Chapter 14
Forest Canopy Structural Properties

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Abstract The forest canopy is the interface between the land and the atmosphere, fixing atmospheric carbon into biomass and releasing oxygen and water. The arrangement of individual trees, differences in species morphology, the availability of light and soil nutrients, and many other factors determine canopy structure. Overviews of approaches for basic measurements of canopy structure are presented including height (maximum stem height), the fraction of ground overlain by foliage (coverage), and the leaf area per unit ground area (leaf area index, LAI). These measures are important for characterizing estimates of ecosystem productivity and development, as well as for interpreting and validating landscape- to regional-scale estimates of vegetation attributes derived from remote sensing data. The approaches outlined are not exhaustive, but rather identify a range of robust ground- and remote sensing-based methods that capture a suite of metrics useful to the goals of the North American Carbon program: to provide robust, ground-based estimates of C uptake, storage, and flux that can be used for validation and scaling.

Keywords Direct measurement, forest structure, indirect measurement, remote sensing, scaling, leaf area index

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14.1 Overview: Supplemental Variables for Carbon Cycle Modeling

The ability to efficiently extend site specific measurements to broader scales enhances our ability to examine key relationships associated with these traits at various levels from the site to the forest stand and, with remote sensing technologies, to larger landscapes. A growing body of research demonstrates the complementary nature (and necessity for integration) of distributed site measurements, remote sensing and ecosystem modeling in studies of terrestrial carbon cycling. Even very comprehensive field measurement campaigns cover only small portions of any landscape. Understanding landscape-scale and larger patterns is difficult, if not impossible, without some means of extending point-based field measurements. There is widespread acknowledgment that remote sensing holds a central role. Remote sensing instruments capture spatially continuous information on the reflectance properties of landscape and vegetation and are now capable of providing regular, high-resolution (10-m to 1-km) mapping and monitoring of land surface characteristics relevant to understanding and modeling of ecosystem processes (Turner et al. 2004). Variables that are now routinely retrieved include vegetation type and cover, biomass, stand age class, phenological status, leaf area index, tree height, and biochemistry (Ollinger et al. 2007). Integration of field-based and remotely-sensed data sets with ecosystem process models provides a means for landscape- to regional-scale assessment of carbon fluxes and analysis of the underlying processes affecting them. In this and the following chapter we present a summary of field methods useful in characterizing the structure and biochemistry of forest canopies, that are commonly used in terrestrial productivity estimation and modeling, and which may be effectively observed and scaled with remote sensing.

14.2 Introduction

The forest canopy is the interface between the land and the atmosphere, fixing atmospheric carbon into biomass and releasing oxygen and water. An understanding of canopy structure is important for modeling the transport and sequestration of atmospheric gases such as carbon dioxide, methane and even metals. The arrangement of individual trees, differences in species morphology, the availability of light and soil nutrients, and many other factors determine canopy structure, with differences contributing to variations in the amount of potential biomass and the availability of resources to understory communities.

Among the most common measurements of canopy structure are height (maximum stem height), the fraction of ground overlain by foliage (coverage), and the leaf area per unit ground area (leaf area index, LAI). Aspects of structure may also be used to predict stand attributes, such as stem density, basal area and aboveground biomass. These measures are important for characterizing estimates of ecosystem productivity and development, as well as for interpreting and validating landscape- to regional-scale estimates of vegetation attributes derived from remote sensing data.

The canopy, as Geoffrey Parker notes in his 1995 work on the structure and microclimate of forest canopies, is the aggregate of all tree crowns, inclusive of foliage and woody materials.

Canopy structure, in his words, is "the organization in space and time, including the position, extent, quantity, type and connectivity, of the aboveground components of vegetation." Many terms are used interchangeably in reference to canopy structure including: physiognomy (the shapes of individual crowns), architecture (the growth patterns and resultant forms of stems), organization (the statistical distribution of canopy components or important characteristics in space or time) and canopy texture (the size of crown units composing the overstory that are apparent from above the stand) (Parker 1995, Parker et al. 2004).

