Assessing forest canopies and understorey illumination: canopy closure, canopy cover and other measures

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Summary

The forest canopy is one of the chief determinants of the microhabitat within the forest. It affects plant growth and survival, hence determining the nature of the vegetation, and wildlife habitat. A plethora of different techniques have been devised to measure the canopy. Evaluation of the literature reveals confusion over what is actually being measured. This paper distinguishes two basic types of measurement: canopy cover is the area of the ground covered by a vertical projection of the canopy, while canopy closure is the proportion of the sky hemisphere obscured by vegetation when viewed from a single point. The principal techniques used to measure canopy cover, canopy closure, and a number of related measures are described and discussed. The advantages and limitations are outlined and some sampling guidelines are provided. The authors hope to clarify the nature of the measurements and to provide foresters with sufficient information to select techniques suitable for their needs.

Introduction

A hierarchy of factors determines the microclimate experienced by any organism within a forest. The prevailing climate is modified first by local weather conditions (particularly cloud cover), and then by the vegetation. Crucially, the structure of the canopy controls the quantity, quality, spatial and temporal distribution of light. It also influences local precipitation and air movements. Combined, these factors determine the air humidity, temperature and to some extent the soil moisture conditions at any given point within the forest.

Many silvicultural methods depend on manipulation of the forest canopy in order to create conditions favouring the survival and growth of desirable plants. These include tree seedlings, which may be the next commercial crop, and non-marketable species that have a conservation value. Light penetration also affects animal habitat, both through direct influences on temperature and humidity regimes and indirectly through the understorey plant community.

Both foresters and forest ecologists have spent many decades devising appropriate measures of the forest light climate. Because their requirements are different, they have followed different paths toward this goal. The most accurate measures have been used widely by ecologists, but are so expensive and time-consuming that they are unsuitable for most forestry purposes. The forestry literature abounds with novel methods and instruments for making indirect measures of the forest light climate. Unfortunately, there has been considerable confusion over what methods are appropriate, what factors are actually being measured and the associated nomenclature. This paper reviews and clarifies these various measurements. An attempt is also made to provide practical guidance for which measures may be appropriate for which purposes.

Direct measures of light

Because ecologists are often interested in the precise factors controlling the survival and growth of small numbers of individual plants, there is a strong requirement for accurate measurements of the forest microclimate. A variety of instruments are commercially available which measure different aspects of solar radiation. Radiation can be measured in three different ways. Each measure has different ecological implications.

1 *Photometric measures.* Lighting engineers and photographers measure illuminance or brightness as perceived by the human eye, or standard photographic emulsions. Illuminance is measured in lumens, lux or foot candles. The spectral response of the eye is different from that of all plant processes and this measure is therefore inappropriate for use in plant ecology. The description of a lux meter by a popular forestry supplies catalogue (Anon., 1998) as 'accurately measuring light density in tree canopies' fails to make clear that measurements made with such instruments are not relevant to tree growth and survival. There is no method for converting photometric measures of light into measures relevant to plant processes without detailed information on the spectral composition of the light being measured. This approach will not be examined any further.

2 *Radiometric measures.* The energy content of solar radiation is measured in joules or when integrated over time, in watts. Measures of the energy content of radiation are of relevance in heat or water balance studies. A pyranometer or solarimeter is used to measure incoming short-wave irradiation (see Oke, 1987 for a detailed description). Plant growth and morphology are sensitive to the spectral composition of light. Spectral variation beneath a forest canopy can be recorded by measuring the energy content of each waveband, but a large number of physiological responses in plants are known to be initiated by the ratio of red to far-red wavebands. A red/far-red sensor measures the ratio of these two wavebands exclusively. This may be of interest to those researching physiological responses of plants to light of varying spectral composition.

3 *Quantum measures.* Measures of the proportion of solar radiation that is available for photosynthesis (photosynthetically active radiation—PAR) are made in terms of the total number or flux of quanta arriving per unit area. The units used are moles. The energy content of a quantum of radiation depends on its wavelength. It is not therefore possible to convert from radiometric measures to a quantum measure without knowledge of the spectral composition of the radiation.

Both radiometric and quantum measures can be made by attaching sensors to dataloggers that control the sampling frequency, store the data and may summarize it by integration. Radiation sensors measure the energy incident at a single point (although some commercially available equipment combines sensors in strips to give an integrated measure over, for example 1 m, Anon., undated). Radiation, at a point, is received from all directions but is conventionally measured on a horizontal plane. Radiation receipts are often cosine corrected, that is they are weighted by the cosine of the zenith angle from which they arrive. Although sensors may measure radiation extremely accurately this measurement convention may mean that they do not accurately repre-

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sent the radiation received by a non-horizontal leaf.

A related technique is the use of ozalid papers (e.g. Friend, 1961; Emmingham and Waring, 1973). The papers are bleached by radiation in the ultraviolet and violet wavebands. Left *in situ*, they integrate the amount of incoming ultraviolet and violet radiation over time. The degree of bleaching is then estimated either visually or by measuring the light transmission through the sheets. They have been used to estimate PAR after calibration with quantum sensors, however, changes in the spectral composition from site to site will alter the calibration. Although they are cheap and quick to install, even with site-specific calibration they give only an approximate estimate of PAR.

The irradiance at any one point within a forest is highly variable on several different time scales (within a day, day-to-day, seasonal, and year-to-year). This is a consequence of the diurnal movement of the sun, of weather patterns and also of changes in the forest canopy. In common with indirect measures (below), the time period over which measurements are made must be appropriate to the problem being addressed. To give an obvious example, there would be little point in measuring the irradiance regime in a temperate deciduous forest during winter for a study on the photosynthetic responses of tree seedlings.

