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by

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3. Some Indirect Methods of Estimating Canopy Structure

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I. INTRODUCTION

Canopy structure is a central consideration in any description of plant-environment interactions. It is strongly coupled to the interception, scattering, and emission of radiation. The architecture of the canopy shapes the signature of the wind as it transports heat, momentum and gasses such as carbon dioxide and water vapor. Structure helps define the spectrum of microclimates found within the canopy; microclimates in which not only the plant itself must live, but also a host of other organisms, be they pathogens, insects, wildlife, or human.

What is canopy structure? The answer to this deceptively simple question could (impolitely, perhaps) be couched in terms of more questions: What are the foliage elements, such as leaves, stems, or fruit? How many of them are there? Where are they located? How are they oriented? What are their sizes? The notion of organization enters into the answer as well, as exemplified by a conifer shoot with its radiating needles, or by the way leaves in a forest understory form horizontal mosaics as they minimize overlap. Of course, organization is along an infinite continuum, of which cells, leaves, plants, and communities are only tiny segments. Canopy structure is also dynamic, changing on timescales ranging from minutes to years. Heliotropic leaves track the sun throughout the day. Other species fold, droop, or drop their leaves in response to water stress, light, or season.

The measurement and description of canopy structure is a task that is at best formidable, at worst impossible; thus, practical descriptions of canopy structure at present must use statistical tools or mathematical assumptions. The question of foliage position is often answered with an assumption of randomness. While a canopy such as turf grass would seem to be quite random, other canopies of rows or widely separated plants are clearly not random. A weighted random approach has been used, in which envelopes such as ellipsoids are used to define the limits of individual plants or rows, within which the foliage is assumed to be randomly distributed (Norman and Welles, 1983). Other approaches involve the use of an empirical coefficient to account for the effects of clumping (Nilson, 1971), and the use of non-random grouping theory (Norman and Jarvis, 1975; Oker-Blom and Kellomaki, 1983).

Foliage quantity is often normalized by ground area, or canopy volume. Leaf area index (LAI) is perhaps the most commonly used canopy structure parameter, and is defined to be total leaf area per ground area. One could similarly define branch area index or stem area index, for example. Note that LAI is independent of leaf orientation. In some canopies, such as a fruit orchard, an LAI based on the total area may not be as useful as some measure of the foliage in each individual tree crown, such as leaf area density (total leaf area per canopy volume), and drip-line LAI (DLLAI):

$$\mathrm{DLLAI} = \frac{\text{Leaf Area Density} \times \text{Canopy volume}}{\text{Area within the plant's drip line}} \tag{1}$$

Foliage orientation is perhaps most completely described by a distribution of fractional areas in various inclination and azimuthal angle classes. A device for direct measurement of leaf orientation and inclination is described by Lang (1973). In radiation models (and presumably in the actual canopies), one effect of foliage orientation is to change the nature of radiation penetration with direction. Thus, foliage orientation is often implicit in a directionally dependent extinction coefficient (Ross, 1981). Hypothetical foliage orientation distributions (de Wit, 1965), such as spherical, extremophile, plagiophile, and planophile, are sometimes assumed for the sake of simplicity. The spherical foliage orientation is popular because the fraction of area projected in any direction is always 0.5, simplifying the extinction coefficient. Goel and Strebel (1984) describe the two parameter beta distribution, which fits a range of real canopy data quite well. A less flexible, but more intuitive one-parameter ellipsoidal distribution is described by Campbell (1986). The one parameter is x, the ratio of an ellipsoid's horizontal and vertical radii. When x is unity, a spherical leaf angle distribution is specified. The mean angle of foliage inclination (Lang, 1986) is yet another simplified foliage orientation parameter.

Because radiative transfer and canopy structure are coupled so tightly, one can often be used to predict the other. Thus, relatively simple measurements of radiation can be used to estimate various structural quantities if a model is available to predict the canopy's influence on the radiation. Typically, a model will use canopy structure information as an input, along with relevant spectral properties and boundary conditions of incident radiation, and predict some component of the radiative environment at some place inside or outside of the canopy. Indirect radiative canopy sensing involves measuring a predicted radiative quantity, then inverting the model to determine the probable canopy structure that caused the measurement results. In the absence of a suitable model, an empirical approach based on regression analysis can be used. One notable exception to the use of radiation measurements for indirect estimates of canopy architecture is a commercially available pasture biomass sensor based on capacitance, discussed below.

