
Canopy structure measurement by gap fraction analysis using commercial instrumentation

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Abstract

In the past few years, a number of systems for making indirect canopy structural estimates have become commercially available. These include linear sensors, such as the DEMON, line quantum sensors, and hemispherical sensors, such as the LAI-2000, the Leaf Laser, and the CI-100. The performance of these instruments as reported in the literature is reviewed for forests, row crops, and individual trees.

Key words: Leaf area index, LAI-2000, DEMON, SunLink, SunScan, Ceptometer, AccuPAR, CI-100, gap fraction, sunflecks, hemispherical photography.

Introduction

A complete structural description of a vegetative canopy might be a map or blueprint of the size, shape, spatial arrangement, and orientations of all of the foliage elements, including branches, stems, shoots, leaves, fruit, etc. Making such a map for a large canopy would be a task of Herculean proportions, further complicated by the fact that the canopy is dynamic; a gust of wind can change everything. Also, such a map would be of limited utility, since for most purposes more integrative or simplified information is required. An ecologist concerned with the photosynthetic potential of a community may consider only leaves, for example, while a forester interested in available timber will consider only primary stems. Another simplification is to use statistical representations, so random arrangements of leaves, spherical leaf angle distributions, and other idealizations are discussed (Ross, 1981). In practice, canopy structural descriptions are reduced to just a few numbers, including relatively easy-

to-measure quantities such as canopy height, row spacing, plant density, etc., and not so easy-to-measure quantities, expressing amount of foliage and how it is oriented. This latter group includes items such as leaf area per ground area (leaf area index, or *LAI*), total foliage surface area per ground area (*SAI*), total leaf area per canopy volume (leaf area density), mean inclination angle of the leaves, and distributions of leaf area in various angle classes.

Direct measurement of these simplified canopy structural parameters is a task whose difficulty is in direct proportion to the canopy size. Fortunately, there are a variety of techniques that use the close coupling between canopy structure and radiation interception to provide an indirect means to this end (Welles, 1990; Andrieu and Baret, 1993). The basic strategy is to use a model which describes how radiation is affected as it passes through a canopy based on some well-defined, geometrical canopy attributes, then make appropriate radiation measurements and invert the model to estimate the value of these attributes. Typically, the radiation model is based on two attributes of the canopy—foliage amount, and foliage orientation—and an assumption of randomness in the spatial distribution of the foliage. The degree to which an indirect method succeeds is determined in large part by how closely the real canopy conforms to the idealized one in the radiation model.

A potential problem with indirect radiation techniques is the fact that randomness lies at the heart of simple (and invertible) radiation models, yet foliage position is never random. On the one hand, leaves or needles don't float freely in space, but are arranged along stems or branches in an orderly manner. This organization makes for more efficient radiation interception than is predicted by a random model, because there is less overlap (Nilson, 1971). On the other hand, the branches or stems and the

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leaves attached to them tend to be separate and distinct, and this apparent clumping effect allows more radiation to pass through unobstructed to the lower parts of the canopy than the random model would predict. While no one has yet come up with a simple model describing these non-random processes in terms of real canopy attributes (the positive and negative binomial models of non-randomness use a curve-fitting parameter that is not directly measurable in a real canopy (Nilson, 1971)), it is fortuitous that these processes offset each other to one degree or another, allowing random radiation models to work reasonably well (within 15%) in many real canopies (ARG Lang, personal communication). An important exception is coniferous forests, as the grouping of needles on shoots represents a serious violation of the random positioning assumption (Norman and Jarvis, 1975; Oker-Blom and Kellomaki, 1983).

Theory

On a sunny day, the ground beneath a large shade tree provides an instructive (and pleasant) place to contemplate radiative transfer through a canopy. The seemingly uniform shade on the ground is interrupted by fuzzy-edged sunflecks of a variety of shapes, sizes, and intensities that are constantly shifting and changing as the sun moves. It is these sunflecks that provide a powerful tool for indirect canopy structure measurements. (Or more correctly, the tool is the gaps in the canopy that cause the sunflecks. The gap fraction of a canopy is the fraction of view that is unobstructed by canopy in any particular direction. The sunfleck fraction is equivalent to the gap fraction at the solar angle.) If the foliage in the tree were truly randomly positioned, then the probability $p(\phi)$ of direct beam radiation passing through the crown without intercepting any foliage would be