A further consequence of the variability of forest irradiance regimes is that a single instantaneous measure does not adequately represent the range of variation at a point. A sensor must be in place for a considerable time period in order to sample the range of variation in the light regime. Sensors and dataloggers are expensive. If there is a limit to the number of sensors and dataloggers available for a study this constrains the total number of points that can be monitored.

Although dataloggers make it comparatively easy to collect large amounts of data at a single point (or several points close together), an adequate estimate of irradiance beneath an area of canopy requires spatial variation to be sampled. It is a maxim of sampling that the more variable the population the larger the sample required in order to estimate the mean value with a given degree of confidence. However, small variations are much more critical for nearly all plant light responses at low levels of irradiance than the same level of variation at high irradiance. Hence plant physiologists may need to sample spatial variation in irradiance much more intensively beneath a more or less uniformly closed canopy than in similarly uniformly open conditions.

Rarely are the costs and the length of time required for adequate direct measurement of irradiance justified in practical forestry, where a high level of accuracy is not paramount. Accurate, direct measurement of light is often considered important in scientific research projects, for example where the photosynthetic responses of plants are to be assessed. However, failure to keep sensors clean and horizontal over long time periods within a forest can introduce significant measurement errors (Biggs, 1986), and will usually result in under-estimates of irradiation. Although sensors may accurately measure irradiance at a point, the ecologist or forester frequently wishes to extrapolate to the whole plant. Plants rarely display all of their leaves horizontally and have considerable self-shading within their own crowns. Mean irradiance on its leaves is therefore likely to be much lower than that recorded by a sensor displayed above or close by and high precision measurements may give a spurious impression of accuracy.

Indirect measurement of the light regime

As a consequence of the difficulties inherent in measuring the light regime directly, many ecologists and the majority of foresters prefer indirect estimates. A number of different measures have been proposed and used. Most of them combine assessments of whether the sky is obscured along a particular line of sight. In general, the measured values are less subject to the large and rapid temporal variations characteristic of irradiance within forests. Unfortunately, there appears to be considerable confusion in the forestry literature over the suitability of particular methods for particular purposes and also over what is actually being measured. The link between many of these measures and light has frequently not been established. The resolution of measurement is often poorly defined.

Canopy closure vs. canopy cover

There are two basic ways of measuring forest canopies. The first is by measuring canopy closure. *This is the proportion of the sky hemisphere obscured by vegetation when viewed from a single point.* 'Canopy density' is a synonym often found in the forestry literature. The term canopy openness is frequently used in the ecological literature, which is the complement of canopy closure (openness = 1 – closure, i.e. the proportion of the sky hemisphere not obscured by vegetation when viewed from a single point).

Canopy cover refers to the proportion of the forest floor covered by the vertical projection of the tree crowns. This is analogous to the use of the term 'cover' by ecologists to refer to the proportion of the ground area occupied by the above ground parts of plants. The important difference between canopy closure and canopy cover is illustrated in Figure 1. Canopy closure measurements integrate information over a segment of the sky hemisphere above one point on the ground. Ideally the entire sky hemisphere should be assessed, although the segment measured varied with the instrument used. Indeed, on steep slopes, light may arrive from angles lower than the horizontal. Measures of canopy cover assess the presence or absence of canopy vertically above a sample of points across an area of forest.

Mean canopy closure (or openness) over an

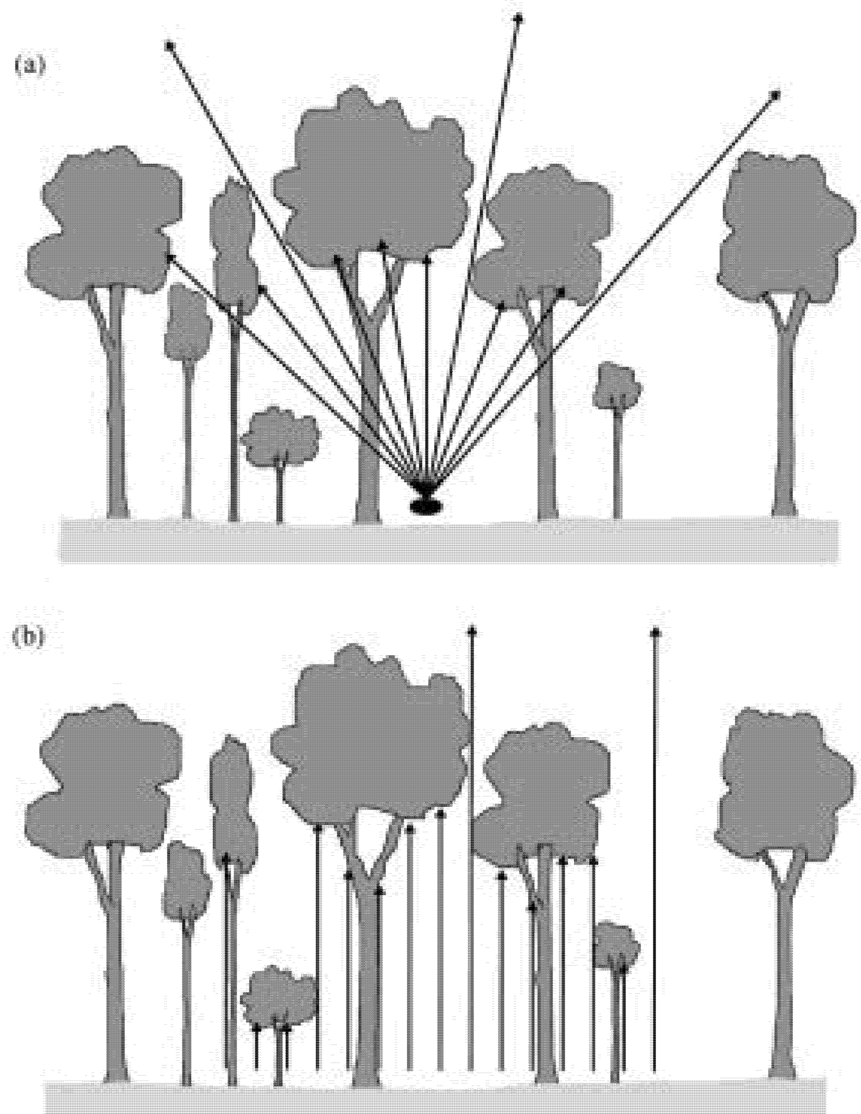

Figure 1. An example of a measure of canopy closure (a) and canopy cover (b).