Different developmental stages of forest canopies yield various structures that use light resources in different ways. While recognizing the continuous nature of forest structural development and the arbitrary nature of classification schemes, Franklin et al. (2002) describe a series of stages in forest stand development. Stages of disturbance and legacy creation, cohort establishment, canopy closure, biomass accumulation/competitive exclusion, maturation, vertical diversification, horizontal diversification, and pioneer cohort loss are broadly applicable across varying biomes. Parker and Brown (2000) advocate for basic efforts to illustrate the distribution of relevant structures across space, maps of structure, function and microclimatic environment that illustrate ecological gradients within the canopy systems.

The sections that follow provide an overview of measurements of height, canopy cover and LAI of use to North American Carbon Program research. The main goal of the NACP sites is to provide robust, ground-based estimates of C uptake, storage, and flux that can be used for validation and scaling. The approaches outlined here are not exhaustive, but rather identify a range of robust ground- and remote sensing-based methods that capture a suite of useful metrics. It is critical to note, however, that such summary measures describe mean conditions; often providing little or no information on spatial variability. Parker et al. (2004) caution that "such summaries are often inadequate for prediction of growth, carbon dioxide exchange, structural complexity and habitat quality; structural information on the spatial distribution of canopy components is more useful than summary measures (Parker 1995, Lefsky et al. 2002)."

14.3 Canopy Height

Vegetation height is a function of species composition, climate, disturbance and site quality. Understanding the vertical distribution of vegetation is an important element in reducing the uncertainty in estimates of the net primary productivity of different ecosystems. When coupled with knowledge of composition, disturbance history, and other environmental factors, height often serves as an estimate of stand age or successional state (Dubayah et al. 2000). Height can be measured from the ground or by remote sensing (inclusive of aerial photography).

14.3.1 Remote Sensing Approaches

Remote sensing approaches to the measurement of height include interpretation of data from passive, optical sensors (e.g. Landsat TM, aerial photography) as well as active, physical sensors (e.g. radar, lidar). In recent years, lidar remote sensing has generated much attention as a breakthrough technology for deriving the three-dimensional characteristics of canopies, most notably height (Dubayah et al. 2000, Lefsky et al. 2002). Dubayah and his colleagues note, "that unlike visible, near-infrared, and radar remote sensing techniques that require sophisticated models to recover basic canopy structure, height is directly measured by lidar systems and, as long as the ground can be determined, is readily obtained." The direct measurements of waveform lidar are canopy height, sub-canopy topography and the vertical distribution of intercepted surfaces between the canopy top and the ground. Other biophysical attributes of forest structure, such as aboveground biomass, are modeled or inferred from these direct measurements, or by integration with data from other imaging sensors (optical or radar) (Dubayah et al. 2000, Lefsky et al. 2002, Treuhaft et al. 2002). Recent work with airborne multi-angle data has also provided results for remote measurements of height that correlate well with waveform lidar measures (Kimes et al. 2006).

Lidar data require some validation with ground measured field data and may require a modest calibration to optimize consistency with more traditional forestry estimates of average stand height. Imaging waveform lidar systems, such as NASA's Laser Vegetation Imaging Sensor (LVIS) (Blair et al. 1999), map continuous fields of heights providing important data on spatial variation of height across the landscape (Dubayah et al. 2000). Several approaches to validating remotely derived height from ground measures are discussed below.

14.3.2 Ground-Based Approaches

Ground-based laser scanning is an emerging technology with great potential for forest measurements and modeling on a smaller scale. Differing applications of ground-based laser scanning have provided high-resolution, spatially explicit measures of plot-level forest canopy structure (Henning and Radtke 2006, Parker et al. 2004, Lovell et al. 2003). Such measurements can provide improved assessments of canopy structure, better linking leaf-level processes to canopy structure and forest growth (Henning and Radtke 2006). These techniques can quantify spatial variation and are an advance over some previous methods, allowing application to long-term studies of vegetation change (Parker et al. 2004).

Laser rangefinders can obtain precise field height data and create detailed stand maps. A combination of direct (i.e. slope distance and inclination) and calculated (i.e. horizontal distance, vertical distance, and percent slope) measurements are used (e.g. Adams and Zuchowski 1997). Terrain and density can influence error and ease of use. Sonic hypsometers can also be used to collect height or horizontal distances. These instruments emit omni-directional sonic pulses that permit distance estimation (i.e. horizontal distance, vertical distance, and percent slope).