$$p(\phi) = \exp(-G(\phi) S(\phi)\mu) \quad (1)$$

where ϕ is the zenith angle of incidence of the radiation, $G(\phi)$ is the fraction of foliage area projected in direction ϕ , $S(\phi)$ is the path length (m) through the foliage, and μ is the foliage density (area of foliage per volume of canopy, m^{-1}). This has been simplified slightly because G and μ may also be functions of position in space and G a function of azimuth angle. For a uniformly homogeneous canopy of height z , path length $S(\phi) = z/\cos \phi$, and $\mu z = LAI$. For a discrete subcanopy such as a tree crown, $S(\phi)$ represents the sum of the path lengths through subcanopies only, and is obtained by direct measurement or by the use of a suitable geometric model, such as the ones described in Charles-Edwards and Thornley (1973) or Norman and Welles (1983). Equation (1) predicts the probability of finding a sunfleck at any location under the tree. Conversely, if the sunfleck fraction and corresponding path lengths $S(\phi)$ are measured and a value of

$G(\phi)$ is obtained, then it is possible to calculate the foliage density μ . Note that this is a simplification, because some of the structural information ($S(\phi)$ and $G(\phi)$) has to be known *a priori*. To extract both foliage density and foliage orientation estimates, more information is required. One recourse is to measure the sunfleck fraction at multiple sun angles.

Armed with sunfleck fraction (or gap fraction) measurements, there are several methods of extracting canopy structural information. To date, methods have concentrated on *LAI* and leaf inclination angle, where azimuthal orientation of the foliage is assumed random. The method of constrained least squares uses simultaneous equations (Equation (1) at several angles) with a constraint that area fractions must be >0 in the leaf angle distribution function G (Norman *et al.*, 1979; Lang *et al.*, 1985; Perry *et al.*, 1988; Norman and Campbell, 1989). This method yields foliage density (or *LAI*) and a fractional distribution of foliage in specified inclination angle classes. The one parameter ellipsoidal foliage inclination distribution of Campbell (1986) allows a very simple solution, easily coded into a short computer program (Norman and Campbell, 1989); it yields *LAI* and the ellipsoid's parameter. Lang (1987) derived the elegant solution

$$\mu = 2(A + B) \quad (2)$$

where A and B are the slope and intercept, respectively, of a plot of $-\ln(p(\phi))/S(\phi)$ versus ϕ (radians). This method yields no formal solution for foliage inclination, but Lang (1986) relates slope B to mean inclination angle with a polynomial. More recent work by Lang (1991) and Chen and Black (1991) indicate that foliage area estimates obtained from gap fractions measured at a range of angles, and for idealized foliage having convex cross-sections, theoretically correspond to 1/2 the total foliage surface area. Thus, total foliage surface area per canopy volume Y is given by

$$Y = 4(A + B). \quad (3)$$

This relation has been tested in conifers (Lang *et al.* (1991)) and broad leaves (Lang and McMurtrie, 1992), yielding indirect estimates of surface area within 24% and 15%, respectively, of actual values.

Tools and techniques

Attention can now be focused on the commercially available instruments that can be used for obtaining canopy structural information indirectly. They can be categorized into two classes: linear sensors and hemispherical sensors. Linear sensors measure in one direction at a time (usually the sun's), and may require movement to achieve a proper average. Such sensors include line quantum sensors and the DEMON. Hemispherical sensors view or sample multiple directions at once, and include hemispheric pho-

tographic methods, the LAI-2000, the Leaf Laser, and the CI-100.