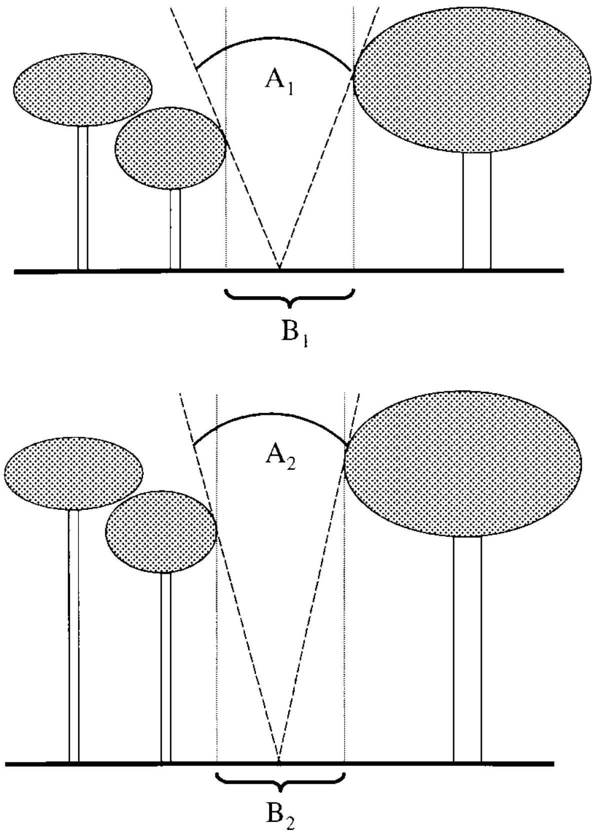

Figure 2. For tree crowns of a given size canopy cover (B) is independent of tree height but canopy closure (A) is not. In this example, $B_1=B_2$ but $A_1>A_2$.

area of forest is not necessarily correlated with the canopy cover of the same area (see Figure 2). Tree height does not affect canopy cover as the vertical projection of the crown alone is assessed. Canopy closure will increase beneath progressively taller trees as more and more of the sky hemisphere is obscured. Canopy closure is likely to be a measure of greater utility to foresters, as it will be directly related to the light regime and microclimate and will therefore be linked to plant survival and growth at the point of measurement. Canopy cover is a measure that reflects the dominance of a site by trees or by particular species of tree.

Canopy cover can also be used to predict stand volume (Philip, 1994). This is because, for a particular species of tree, there is a nearly linear relationship between the area occupied by its crown and the basal area of its trunk (Dawkins, 1963). This relationship applies within the age-range of a commercial rotation but breaks down as trees reach biological maturity. In a stand of young trees (such as a commercial plantation) basal area will be a function of canopy cover. A local measure of basal area may therefore give an estimate of canopy cover. In natural forest where many trees may be over-mature the relationship is poor. In mixed species stands the basal area of each species should be tallied separately.

Canopy cover is an important variable required in estimating stand statistics from remotely sensed images. Several remote sensing techniques are used in forest inventory, including visible and infrared scanner systems (satellite or airborne), airborne laser systems, imaging spectrometry and imaging radar systems (reviewed by Leckie, 1990). In Canada in particular, aerial photography has been used for large-scale inventories for many decades. An estimate of stand volume is usually desired, but this cannot be measured directly from an aerial photograph. Forest hydrologists have used detailed mapping of canopy cover for the prediction of interception losses (wetted-canopy evaporation) from forests (Molicova and Hubert, 1993).

Unfortunately, canopy cover and canopy closure have been considered to be synonymous by the authors of several standard textbooks (e.g. Philip, 1994: 132, Avery and Burkhart, 1994: 269). This has led some authors to attempt comparisons between measurements of canopy cover and canopy closure without recognizing that they are distinct variables. The finding that one or other measure is 'biased', is therefore hardly surprising (e.g. Ganey and Block, 1994). Frequently, authors state that they are measuring one variable, when in fact they are measuring the other (e.g. Garrison, 1949; Cook *et al.*, 1995; Kim *et al.*,1995; McLaren and Janke, 1996; Mitchell and Popovich, 1997; Norton and Hannon, 1997).

A number of authors have noted that different instruments or techniques incorporate different angles of view (e.g. Bonnor, 1967; Bunnell and Vales, 1990; Cook *et al.*, 1995). This is an important point influencing any approach to the measurement of canopy closure, and will be discussed more fully below. It was, however, incorporated into the idea of 'mean crown completeness' (Bunnell *et al.*, 1985, in Bunnell and Vales, 1990). This was defined as 'the proportion of the sky obliterated by tree crowns within a defined angle (or determined with a described instrument) from a single point.' The present authors believe that it is better to use the terms 'canopy cover' and 'canopy closure' (or openness) to differentiate between the two conceptually different variables.

