

equidistant projection The projection of hemispherical lenses used in most ecological work wherein zenith angle (q.v.) is linearly related to distance on the hemiphot from the centre towards the edge.

equinox The days in the year (around 21 March and 21 September) when day (sunrise to sunset) and night are each 12 hours long. The sun rises at due east and sets at due west.

forward scattered radiation When a ray interacts with a molecule or particle in scattering its path is diverted. However, those rays that are re-emitted after scattering so as to continue in the same direction as before are called forward scattered.

gap (canopy gap) The spaces between tree crowns in an incomplete canopy. Gaps occur on the spatial scale of tree crowns and are created and filled up during the forest growth cycle, cf. hole.

hemiphot A contraction of hemispherical photograph. We prefer the word hemispherical to fish-eye because there are a variety of fish-eye lenses having angles of inclusion from about 100° to 180°.

hole The spaces between leaves and branches in a canopy, cf. gap. Holes are on the centimetre to decimetre scale (larger in very sparse canopies); their precise location varies from year to year with different sets of leaves, and they fluctuate as wind moves the leaves.

Holy Grail Figuratively, as here, the object of a difficult and ultimately fruitless search. (Literally, the chalice used at the Last Supper, the object of prolonged but unsuccessful quests by knights in the age of chivalry.)

image analysis system A means of transferring the hemiphot to a computer memory and display by digitization. Each element in the display is a pixel and it has a value representing its greyness. Once digitized and stored as an image the full range of computer-based image analysis methods developed over recent decades by materials scientists and geographers is in principle available.

indirect radiation Solar radiation that reaches the earth's surface only after scattering in the atmosphere, i.e. the diffuse radiation from all parts of the celestial hemisphere. See Fig. 3.

indirect site factor (ISF) The site factor (q.v.) for indirect radiation.

irradiance Radiation received on a surface as an instantaneous rate, i.e. amount of radiation per unit area per unit time.

irradiation Radiation received on a surface as a total for a specified period, i.e. amount of radiation per unit area. It is convenient, although not essential, to put the period into the units, e.g. joules per square metre per day.

light quality A general term to emphasize the importance of the spectral composition of radiation in contrast to the amount (quantity).

lumen See luminance.

luminance Light in the strict sense emitted from a surface, here treating the sky as an apparent surface. Light in the strict sense is radiation in the waveband 400–700 nm weighted by wavelength according to a standardized distribution based on the spectral sensitivity of the human eye. Light has units of lumen and lux (lumens per square metre) and is relevant only to human vision, not the growth of plants or other biological phenomena.

lux See luminance.

openness The proportion of the hemiphot that is open to the sky. It should be corrected for area distortion on the hemiphot but is not cosine-corrected or weighted in any other way.

penetrated radiation Radiation that has been transmitted by the canopy by passing through gaps in the canopy and holes between leaves and twigs without touching any part of a plant. See Fig. 3.

penumbra The annulus of lower irradiance around the bright central spot in pinhole images of the sun that are formed on the ground when the sun shines through a hole in the canopy of a size similar to its apparent size.

photon See quantum.

photosynthetically active radiation (PAR) Radiation in the waveband 400–700 nm which is conventionally assumed to be utilizable in photosynthesis. It may be measured in energy or quantum units according to which is thought most relevant: usually energy units for its heating effects or to consider it as a fraction of solar radiation; and quantum units when bearing in mind that photosynthesis is a quantum process.

pixel The individual element of a digitized image.

polar projection = equidistant projection.

quantum Radiation can be thought of as a stream of particles or packets of energy called quanta or, especially for visible radiation, photons.

radiance Radiation emitted from a surface, here treating the sky as an apparent surface.

scattered radiation Radiation in the atmosphere which has interacted with a molecule, particle of dust, water droplet, etc. By extension, scattering in a canopy is caused by radiation interacting with a leaf or twig. Here it includes reflection from and transmission through leaves for which the distinction is whether the scattered ray is on the same side or opposite side of the leaf as the incident ray. See Fig. 3.

site factor The site factor is the radiation received beneath a canopy as a fraction of that incident on the canopy, all measurement conditions being identical. Site factors computed from hemiphots are for penetrated radiation only; those measured by instruments include scattered radiation (q.v.)

solar constant The flux of radiation from the sun outside the atmosphere at the mean distance of the earth from the sun. On a surface normal to the solar beam it is 1373 W m^{-2}.

solar radiation Radiation from the sun, almost all of which lies in the waveband 300–3000 nm.

solar track The path of the sun during the day across the celestial hemisphere as recorded on the hemiphot.

solstice The days in the year when the sun at midday is at its highest (summer, around 21 June in the northern hemisphere) or lowest (winter, around 21 December) point in the year.

Standard Overcast Sky (SOC) The standardized distribution of indirect radiation over the sky where the zenith is three times as bright as the horizon. Strictly, it applies to luminance only but following Anderson (1964) we use it for radiance as well.

transmittance of the atmosphere (T) The factor by which radiation traversing the atmosphere is attenuated because of scattering.

tropic The lines of latitude on the earth's surface (about 23.5°N, Cancer, and 23.5°S, Capricorn) at which the sun reaches the zenith at midday at the summer solstice (q.v.).

Uniform Overcast Sky (UOC) The distribution of indirect radiation over the sky which is uniform.

waveband The range of wavelengths for a defined kind of radiation.

zenith angle The angle of the sun with respect to the zenith, i.e. to the point directly overhead.

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