Line quantum sensors

In the photosynthetic wavelengths leaves absorb about 90% of incident solar irradiance. This fact, together with the availability of radiometers which measure this waveband, and the predominance under clear skies of *PAR* arriving directly from the sun, makes direct *PAR* an appropriate method for gap fraction measurements (Fuchs *et al.*, 1984). Gap fraction at a particular solar angle is measured by dividing beam *PAR* (total – diffuse) below the canopy by beam *PAR* measured above the canopy. Commonly, reference measurements above or outside the canopy are made simultaneously or interpolated from measurements made before and after the series below the canopy. Since the measurements below the canopy include a component resulting from penetration of diffuse sky radiation and that scattered by the leaves, some correction must be made. One approach is to account for these with semi-empirical formulations (Campbell, 1991). Another is to measure the diffuse and scattered component with a shaded sensor (Walker *et al.*, 1988). A third approach is to use an empirically determined extinction coefficient k that relates *PAR* to *LAI* (Jarvis and Leverenz, 1983; Pierce and Running, 1988):

$$LAI = -(1/k) \ln(Q_b/Q_a) \quad (4)$$

where Q_a is an unobstructed *PAR* reading, and Q_b is an average below-canopy *PAR*. k is often assumed to be close to 0.5, but Runyon *et al.* (1994) found a wide range ($k=0.32$ to 0.71) across six forest types, and Smith *et al.* (1991) indicate that an average extinction coefficient—even for one species—is not necessarily applicable, based on measurements of 15 lodgepole pine stands.

Line quantum sensors are currently available from three manufacturers: Decagon Devices (Box 835, Pullman, WA 99163, USA) manufactures The SunLink and AccuPAR (the first generation was called the Sunfleck Ceptometer). Both of these devices use the same sensor array, consisting of 80 separate sensors spaced 1 cm apart along a probe. This multi-sensor approach, in principle, allows for sunfleck fractions to be directly measured by selecting a threshold value; however, penumbral effects as well as the short length of the sensor render this technique acceptable only for very short canopies or canopies with large leaves (Norman *et al.*, 1971). LI-COR (Box 4425, Lincoln, NE 68504, USA) manufactures the LI-191, which consists of a single detector that receives light from a 1 m quartz rod. Delta-T Devices (128 Low Rd, Burwell, Cambridge CB5 0EJ, England) have recently introduced the SunScan SS1, a Ceptometer-like device whose data logger also reads a pair of reference

sensors (shaded and unshaded), and uses a light model to provide a direct readout of *LAI* estimates.

DEMON

First described by Lang *et al.* (1985), this instrument is available from CSIRO, Centre for Environmental Mechanics, GPO Box 821, Canberra, ACT 2601, Australia. The DEMON measures direct beam radiation from the sun through a narrow acceptance angle (0.302 sr) to eliminate diffuse radiation from 95% of the upper hemisphere. ('sr' is steradians, a measure of solid angle. There are 2π sr in a hemisphere.) Filters are used to limit the spectrum of received light to a band near 430 nm, thus minimizing the effects of scattering by the foliage. In use, the sensor is continuously aimed at the sun and moved beneath the canopy along a transect. In very tall canopies, the operator can carry the sensor while walking the transect, keeping the sensor aimed with a sighting device. In short canopies, the sensor can be mounted on a traversing system or put on the end of a stick. The data collected consists of 1000+ light readings made during the 30 s period as the sensor moves along the transect. The data are grouped into groups of n readings, where n is large enough so that the distance travelled by the sensor while collecting those n points is at least 10 times the characteristic foliage element size. The average transmittance of each subgroup is computed using a prior reference reading of uninterrupted sun, and the subgroups are combined by averaging the logs of the transmittances. This procedure accommodates natural gaps in the canopy (Lang and Xiang, 1986). Gap fraction as a function of angle is determined by repeating measurements at various times over the course of half a day. The instrument can hold a large number of processed measurements for a number of sites, but final conversion to *LAI* is done on an external computer.

Hemispherical photography

Hemispherical photography has long been a canopy analysis method (Anderson, 1964; Bonhomme and Chartier, 1972; Cohen and Fuchs, 1987; Wang and Miller, 1987; Chen *et al.*, 1991). Photographs are taken with a 180° equidistant projection lens (many commercial lenses are suitable), from below the canopy looking upwards and in conditions where there is high contrast between the leaves and the sky. These conditions usually occur when skies are uniformly overcast, or at dawn or dusk. Care must be taken in setting exposures, as they influence the results (Chen *et al.*, 1991). Gap fractions are computed from such an image by determining the fraction of exposed background within rings or bands about the centre of the photograph (Anderson, 1964). The radius of the ring is proportional to the zenith angle.