Measuring canopy cover

For ecologists working in low vegetation, canopy cover is usually measured visually from above on a percentage or an ordinal scale. More accurate measures can be obtained by using a cover pin frame, in which pins are dropped vertically on a regular grid, through a rigid frame. The proportion of points at which the pin touches the vegetation gives an estimate of cover for that area.

An analogous measurement has been used widely in forestry. At each measurement point the forester looks vertically upwards and records whether or not the forest canopy obscures the sky. The proportion of points where the sky is obscured gives an estimate of forest canopy cover. Sights may be taken without any instrumentation (e.g. Vales and Bunnell, 1988), although measurement is made both more accurate and more repeatable by ensuring that the observer is looking vertically upwards, and that the measure is for a point and not an area (which would introduce an angle of view). Combining data from several different Canadian forests, Bonnor (1967) estimated that significant biases were introduced only when sighting angles were greater than approximately 5° from the vertical. The magnitude of non-vertical sighting biases will be vegetation specific.

In order to reduce non-vertical sighting biases, equipment such as the gimbal balance (Walters and Soos, 1962) or the sighting tube, often with internal crosshair (Johansson, 1985), have been developed. Commercial versions of the sighting tube may incorporate bubble levels to ensure vertical positioning of the tube and also 45° mirrors to allow a horizontal head posture when in use. In fact, many of the instruments designed to facilitate measurement of the vertical projection of individual tree crowns could also be used to measure canopy cover (e.g. Jackson and Petty, 1973; Montana and Ezcurra, 1980; Pryor, 1985).

Sighting tubes are sometimes called 'densitometers' in the forestry literature and in forestry suppliers' catalogues (e.g. Anon., 1998). This term suggests similarities with the spherical densiometer, which is used to make an entirely different measurement (see below). The term also implies that canopy density is being measured, which is not the case. It is recommended that the term (canopy cover) sighting tube is used. More confusingly still, some authors have referred to the measure derived from using a sighting tube as 'canopy closure' (e.g. Ganey and Block, 1994). What is being measured is (canopy) cover, and this term alone should be used. This is consistent with the use of the term in ecology.

Estimates of stand canopy cover are derived from several measurements. The sampling strategy used to obtain canopy cover estimates must therefore be considered. When ecologists use a cover pin frame in low vegetation, they are using a systematic sampling design (a random element may be introduced when selecting the exact location where the frame is placed). Using a sighting tube in forest vegetation, a systematic sampling design might introduce serious bias, particularly when sampling a regularly spaced plantation. Under such conditions, random sampling is preferable to the systematic sampling advocated by Johansson (1985).

A complication is added by the spatial autocorrelation of features such as tree crowns or canopy gaps. To give an obvious example, if one measurement point is within a clearing, a second point close-by is more likely to also be within that clearing than is a point further away. As a rule of thumb, if systematic or cluster samples are used, it is suggested that the distance between sampling points should be greater than the size of the major spatial features within the forest (e.g. greater than the larger tree crowns, gaps or clearings).

The second sampling consideration is the number of measurements required to make accurate estimates of canopy cover. Canopy cover (C) is calculated from:

$$C = \frac{N_c}{N_t} \qquad (1)$$

Where N_c is the number of sample points covered by the canopy and N_t is the total number of points sampled. Confidence intervals for an estimate of canopy cover can be made from the binomial distribution using the following equations (adapted from Sheil and May, 1996):

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$$C_u = 1 - \left[\frac{1}{(1 + {}^{\text{inv}}F_u N_c/(N_t - N_c + 1))}\right] \quad (2)$$

Where C_u is the upper confidence limit and ${}^{\text{inv}}F_u$ is the value of the inverse cumulative F distribution. The value of the inverse F distribution for the upper confidence limit should be determined with X numerator degrees of freedom and Y denominator degrees of freedom where:

$$X = 2 + 2\,(N_t - N_c) \quad (3)$$

and

$$Y = 2N_t \quad (4)$$

The lower confidence limit C_l is calculated from:

$$C_l = 1 - \left[\frac{1}{1 + {}^{\text{inv}}F_l (N_c + 1)/(N_t - N_c)}\right] \quad (5)$$

The value of the inverse F distribution for the lower confidence limit ${}^{\text{inv}}F_l$ should be determined with X numerator degrees of freedom and Y denominator degrees of freedom where:

$$X = 2(1 + N_t) \quad (6)$$

and

$$Y = 2(N_t - N_c) \quad (7)$$

Figure 3 shows, for a range of canopy cover values, how the 95 per cent confidence intervals around estimates of canopy cover vary with the number of observations. With 20 observations per plot an estimated canopy cover of 50 per cent has 95 per cent confidence intervals that range from less than 30 per cent to in excess of 70 per cent. Any estimate made with fewer than 100 observations will be of very little utility in distinguishing between forest plots with all but the grossest differences in canopy cover. Ganey and Block's (1994) recommendation that at least 20 observations per plot should be made is a serious underestimate of the minimum number of samples required.

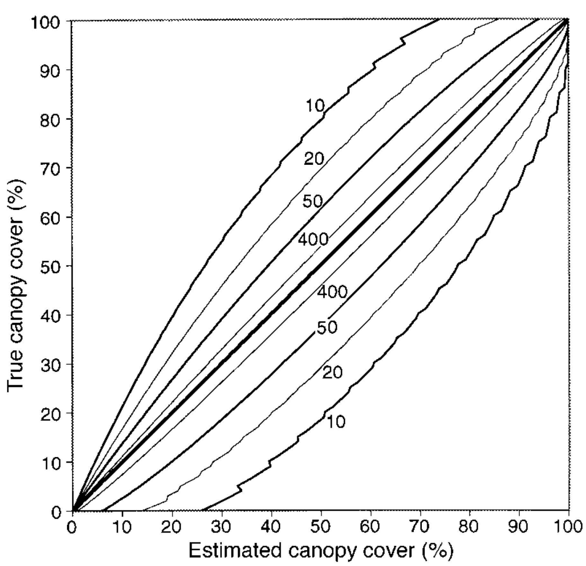

Figure 3. The 95 per cent confidence intervals around estimates of canopy cover for 10, 20, 50 and 400 observations.