The scope of radiative techniques for estimating canopy structure is broad, as is the complexity of the mathematical models on which they are based. A recent review of several techniques can be found in Norman and Campbell (1989). This chapter will focus on several specific, practical techniques for estimating the amount of foliage and its orientation.

II. INVERTING GAP FRACTION DATA

Several of the techniques to be discussed in this chapter estimate structure parameters by means of gap fractions. The gap fraction of a canopy is the fraction of view in some direction from beneath a canopy that is not blocked by foliage. The fractional sunfleck area is equivalent to the gap fraction in the solar direction. Gap fraction information for a range of angles contains much structural information, and is at present the most powerful and practical tool available. It can be applied not only to continuous canopies, but also to settings which can be modelled by discrete, foliage containing envelopes, such as row structure or individual trees.

The general problem can be stated as follows: If foliage is randomly distributed about some path of length $S(\theta)$ in direction θ, then the average, non-intercepted fraction $T(\theta)$ of a beam of radiation travelling that path is related to mean foliage density μ by

$$\frac{-ln(T(\theta))}{S(\theta)} = G(\theta)\,\mu \equiv V(\theta) \tag{2}$$

where $G(\theta)$ is the fraction of foliage area projected in direction θ. $T(\theta)$ and $S(\theta)$ can be measured; $G(\theta)$ and μ are to be deduced. $V(\theta)$ is equal to contact frequency as defined by Warren Wilson (1959). The assumptions implicit in Equation (2) are that the elements of projected leaf area are distributed at random on the projection plane and that the leaves are opaque. In principle, measurements of $T(\theta)$ and $S(\theta)$ in a variety of angles will lead to a mean foliage density μ, and the proper functional relation $G(\theta)$. For a horizontally homogeneous canopy of height z, $S(\theta) = z/\cos\theta$, and $\mu z = \text{LAI}$. For a discrete subcanopy, such as a tree crown, $S(\theta)$ is obtained by direct measurement or by use of a suitable geometric model, such as Charles-Edwards and Thornley (1973).

There are several methods of getting structural information from gap fraction data. The method of constrained least squares uses simultaneous equations, representing Equation 2 for various angles, with a constraint involving acceptable (area fractions > 0) leaf angle distributions (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. It is assumed that the foliage faces all compass directions with equal probability.

The one parameter ellipsoidal foliage distribution of Campbell (1986) allows a very simple solution, easily coded into a very short program (Norman and Campbell, 1989). The inversion results in an LAI, and the ellipsoidal parameter x.

Miller (1967) notes that an exact solution to Equation (2) is

$$\mu = 2 \int_0^{\pi/2} V(\theta)\, sin\theta \, d\theta \tag{3}$$

Lang (1987) shows that $V(\theta)$ is a fairly linear function of θ for idealized distributions, as well as in actual canopy measurements. If linearity is assumed, then Equation (3) becomes

$$\mu = 2(A + B) \tag{4}$$

where A and B are the intercept and slope, respectively, of a plot of $V(\theta)$ against θ (in radians). This simple method by itself does not yield any estimate of foliage orientation, but Lang (1986) relates the slope B to mean tip angle with a polynominal, assuming randomness in azimuthal orientation.

A sampling of results using gap fraction analysis is shown in Figure 1.