Systems for automatic analysis of hemispherical canopy photographs have been developed (Bonhomme and Chartier, 1972; Cohen and Fuchs, 1987). Recently, commercial image analysers (Rich, 1988, 1990) and scanners (Smith and Somers, 1993) have been used for digitizing the images, and software has been developed for analysing the digital images. Table 1 lists details of several software packages that have been written specifically for analysing digitized fish-eye canopy photographs. More information on these programs can be found in the International Canopy Network's BBS (<http://esnet.edu/ican>).

CI-100

The CI-100 digital fish-eye camera and data storage system from CID (4018 NE 112th Ave. Suite D-8, Vancouver, WA 98682, USA) represents a recent and relatively portable automation of hemispherical photography. The instrument consists of a small box with a 1 m × 1.5 cm × 1.5 cm probe at the end of which is a fish-eye lens. An image is resolved into 180 000 pixels, and up to 32 images can be captured and stored by the device for downloading to a PC for viewing and data analysis. Typical limitations of fish-eye photography are sky condition and resolution, especially in tall canopies. Since gap fractions are obtained by picking a threshold (pixels brighter than the threshold are sky, darker are foliage), one wants all of the sky to be brighter than all of the foliage. The manufacturer claims to have circumvented this limitation via software, however.

LAI-2000

The LAI-2000 Plant Canopy Analyzer is described in Welles and Norman (1991), and is available from LI-COR, Box 4425, Lincoln, NE 68504, USA. It uses hemispherical optics and a ringed detector that simultaneously measures diffuse radiation in five distinct angular bands about the zenith. A reference reading is made above the canopy, followed by one or more below canopy readings. Gap fractions at the five angles of view are

computed by dividing the below-canopy readings by the above-canopy readings. The light sensor includes a filter to limit the spectrum of received radiation to <490 nm, minimizing the effect of light scattered by foliage. Use of this device generally requires the sun to be obscured, since directly illuminated foliage will scatter more light in the canopy than can be accounted for by the above-canopy reference reading, thus reducing apparent LAI values by 10–50% (Welles and Norman, 1991). View caps limiting the azimuthal field of view are used for several purposes, including obscuring the operator, limiting the measurement in small plots, and compensating for gaps in the canopy (e.g. inter-row paths). The need for an above-canopy reference reading can be problematic in tall canopies, or when sky conditions are changing rapidly. The LAI-2000 control box is designed to accommodate two sensors, one of which can be at the end of a long extension. This allows simultaneous above- and below-canopy readings in shorter canopies. A more expensive approach is to use two separate LAI-2000 instruments: one sits unattended outside or above the canopy logging at regular intervals, while the other is used to collect the below-canopy data. The data sets can be merged either by connecting the control boxes together, or by using an external computer (software supplied with the instrument).

Leaf laser

The sky conditions that are so important to most hemispherical techniques are irrelevant with a new laser scanning device from Decagon Devices, Box 835, Pullman, WA 99163, USA. This device, called the Leaf Laser, measures gap fractions via a self-scanning laser and detector. A small, motor-driven mirror is used to steer a tightly focused laser beam through an inverted conical pattern. A detector monitoring the returns determines whether any canopy element was hit. The Leaf Laser divides its measurements into sectors of 10° azimuth and 10° zenith, gap fractions for each being determined by

Table 1. Computer software written for analysis of hemispherical canopy photographs

The authors have not tested the programs. (Information provided by P.J. Burton, Symbios Research and Restoration, Delta, BC, Canada and R. McGhee, School of Resource and Environmental Management, Simon Fraser University, BC, Canada.)

Name	Authors	Address	Computer system	Conversion
SOLARCALC	R. Chazdon } C. Field }	chazdon@unconnvm.uconn.edu	MAC	Scanner
HEMIPHOT	H. ter Steege	The Tropenbos Foundation, PO Box 232, 6700 AE Wageningen, The Netherlands Fax: +31 (8370)23024 rick@wrs.sfr.msstate.edu	PC/DOS	Scanner
SUNSHINE	R. Smith		PC/DOS SUN/MOTIF	Scanner
GLI CANOPY	C. Canham P. Rich	73611.747@compuserve.com prich@oz.kbs.ukans.edu	unknown PC/DOS	unknown Image analyzer

the fraction of the approximately 400 pulses made in that sector that generated returns. A complete scan covers elevation angles of 10–60°, 280° of azimuth (the operator's quadrant is left unmeasured), and takes a few seconds. One limitation of this device is the effective range of the laser; the specifications state a 10 m effective distance, thus limiting the device to canopies shorter than, say, corn. Another potential problem is the beam width, 6 mm at 4.5 m. Study of point quadrat theory shows that for measuring gap frequency beam width should not exceed 1 mm (Caldwell *et al.*, 1983).