There are different opinions in the literature as to the importance of between observer differences in measures of canopy cover. This results in part from differences in equipment, sampling strategies and analytical techniques used by different workers, which made comparisons difficult. Vales and Bunnell (1988) found inter-observer differences of <10 per cent either when no instrumentation was used or when a gimbal sight was used. Johansson (1985) analysed between-observer differences of measurements of canopy cover taken with a sighting tube with internal crosshair. Although it is not possible to calculate percentage differences from the information presented, given the number of canopy cover measurements likely to be required by most workers (see above), it is of interest that Johansson found significant differences between observers when 200 readings were made, but not when 100 or 50 were done.

Although individual observations of canopy cover made with the sighting tube method are quick and easy, accurate estimates require a very large sample size. This is true whether the plot for which an estimate is being made is small or large. It therefore would seem to be a method of limited application in forestry. Its widespread use has probably resulted from (1) the misunderstanding over what is actually being measured and how large a sample is required, and (2) the apparent rapidity and simplicity with which individual observations can be made.

A different technique for measuring canopy cover is by detecting canopy edges along lines (often tape-measures) laid within a forest. The length of the line that is covered by canopy is then recorded. This method typically works at the resolution of crowns rather than leaves. Each line provides a single estimate of cover, and is therefore a continuous variable, rather than a binomial as with point measures.

Canopy cover is frequently assessed from aerial photographs in order to make estimates of the timber volume of a stand. Rapid visual assessments have conventionally been made by using a crown density scale (Moessner, 1949; Husch *et al.*, 1982). This consists of a series of standard squares containing black dots that cover from 5 to 95 per cent of the area. The level of cover on this scale that most resembles the canopy cover seen on the aerial photograph is then selected. It should be noted here that in fact the measurement of 'canopy cover' from aerial photographs actually incorporates angles other than the vertical. In practice, angles are assumed vertical when tilted by <3° (Avery and Burkhart, 1994). Similarly, parallax differences between different parts of the same photograph are ignored.

Measuring canopy closure

Canopy closure is the proportion of the sky hemisphere obscured by vegetation when viewed from a single point. Measurements of canopy closure can provide information on the growth conditions of seedlings, saplings and sub-dominant trees, and can be used to guide the level of canopy manipulation necessary for successful natural regeneration and enrichment planting. An allied group of measurements, the 'crown position indices', allows trees of all heights to be assessed. When canopy closure is used as an indirect measure of the amount of PAR available it is usually assumed that the canopy neither transmits nor reflects light. Although this will introduce bias into estimates of total PAR receipts none of the methods described below provides a method for assessing transmission and reflection of light.

The light received at any point is the sum of the direct (sunlight) and indirect radiation that includes skylight from all parts of the sky. Beneath a forest canopy, indirect skylight including lateral light penetration may contribute a large proportion of the total. Ideally then, the entire hemisphere should be assessed. The various techniques of estimating canopy closure differ in the proportion of the hemisphere measured, i.e. the angle of view, and are therefore not equivalent.

Hemispherical photography The most complete measure of canopy closure can be made by taking a photograph at the measurement point with a 180° 'fisheye' lens. The image is then digitized and a 'threshold' set, where all pixels darker than the threshold are treated as canopy, all pixels paler than the threshold are considered to be sky. Several computer programs are available to calculate percentage canopy closure from these images (Mitchell and Whitmore, 1993). Although, when carefully applied, hemispherical photography can be the most accurate method of estimating canopy closure, it is vulnerable to a number of sources of error and very little is known about the consistency or repeatability of this method (Rich, 1990). Canopy can only be reliably distinguished from sky when there is considerable contrast between the two on the photographic image. Brightly lit or reflective vegetation and the 'pinhole effect' of sunlight shining through tiny holes in the canopy can make it difficult to find a consistent threshold value (Rich, 1990). Small changes in the threshold value selected may result in relatively large changes in the estimated canopy closure beneath dense canopies. Hence the technique may be inaccurate at high levels of canopy closure (Roxburgh and Kelly, 1995; Jennings, 1997).

Despite these limitations, hemispherical photography has become an important tool in ecological studies (e.g. Evans and Coombe, 1959; Anderson, 1964; Chazdon and Field, 1987; Rich, 1990; Brown, 1993; Clark *et al.*, 1993; Mitchell and Whitmore, 1993; Whitmore *et al.*, 1993). However, both the hardware and the software required are, at present, extremely expensive and the analyses relatively time-consuming. There are no practical forestry, and a limited number of forestry research, applications where the accuracy of this method justifies the time and expense of the technique.

Similar ideas, but using a pinhole camera (Clark, 1961) or cameras with standard lenses (Bunnell and Vales, 1990) have been proposed. Although the equipment is cheaper than that required for hemispherical photography, they do not alter the logistical constraints, while reducing the angle of view below 180°.

The moosehorn Before the development of hemispherical photography, two important instruments, the 'moosehorn' and the spherical densiometer, had already been designed to reduce the subjectivity of simple visual estimates of canopy closure (below). The moosehorn (Robinson, 1947; Garrison, 1949; Bonnor, 1967), has mostly been used in Canada. The recorder views the canopy through a transparent screen, on which is marked a grid of evenly spaced dots. The recorder counts the number of dots that overlap with the canopy. A bubble level fixed to the screen ensures that the instrument is held vertically. A 45° mirror and sighting aperture may be incorporated allowing the observer a horizontal head posture.