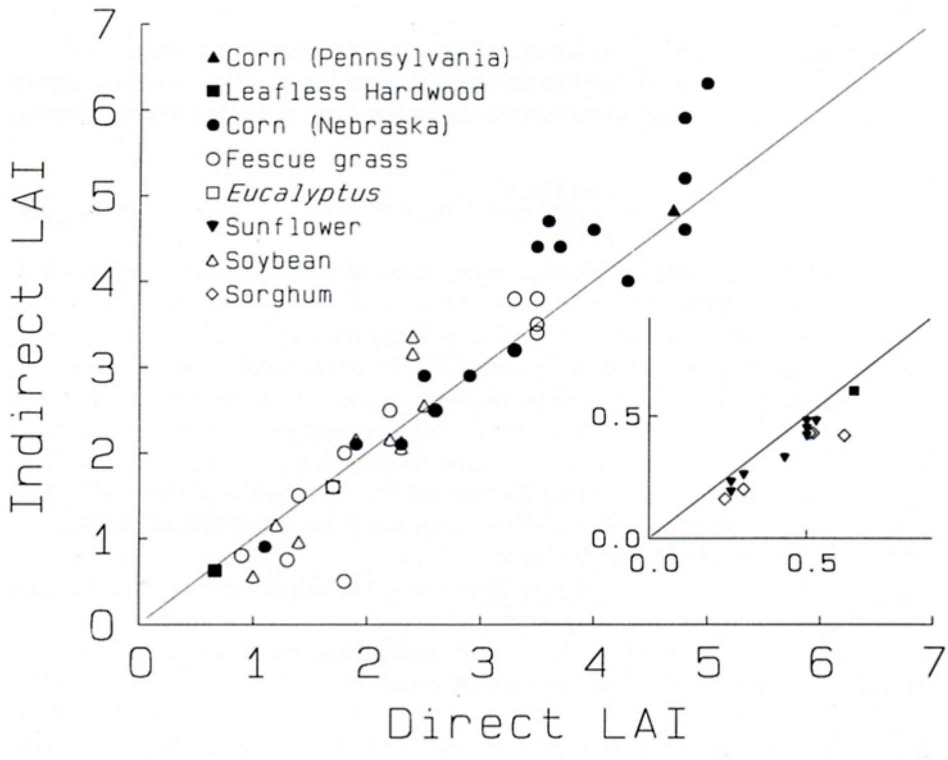

FIGURE 1 Indirectly determined LAIs using a variety of data collection techniques, but reduced using gap fraction analysis. (*After* Norman and Campbell, 1989). Used with permission.

III. SOME SPECIFIC TOOLS

A. Line Quantum Sensors

There are several techniques for estimating canopy structure that make use of a sensor that averages over some spatial length. Such a sensor that is sensitive to the photosynthetically active radiation (PAR) band is known as a line quantum sensor. One such sensor is available from LI-COR, Box 4425, Lincoln, NE, USA 68504, Tel.: 402-467-3576 (model LI-191, approximate cost without a readout device $1,800) and from Decagon Devices, Box 835, Pullman, WA, USA 99163, Tel.: 509-332-2756. (model SF-80 Ceptometer, approximate cost $1,800 including readout device). The LI-COR device senses over a continuous 1 m length by channelling the light through a quartz rod to the actual detector at the end of the unit. The Decagon device uses 80 separate photodiodes spaced at 1 cm along a rod. They also offer a 40 cm, 40 sensor device.

Norman (1988) has devised a technique for estimating LAI from quantum sensor measurements based on observations of model results. According to him:

$$LAI = \frac{(f_b(1 - cos\theta) - 1)\, ln(E_i/E_a)}{0.72 - 0.337 f_b} \tag{5}$$

where E_a is PAR incident on the horizontal above the canopy with the sensor unshaded, E_{ad} is PAR incident on the horizontal above the canopy with the sensor shaded, E_i is PAR incident beneath the canopy, and θ is the solar zenith angle. The beam fraction f_b is given by

$$f_b = \frac{(E_a - E_{ad})}{E_a}$$

Measurements of E_a and E_{ad} could be made with a point sensor, as long as the sensor is calibrated to the line quantum sensor.

Equation (5) was derived by empirically fitting the results of a radiation transfer model which assumes a spherical leaf angle distribution and random leaf positioning within the canopy. At solar zenith angles near 57°, however, the potential error caused by assuming the orientation distribution is minimized (Warren Wilson and Reeve, 1960). Solar angle can be computed from the length on the horizontal of the shadow of an object of known height, or else obtained from equations or tables based on location and time (List, 1958).

Pierce and Running (1988) use a line quantum sensor to estimate LAI in several coniferous forest stands under cloudless skies. They compute a mean transmittance to PAR based on reference readings (E_a) made in clearings and 1600 in-canopy readings (averaged to yield E_i) made along a 360 m transect. They assume an extinction coefficient of 0.52 based on measurements of Jarvis and Leverenz (1983), and calculate LAI from

$$LAI = -0.52\, ln(E_a/E_i) \tag{6}$$

The two line quantum sensor techniques based on Equations (5) and (6) are somewhat empirical, and yield no foliage orientation information. A line quantum sensor can be used to estimate canopy gap fraction as a function of angle, from which both foliage amount and orientation information can be derived. The technique is illustrated by Walker *et al.*, (1988). Four observations are required: E_a, E_{ad}, E_i and E_{id}, where E_{id} is an in-canopy diffuse measurement, made with the line quantum sensor shaded by an appropriately sized object. Gap fraction f at the solar angle is then

$$f=\frac{E_i-E_{id}}{E_a-E_{ad}} \tag{7}$$

Determinations of f are made at a range of sun angles.