Applications

The applications have been divided into three parts: forests, row crops, and individual trees and shrubs according to increasing geometrical complexity. Forests are seen as homogeneous in all horizontal directions, varying only in the vertical, and are therefore envisioned as one dimensional. Row crops can still be seen as homogeneous along the row, and vary in the vertical and cross-row directions, so they are considered two dimensional. Individual trees and shrubs are not homogeneous in any direction and are considered three dimensional. Sampling strategies and protocols must be developed and used for each situation independently. Many studies have been done to evaluate gap fraction techniques in different situations. In general, 'good' results are those which agree to within 20% of direct measurements, without application of empirical calibrations.

Forests

Indirect techniques have been much applied, compared, and evaluated in forest canopies, largely due to the great difficulty of making direct measurements. In principle, hemispherical measurement techniques are fastest, because they obtain a wide range of angles at each sampling. Hemispherical photography and the LAI-2000 have been shown to agree with each other to within 10% in oak–maple (Wang *et al.*, 1992) and Douglas Fir (Chen and Black, 1992), but this is sensitive to sky condition, exposure, field of view, and snow in the trees. The above-canopy measurement required by the LAI-2000 can be especially problematic in tropical rain forests, although elaborate solutions have been found (Laumonier *et al.*, 1994). Linear techniques, on the other hand, require large grids in order to get useful estimates of leaf area index (Whitford *et al.*, 1995; Martens *et al.*, 1993). A number of comparisons of hemispherical and linear techniques in a number of broad leaf and conifer forests show that all methods gave results highly correlated with direct estimates of LAI, but are biased low (Neumann *et al.*, 1989; Chason *et al.*, 1991; Chen and Black, 1991; deBlonde *et al.*, 1994; Fassnacht *et al.*, 1994; Runyon *et al.*, 1994).

This suggests clumping not accounted for in a random model. In conifer forests, the clumping of needles on to shoots provides clear theoretical reasons for underestimating LAI, which has led some researchers to search for a directly measurable correction factor involving ratios of shoot areas to needle areas. Gower and Norman (1991) proposed such a correction factor, but it turned out to be faulty (deBlonde *et al.*, 1994; Fassnacht *et al.*, 1994; Smith *et al.*, 1993). Presently, a slightly more complicated, but still measurable, correction factor has given good results in several pine canopies with the LAI-2000 (Fassnacht *et al.*, 1994; Stenberg *et al.*, 1994). On the other hand, Sampson and Allen (1995) found little or no correlation between LAI-2000 measurements and allometric and litter-fall measurements in lodgepole and loblolly pine, and question the efficacy of any correction factors. In a sparse *Eucalyptus* canopy, Whitford *et al.* (1994) found linear and hemispherical techniques overestimated leaf area by 77% and 43%, respectively, suggesting a possible regularity of foliage spacing in this species. It is clear that all forests have complicated, non-random structures that make all current indirect techniques less than ideal.

Some recent work provides some hope for the future, however. Chen and Cihlar (1995) show that the use of gap size distribution in conjunction with gap fraction provides a quantitative measure of the non-randomness of the canopy. They used this technique with an LAI-2000 to measure two pine canopies' LAI to within 9%. Kucharik and Norman (1996) use a 16-bit charge-coupled device (CCD) camera that captures visible and near-infrared images within 50 ms of each other. This Multiband Vegetation Imager (MVI) provides a measure of a variety of canopy architectural components, including sunlit leaf area, foliage angle distributions, and quantitative measures of non-randomness. This approach differs from prior canopy imaging methods because it centres on measuring the fraction of view occupied by various scene components (such as branches, shaded leaves, sunlit leaves, etc.) rather than simply the canopy gap fraction under uniform sky conditions. While this device is still in the developmental stage, it holds much promise for providing not only more accurate LAI estimates, but measures of canopy structural components that have heretofore been nearly impossible to directly measure.