The central dot on the grid is projected vertically. The angle of view provided by the other dots in the grid depends upon the exact construction of the instrument. The Hilborn moosehorn (Bonnor, 1967) included angles of up to 5.1° from the vertical. The size of the confidence intervals around an estimate of canopy closure is dependent upon the level of canopy closure. For a given level of confidence, the maximum number of readings required will be greatest at 50 per cent canopy closure, declining towards 0 and 100 per cent. Bonnor (1967) calculated that at a maximum allowable error of ±5 per cent canopy closure at the 95 per cent probability level, approximately 300 readings would be needed at 50 per cent canopy closure. Similarly, Vales and Bunnell (1988) reported that differences between observers are greatest at the mid-range of canopy closure. As a practical guide, Bonnor (1967) suggested that 40 readings should be taken in a stand, the canopy closure calculated, and then the actual sample size required could be read from his Figure 2. A random sampling strategy should be employed (Bonnor, 1968).

Garrison (1949) erroneously suggests that the instrument can be used to measure canopy cover. He maintains that measurements taken in stands of different heights cannot be compared. In fact measurements of canopy closure made with the moosehorn in stands of different heights can be compared. The moosehorn has been used to calibrate estimates of canopy cover from aerial photographs from which stand volumes are derived. At the scale commonly used in aerial photographic estimates in Canada (1 : 15 840), canopy cover estimated from photographs was consistently 10 per cent less than mean canopy closure estimated with a moosehorn (Bonnor, 1968). This is probably a result of the wider angle of view incorporated into moosehorn measures (see below), and/or the result of the different resolution of the two measures.

The spherical densiometer A rather more commonly used instrument for measuring canopy closure is the spherical densiometer (Lemmon, 1956; Lemmon, 1957). This consists of a mirror shaped as either a convex or a concave segment of a sphere (conventionally a sphere 15.3 cm in diameter). The mirror is engraved with a graticule. Due to its curvature, the mirror reflects a large area of the sky hemisphere. To take readings, the forester assumes four equally spaced dots in each square of the graticule. The forester counts how many of these dots intercept with the reflection of the canopy. Most densiometers are hand-held but incorporate a bubble level to ensure that they are held horizontally when readings are taken.

Strickler (1959) suggested that four readings be taken at each point, one in each of the cardinal directions. The mean of these four readings is then taken as the estimate for that point. This effectively increases the angle of view, and has been used successfully (Cook *et al.*, 1995).

The concave version allows the forester to take readings without significantly shifting viewpoint, except over the part of the mirror obscured by the observer's own reflection. This reduces potentially important errors caused changing the viewpoint as the readings are taken. The concave densiometer reflects less of the sky hemisphere than does the convex instrument, and is therefore likely to give less accurate estimates of canopy closure. Measurement errors are particularly large at the mid-range of canopy closure (Lemmon, 1956; Cook *et al.*, 1995). With either version, differences in viewpoint can introduce significant variation between observers (Vales and Bunnell, 1988; Ganey and Block, 1994), although this has not always been found (Lemmon, 1956). Because the reflection of the canopy is small, spherical densiometers are likely to suffer from poor resolution.

The spherical densiometer does not give a highly accurate measure of canopy closure. It is, however, both portable and robust. Several authors suggest mounting the densiometer on a tripod to ensure that it is exactly horizontal

(Strickler, 1959; Ganey and Block, 1994). The slight gain in accuracy that this might give is far outweighed by the reduced portability.

Simple visual assessment of canopy closure The most basic way of estimating canopy closure is by simple visual assessment. The methods are rapid, require no specialized equipment and can be used to estimate the canopy closure above the crowns of trees much taller than the recorder. Estimation may be made by comparing the area of canopy with a standard scale. Simple visual assessment is the method most commonly used by forest managers, who typically learn by experience rather than by accurate measurement the level of canopy closure required to achieve desirable growth of the tree crop. As the results are used to inform (local) management decisions, there is little need for greater accuracy or of comparability of data. Greater accuracy may be required in forestry research and if written advice is being given to forest managers. The human eye is notoriously poor at making consistent assessments of light. For example, if visual estimates of canopy closure are repeated at the same point, but in different weather conditions, the estimates can be hugely different.

Crown position indices A group of measurements, the 'crown position indices', have been developed to allow standardized visual assessments of the position of individual tree crowns relative to the rest of the forest canopy. The scale of resolution is at the level of crowns rather than individual leaves or branches. They are used as a guide to the relative competitive status of an individual stem. They are broadly analogous to estimates of canopy closure, but record the position of a crown relative to the canopy rather than measuring the canopy *per se* and are measured on an ordinal (rather than interval) scale.

References to suppressed trees are apparently found in fifteenth century German forest ordinances (see Baker, 1950), but one of the first formal and popular classifications was published by Kraft in 1884. One of the simplest crown position indices is defined in Table 1 and illustrated in Figure 4a (e.g. Baker, 1950; Smith, 1986). Stems are categorized as being dominant, co-dominant, intermediate or overtopped (suppressed). This scale is particularly applicable to plantation forestry, where it is a useful decision-making tool in thinning operations. It allows the identification of future crop trees, and guides which stems should be removed to reduce competition, allow crown expansion and increased stem diameter increment of those crop trees. Use of this index in uneven-aged forest would lead to anomalies (see Baker, 1950), such as the trees marked 'x' in Figure 4a. Nicholas *et al.* (1991) found a 89.7 per cent agreement in classification between trees measured on two separate occasions in mature Appalachian pine–spruce plantations. This fell to 68.4 per cent in logged secondary growth forest. The stems with the lowest repeatability of measurement were those classified as dominants on the first measurement.