Another line quantum sensor technique that is specific to the Decagon Ceptometer makes use of that device's threshold feature. Since there are 80 individual sensors, a threshold value can be selected, and the fraction of the detectors that are reading above that amount is computed. Thus, gap fraction can be read directly, without the need for above canopy readings or shading devices. This technique is limited by penumbral effects, however. If the canopy height and foliage element size are near the same order of magnitude, the underlying sunflecks will be bright and distinct, and the threshold technique will work quite well. However, as canopy height increases, and/or foliage element size decreases, sunflecks broaden and lose brightness, and it becomes increasingly difficult to pick a threshold value.

B. DEMON

This instrument for measuring the direct beam transmission of the sun was first described in Lang *et al.*, (1985). It has since been named the DEMON, and is available from Assembled Electrics, 66 Smith St., Yagoona NSW, Australia, Tel.: 61-2-645-3974. The approximate cost in Australia is US$2,800. The DEMON instrument measures direct beam radiation from the sun through a narrow acceptance angle (0.302 sr in the prototype) to eliminate diffuse radiation from 95% of the upper 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 moved beneath the canopy along a transect, all the while aimed at the sun. In very tall canopies, such a forests, an operator carries the sensor while walking the transect, keeping the sensor aimed at the sun using the attached sighting device. Used in short canopies, the sensor would have to be mounted on a traversing system.

Data collection consists of 1000 + light readings made during a 30 s period as the sensor moves along the transect. Gap fraction is computed in the sensor's data logger by log averaging the transmittances of subgroups of the data. That is, the 1000 data points are taken in groups of N points, where N is large enough so that the distance travelled by the sensor when collecting those N data is at least 10 times the characteristic foliage element size. The average transmittance for the subgroup is computed using a prior reference reading of uninterrupted beam radiation, and the subgroups are combined by averaging the logs of their transmittances. This procedure accommodates natural gaps in the canopy (Lang and Yueqin, 1986).

Gap frequency is also computed as a simple linear average of the transmittance.

Gap fraction as a function of angle is determined by repeating measurements at various times (sun angles) over the course of half a day. While the data logger can hold a large number of processed measurements for a number of different sites, the final LAI computations are performed externally on a computer. Software to do this inversion can be purchased from the manufacturer for approximately $390.

C. LAI-2000

The LAI-2000 Plant Canopy Analyzer uses a fisheye light sensor that measures diffuse radiation simultaneously in five distinct angular bands about the zenith point. It is available from LI-COR, Box 4425, Lincoln, NE, USA 68504 for approximately $4,000. The sensor consists of five photodiodes whose active surfaces are arranged in concentric rings. The image of its hemispheric view is projected onto these rings, allowing each to measure the radiation in a band at a known zenith angle. An optical filter restricts transmitted radiation to below 490 nm, minimizing the contribution of light that has been scattered by foliage.

In use, gap fractions at five zenith angles can be measured by making a reference reading above the canopy (sensor aimed up at the sky), and one or more readings beneath the canopy (sensor again looking up). The below readings are divided by the above readings to obtain an estimate of the gap fraction at the five angles. Snap-on view restrictors can be used to limit the sensor's azimuthal field of view. This is necessary in small plots, or very clumped canopies, or when the sun is shining.

It is best if the sun is obscured when using the LAI-2000, since the sensor's below canopy readings will be increased by scattering from sunlit foliage. Also, since the measurement is based on the difference in diffuse radiation above and below a canopy, direct sunlight in any of the five rings will cause that relatively subtle difference to be lost; thus, the sensor should always be shaded from direct sun when in use.

A potential weakness of the LAI-2000 approach is the requirement for an above canopy reference reading. There exists the potential for the sky conditions to change between the reference and below canopy readings, and in forests, getting the above canopy reading may be a problem. The LAI-2000 system addresses these problems with several provisions in its design. The control box will accommodate two sensors, and very long extension cables can be used, allowing above and below canopy readings to be made simultaneously. If two separate systems are employed, one system can be made to log readings unattended outside the canopy, while the other system is used to collect the in-canopy data. Later, the two data sets can be merged and calculations performed. This merging can be done by connecting the two control boxes together, or else by using an external computer with software supplied with the instrument.