Row crops

In row crops and hedgerows the sampling geometry becomes critical (Cohen *et al.*, 1995). Lang and Xiang (1986) show both theoretically and experimentally that a good strategy for linear sensors is to sample perpendicular to the rows, to take linear averages of subsamples corresponding to 10 times the average leaf width, and finally average the linear averages logarithmically. Results for

sorghum and wheat (Lang and Xiang, 1986) and for two grape trellis systems (Sommer and Lang, 1994) show good agreement between indirectly and directly measured leaf area. Hemispherical sensors can also be used successfully in row crops, but require proper measurement and analysis protocol. To emulate the same technique as outlined by Lang and Xiang (1986), not only must samples be taken at locations crossing a row, but also for each location compute a linear average transmittance for each zenith angle using a very restricted azimuthal range. Also, since the Lang and Xiang (1986) technique involves a range of solar azimuth angles, transmittances should be computed for azimuthal segments over a range of azimuths, which are then log averaged together (Welles and Norman, 1991). With hemispherical photography, the CI-100, and the Leaf Laser, this is a function of the software doing the analysis. With the LAI-2000, it is a bit more problematic, since the full azimuthal range of the sensor is linearly averaged by the detector ring. For this reason, the LAI-2000 provides view-restricting caps which must be used at the time of data collection, and multiple readings must be taken with the view aimed in various directions. Good agreement between direct measurements and the LAI-2000 using a two-azimuth protocol (down-row and cross-row views) was found in soybeans and emergent corn (Welles and Norman, 1991), sugar beets (Rover and Koch, 1995), and cotton (Hicks and Lascano, 1995). However, unsatisfactory results in cotton (Grantz *et al.*, 1993) and grape vines (Grantz and Williams, 1993) occurred using a single azimuthal view measurement protocol.

Individual trees and shrubs

As with hedgerows, the problem of measuring foliage areas in individual trees or shrubs becomes one of selecting appropriate grid and averaging strategies for the measurements. One approach is to use Equation (1) and measure relevant path lengths in the canopy. This technique is useful with hemispherical sensors with transmittances measured from near the bottom centre of the canopy, looking out. Path lengths must be measured directly or computed from models of idealized canopy shapes. (A laser-based device has a potential advantage here in that canopy path lengths can, in theory, be measured automatically at each view angle using the time delays of the laser returns. Doing this in a low cost instrument is still in the future, however.) Acock *et al.* (1994) used an LAI-2000 and an elliptical canopy model to estimate leaf mass in individual crowns of *Erythroxylum*, yielding results superior (slope=0.91, $r^2=0.89$) to that obtained with a Ceptometer (slope=0.64, $r^2=0.73$). Villalobos *et al.* (1995) used the LAI-2000 to measure foliage density in individual olive trees, with good results (slope=0.93, $r^2=0.92$). Another approach

is to use an integrated form of Equation (1) so that canopy path lengths need not be known. Lang and McMurtrie (1992) derived an equation for this, and tested it on individual *Eucalyptus grandis* with good results (underestimating by 14% on average) using the DEMON. Brenner *et al.* (1995) compared the DEMON, LAI-2000, and Ceptometer on individual *Retama sphaerocarpa* bushes, with similar results: DEMON 12% low, Ceptometer 23% low, LAI-2000 18% high on average.

Discussion and summary

Indirect canopy measurements have had the support of commercial instrumentation for several years, and have been well tested in a variety of settings. The instruments generally provide an accuracy within 20%, except in canopies where non-randomness becomes significant. Each technique has its own set of advantages and disadvantages, and presently each is mostly limited by the assumption of randomness made in the inversion process. Gap size distribution analysis has the potential of overcoming this limitation, but the measurement of this distribution remains difficult. Laser technology provides potential for highly detailed canopy sampling, but perhaps lends itself best to measuring distance to the first canopy object, rather than determining gap fractions or gap sizes, due to beam size limitations. Probably the most exciting development in this whole area lately is the Multiband Vegetation Imager (MVI) being developed by Kucharik and Norman (1996).

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