In 1956, and again (and more accessibly) in 1958, Dawkins published a 'crown illumination index', which differs from the above mainly in the more precise class definitions and in the addition of a further class (Table 1 and Figure 4b). This extra class (Class 2) allows the differentiation of overtopped crowns that receive some lateral illumination from those which do not. This index has been used in both tropical (e.g. Dawkins, 1958; Alder and Synnott, 1992) and temperate forests (Dawkins and Field, 1978). Significant correlations between stem diameter increment and crown illumination class were found for several of the species studied by Daalen (1993).

Dawkins' index was further refined by Clark and Clark (1992). They found that most seedlings and saplings in tropical rain forests occurred in Dawkins' Class 2, a class that contained widely different illumination conditions. They therefore divided this class into three: high, medium and low lateral light (Table 1 and Figure 4c).

How reliable are these measures, and quite how do they relate to canopy closure? Significant relationships have been found between Clark and Clark's index and various measures derived from hemispherical photographs (Clark and Clark, 1992; Clark *et al.*, 1993). Despite being significant, the variance accounted for by a linear correlation between total site factor and the index was low ($r^2 = 0.34$; Clark *et al.*, 1993): this may be a consequence of correlating a continuous with a categorical variable.

Repeatability of measurements was reported by Sheil (1996), who found that inventory teams

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Table 1: Definitions of three crown position indices (following Dawkins, 1958; Dawkins and Field, 1978; Smith, 1986; Clark and Clark, 1992)

Crown position		Crown illumination (Dawkins)		Crown illumination (Clark and Clark)	
Class	Definition	Class	Definition	Class	Definition
Overtopped (O) (= Suppressed)	Shorter than the canopy level and receiving no illumination from above	1	No direct light (crown not lit directly either vertically or laterally)	1.0	No direct light (crown not lit directly either vertically or laterally)
				1.5	Low lateral light (crown lit only from side: no large or medium openings)
		2	Lateral light (<10 per cent of the vertical projection of the crown exposed to vertical light, crown lit laterally)	2.0	Medium lateral light (crown lit only from side: several small or one medium opening)
				2.5	High lateral light (crown lit only from side: exposed to at least one major or several medium openings)
Intermediate (I)	Shorter than the general canopy level, but still illuminated from above	3	Some overhead light (10–90 per cent of the vertical projection of the crown exposed to vertical illumination)	3.0	Some overhead light (10–90 per cent of the vertical projection of the crown exposed to vertical illumination)
Codominant (C)	Crown within the general level of the canopy	4	Full overhead light (≥90 per cent of the vertical projection of the crown exposed to vertical light, lateral light blocked within some or all of the 90° inverted cone encompassing the crown)	4.0	Full overhead light (≥90 per cent of the vertical projection of the crown exposed to vertical light, lateral light blocked within some or all of the 90° inverted cone encompassing the crown)
Dominant (D)	Crown above the general level of the canopy	5	Crown fully exposed to vertical and lateral illumination within the 90° inverted cone encompassing the crown	5.0	Crown fully exposed to vertical and lateral illumination within the 90° inverted cone encompassing the crown

were able to score 68 per cent of the stems (>10 cm d.b.h.) in a Ugandan rain forest into the same Dawkins class on repeated measurement. He noted that the majority of misclassified stems were those that had multi-part crowns, were infested with strangler figs or lianas, were difficult to observe, or were genuinely borderline cases. Clark and Clark (1992) reported 70 per cent repeatability for their index (mean score of two observers). Working on seedlings (≤3 m