D. Fisheye Photography

An image of a vegetative canopy made with a hemispherical lens provides detailed information about the canopy's structure (Anderson, 1971, 1981; Bonhomme and Chartier, 1972; Baldochi *et al.*, 1985; Neumann *et al.*, 1989). Images can be made looking up through the canopy, or from above looking down. The latter works well in the near-infrared region of the spectrum, where foliage is much brighter than the typical soil. Gap fractions can be computed from such an image by determining the fraction of exposed background (sky or soil) within rings or bands about the center of the photograph; the radius of a ring is proportional to zenith angle. This analysis can be automated if there is sufficient contrast between foliage elements and the background, and sufficient resolution so that foliage elements remain distinguishable. Fisheye imaging is best under diffuse sky conditions, since the range of brightness of foliage is minimized; otherwise, a sunlit leaf could be mistakenly identified as sky, for example.

E. Crownmeter

Van der Roest and Kopinga (1989) describe a device known as the Crownmeter designed to provide a rapid, objective indicator of the relative vigor of urban trees. The relative indicator is the mean transmittance of the canopy, measured with an up-looking, narrow view (1.5° half angle) sensor sampled at up to 10 Hz as the user walks a transect beneath the tree close to the trunk. Unobstructed sky readings are taken before and after the traverse, and measurements near the tree's periphery are not included in the mean. The authors feel that the useful range of the transmittance indicator is from a high of 28%, representing a sparse canopy, to a low of near 0%, representing a thick, vigorous canopy. No attempt is made to invert the readings to obtain a foliage density or LAI, although the possibility is mentioned. Such a procedure would likely require accounting for the light scattered by foliage in the visible part of the spectrum, since the sensor is sensitive over this entire region. Also, knowledge of the path length of the sensor's view through the canopy and measurements at more than one angle may be needed. As of this writing, the Crownmeter exists as a prototype, and has not been commercialized.

F. Pasture Probe

The Pasture Probe is a commercially available tool used in management of grazing land, manufactured by Design Electronics, Box 898, Palmerston North, New Zealand, Tel.: 64-63-85-702. This instrument does not use radiation techniques, but rather measures the capacitance along a 30 cm hand-held probe whose end is pressed lightly into the soil. The amount of dry matter within 5 cm of the probe is the dominant contributor to capacitance changes relative to an in-air reference reading, and biomass (kg dry matter ha^{-1}) is calculated from the average of many readings (typically 50) using a calibration curve.

G. Model Trains, Meter Sticks, and Mice

There are a variety of miscellaneous techniques for obtaining gap fraction information in vegetation canopies. Laisk (1969) and Matthews *et al.*, (1987) describe a light sensor ("mouse") that is pulled through a square section aluminium tube with holes drilled in its top. The fraction of holes receiving irradiance greater than some threshold amount is taken to be the gap fraction for that sun angle. Lighted rods have been placed beneath the canopy and photographed at night (Kopec *et al.*, 1987). Takenaka (1987) used a telephoto lens to photograph forest canopies from below at discrete angles of view. Model trains have been pressed into service to pull light sensors through the canopy (Perry *et al.*, 1988). Simplest of all is a meter stick to measure the fractional size of sunflecks on the ground.

IV. COMPARISON OF THE COMMERCIAL SYSTEMS

We now consider some trade-offs between the line quantum sensor, the Pasture Probe, the Ceptometer, the DEMON and the LAI-2000. (References to "Ceptometer" imply its sunfleck fraction mode, but note that it can also be used as a line quantum sensor.) The three line quantum sensor techniques will be referred to as P&R (Pierce and Running, 1988), NORM (Norman, 1988) and WALK (Walker *et al.*, 1988). Note that the P&R and NORM techniques do not involve gap fraction analysis, and are limited to continuous canopies with a known (or assumed) extinction coefficient.

Sky conditions:

The Ceptometer, DEMON, and WALK require unobscured sun, and a range of sun angles. This may be a limiting factor in certain climates (cloudiness) and at high latitudes in the winter (too narrow a range of sun angles). The LAI-2000 approach is most accurate without direct sun, since bright foliage increases the error in the LAI determination. However, if one can shade the canopy, or else work with the sun at or below the horizon, then the LAI-2000 can be used on any day at any location. P&R require direct sun, but only at one sun angle, and NORM can be used with any beam fraction (f_b) from clear sky to overcast. The Pasture Probe is not affected by sky conditions.

Reference Readings:

All of the techniques require reference readings. The DEMON and Ceptometer (in sunfleck mode) require an unobstructed view of the sun, so the reference reading can be made beneath the canopy in a large sunfleck. P&G, NORM and WALK reference readings should be above the canopy, but a large gap can suffice. The LAI-2000 with its wide angle view requires the largest gap for a reference reading, if an above canopy reading cannot be obtained. The Pasture Probe requires a reference reading in the air above the turf.

Sample Size (1 Reading):

The LAI-2000 senses canopy in all directions (reducible with use of a view restrictor). The Ceptometer and DEMON sense only the portion of the canopy that is between the sensor and the sun, although penumbral effects erode the contribution of more distant foliage for the Ceptometer. The sensing element of the Ceptometer is 80 cm long. The effective sample length of 1 measurement with the DEMON in a forest is about 20 m (how far the sensor moves in 30 seconds). NORM, P&R and WALK sense the canopy between the sun and the sensor, but surrounding canopy plays a role in reducing the diffuse light. The Pasture Probe senses only biomass within a few centimeters of the probe.

Time per site:

The Ceptometer, DEMON and WALK require hours to complete the necessary readings at a particular site, since a range of sun angles is needed. The LAI-2000 collects all necessary angular responses at once, and P&R and NORM do not need a range of sun angles, so the time per site can be short for these techniques. Each Pasture Probe reading takes less than 1 second, and a typical plot is completed in one to two minutes.

Use in turf grass:

The Pasture Probe was specifically designed for, and is only suited for, this type of canopy. For the optical methods, sensor size is the most important consideration. The smallest sensor is the Ceptometer, which has a cross section of about 1 cm; however, the control box is fixed to the sensor bar and thus may limit its use. The LI-COR line quantum sensor's cross section is 2.5 cm, and 1 m of smooth ground is required. The LAI-2000 has just under a 3 cm cross section, and the required smooth length of ground is 19 cm. The DEMON is not suitable for turfgrass.

Use in soybean:

All of the optical techniques and instruments work well in soybean, however the DEMON will require a traversing system.

Use in a forest:

In its sunfleck mode, the Ceptometer is not suitable in forests, due to penumbral effects. The LAI-2000 works in a forest provided a tower or nearby large clearing (radius about 3 to 4 times canopy height) is available for the reference readings. The DEMON is designed for forest settings, but the operator must be able to walk steadily along the forest floor keeping the sensor aimed at the sun, so underbrush and litter is a potential problem. The only tested line quantum sensor technique in forests is P&R, but NORM may also work.

On-board computing:

The DEMON has on-board processing for computing and storing log-averaged gap fractions for a large number of transects. LAI is calculated later on a computer. The Ceptometer computes and stores gap fraction information, and LAI is computed externally. The LAI-2000 is capable of doing all computations on-board, and stores measurements and results. None of the line quantum techniques come commercially packaged, so analysis is up to the user.

V. SUMMARY

Inverting gap fraction data is a powerful technique for estimating canopy structure. There are a number of methods for obtaining gap fraction data, generally having time vs cost trade-offs. With virtually no capital investment and a lot of labor, a meter stick can be used to obtain gap fraction data. The Ceptometer, DEMON and LAI-2000 (Table 1) represent increasing costs of equipment, but decreasing time needed to obtain results. In addition, the choice of the best method for a particular application should be based on the constraints imposed by reference readings and the frequency of suitable sky conditions.

TABLE 1
Summary of Instrument Suppliers

Instrument	Approxiate List Price (US Dollars)	Measurement	Supplier
Ceptometer	$1,800	PAR line sensor, Gap fraction in small canopies	Decagon Devices PO Box 835 Pullman, WA 99163 Tel.: 509-332-2756
DEMON	$2,800	Gap fraction	Assembled Electrics 66 Smith St. Yagoona, NSW Australia Tel.: 61-2-645-3974
LI-191	$1,200	PAR line sensor	LI-COR, Inc PO Box 4425
LAI-2000	$4,000	Gap fractions at 5 angles	Lincoln, NE 68504 Tel.: 402-467-3576
Pasture Probe	$800	Biomass in turf	Design Electrics PO Box 898 Palmerston North New Zealand Tel.: 64-63-85-702

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