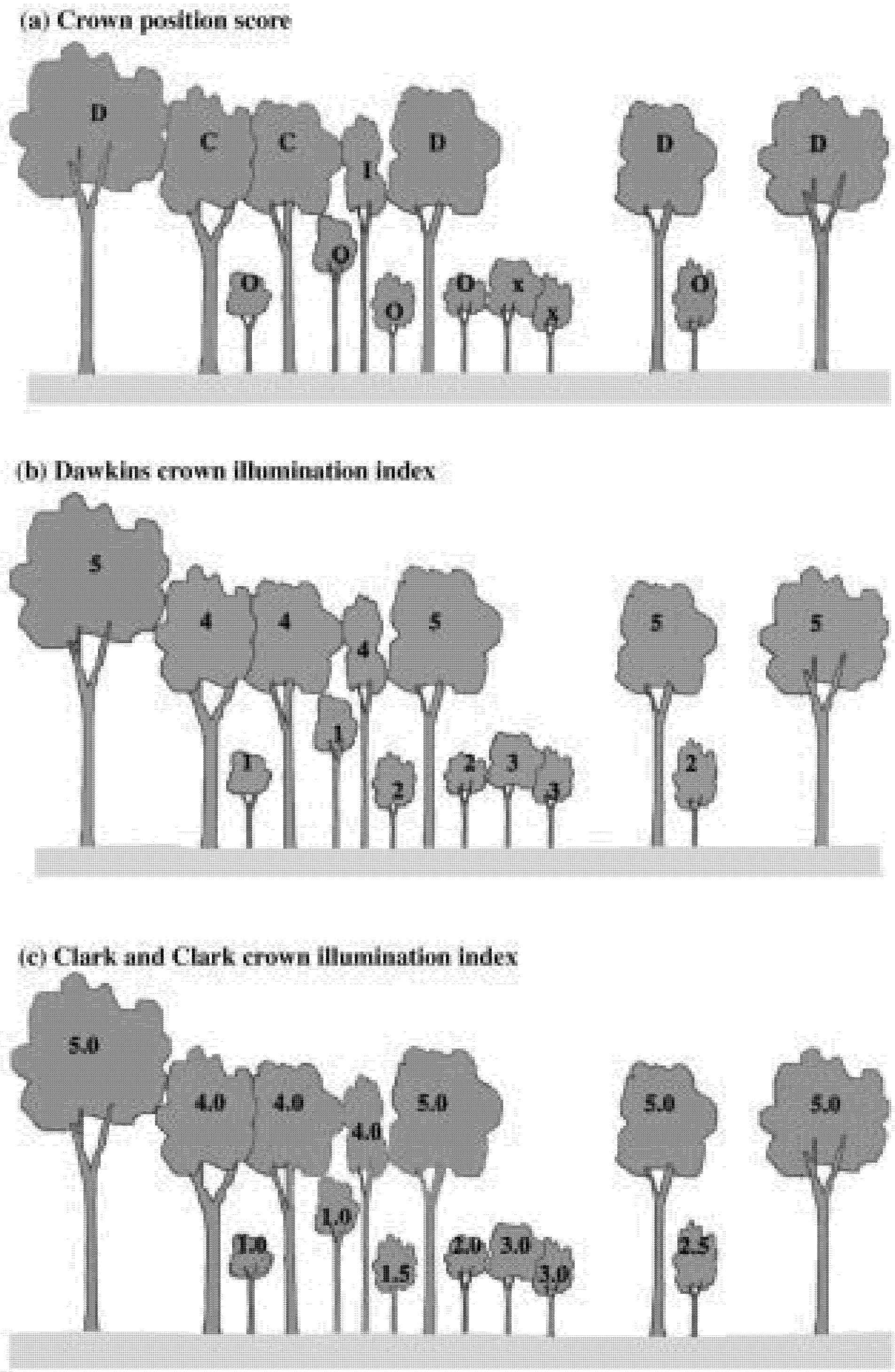

Figure 4. Examples of the crown position indices described in Table 1.

height) alone, rather than all size classes, Jennings (1997) reported 76 per cent repeatability of the Clark and Clark index. This level of repeatability may be unsatisfactory for many purposes. The problem could be mitigated if sample sizes are large, and if measurement errors do not contain large biases. As it takes a trained operator only a few seconds to assess and record a stem using these indices, they have considerable potential when large numbers of stems are being measured.

Canopy closure measures compared Several studies have sought to compare different techniques of measuring canopy closure. Some have, mistakenly, also included measurements of canopy cover, and this was dealt with earlier. A crucial difference between instruments is the angle of view incorporated into the measure. The area of canopy measured by an estimate of canopy closure is a result of the trigonometric relationship between the angle of view, the height at which the measurement is taken and the height to the base of the live crown. Bunnell and Vales (1990) showed that as the angle of view increased, the range of the various estimates of canopy closure decreased and that estimated canopy closure increased (see also Cook *et al.*, 1995). As canopy closure increased, the differences in techniques became less. Techniques with narrow angles of view were more affected by variations in the height to the base of live crown than were instruments with a wide angle of view.

The ranges at which the various instruments used to measure canopy closure are least accurate have been outlined above. These should be taken into account when deciding which of the techniques is the most appropriate for the task in hand. Other considerations will include cost, logistical constraints, degree of training of field operators, amount of field time available and the degree of accuracy required. The exact research priority will also determine the zenith angles measured (Chan *et al.*, 1986; Bunnell and Vales, 1990). For example, rain interception, snow interception and plant growth studies will require the inclusion of increasingly wide angles of view respectively (Bunnell and Vales, 1990). It is recommended that details of the angle of view measured (Bunnell and Vales, 1990), height to base of live crown, slope and area of forest measured are included in published accounts where canopy closure is reported.

Resolution of measurements

Just as Mandelbrot (1967) demonstrated that the length of a coastline depends on the scale of measurement, both canopy cover and canopy closure are influenced by the spatial resolution of measurements. When canopy cover is estimated from an aerial photograph the crown of an individual tree may be regarded as a solid object providing complete cover within the projected area of the crown. However, when viewed at a much higher resolution, from the ground, the crown is heterogeneous with many vertical holes of a range of sizes. A decision must be made as to how small a canopy hole must be in an otherwise complete canopy before it is ignored when it coincides with the point of measurement. An analogous decisions must be made as to how large an obstruction will be ignored in an otherwise open sky. The apparently straightforward 'yes' or 'no' decision required for each measurement becomes problematic when the canopy components are small (e.g. pine needles). Movement of the canopy adds further complications and it is clear that, as far as possible, measurements should be made on still days.

Similar problems of resolution confront measures of canopy closure. The limits to the resolution of hemispherical photographs are set by the grain of the film used and the number of individual pixels into which the image is digitized. In contrast visual estimates of canopy closure made using crown position indices make an estimate of illumination for the canopy as a whole. An a priori decision should be made as to the relevant resolution of these measures for any particular study.

Conclusions

The importance of the forest canopy to forestry and forestry research has been reflected in the ingenuity of foresters in devising methods and instruments to measure it. Despite this, there remains considerable confusion in the forestry literature as to what is actually being measured. In this paper a distinction is drawn between canopy cover and canopy closure.

It is not possible to prescribe a 'best method'. The different measurements and instruments have different properties. The decision as to which is most appropriate for a particular researcher will depend partly upon the nature of the problem being addressed. Logistical and operational constraints will exert perhaps an even greater role in determining which is used. To this end, the authors have presented the advantages and limitations of each of the major methods, and attempted to give guidelines that will allow the design of appropriate sampling strategies in order to assist foresters in making their decisions.

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[1] This was published under the name ‘Ecologist’, which was the *nom de plume* of H.C. Dawkins at that time (M. Philip, personal communication).

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