Clinometers are surveying instruments for measuring angles of elevation, slope, or incline. By using the principles of trigonometry, the height of tall objects is calculated from the angles measured. Measured poles are used to assess trees, generally of shorter stature, with excellent accuracy. These traditional methods are, however, typically quite time intensive.

Throughout its century-long history, forestry has relied on various types of tree volume and dry weight (aboveground biomass) tables (Avery and Burkhart 1983) to explain relationships between tree volume and diameter at breast height (DBH), tree height, and at times tree form. Height in these tables is typically expressed as total tree height or length of merchantable stem. Although many independent variables have been incorporated into regression equations for predicting tree volume, measurements of stem diameter and height tend to account for the greatest proportion of the variability in volume. Numerous height-diameter regression models have been proposed and used in the past and continue to evolve today. Because the basic height-diameter relationship is not linear, but is sigmoid in shape over the full range of diameters, transformation is required to apply linear regression methods for estimating coefficients in the relationship. Clark and Clark (2000) correctly caution, however, that "while tree height can be well predicted from DBH measurements, generalized allometric equations for a given life zone may not correctly describe the allometry of tree species at a particular study site."

14.4 Canopy Cover

Measurements of canopy cover can provide information on forest productivity, solar energy balance, the history of natural and anthropogenic disturbances, below canopy processes, stand density, and overall system change. Cover metrics are widely used as a means of defining forests and classifying forest types (e.g. the United Nations Food and Agriculture Organization (FAO 2000)) and are often considered in land and watershed management decision-making. Canopy cover has been defined by Korhonen et al. (2006) as the "proportion of the forest floor covered by the vertical projection of the tree crowns, and should be distinguished from canopy closure, which is defined as the proportion of sky hemisphere obscured by vegetation when viewed from a single point (Jennings et al. 1999)." In other words, "if canopy is measured with instruments that have an angle of view (i.e. measure a larger area than just a vertical point), like cameras (Kuusipalo 1985) or spherical densiometers (Cook et al. 1995), the results are estimates of canopy closure" (Korhonen et al. 2006).

As such, canopy cover measurements, by definition, should be made in the exact vertical direction (Jennings et al. 1999). If instruments with an angle of view are used, canopy cover is usually overestimated (Bunnell and Vales 1990, Cook et al. 1995, Jennings et al. 1999, Korhonen et al. 2006). In practice, however, if the angle of view is narrow (i.e. less than 30°) the bias is considered insignificant (Bunnell and Vales 1990). Another issue worth noting is that while tree height and length of the live crown do not affect the estimates of canopy cover, canopy closure increases as the trees become taller, and as the height to the live base of the crown decreases (Jennings et al. 1999). Canopy cover can be measured from the ground or with remote sensing (inclusive of aerial photography). It can also be modeled statistically from stand parameters (e.g. Forest Vegetation Simulator (FVS), Donnelly and Johnson 1997).

14.4.1 Remote Sensing Approaches

By virtue of their high spatial resolution, aerial photographs and digital imagery are often used for measuring canopy cover across a landscape, providing metrics at a resolution of 1–30 m, while generally lower resolution satellite imagery is used to measure landscape cover and change at the regional to global scale with pixel size ranging from 250 m–2 km.

The January 2007 release of the National Land Cover Dataset by the interagency Multi-Resolution Land Characteristics Consortium (MRLC) includes Landsat 7 (ETM+) - derived percent forest canopy density coverage at 30-m resolution for the conterminous United States. These products are web enabled for download from the MRLC website at http://www.mrlc.gov. Other NLCD 2001 products include 21 classes of land cover and percent urban imperviousness. The method employed to map tree canopy density for NLCD 2001 is based on empirical relationships between tree canopy density and Landsat data established using regression tree techniques. One-meter digital orthophoto quadrangles were used to derive tree canopy density data needed for calibrating the relationships between canopy density and Landsat spectral data. This method is described in detail in Huang et al. (2001).

Tree cover and canopy density estimates can be obtained from the MODIS (15 arc-seconds) Vegetation Continuous Fields (MODIS VCF) - Tree Cover Dataset. The Vegetation Continuous Fields collection contains proportional estimates for vegetative cover types: woody vegetation, herbaceous vegetation, and bare ground. The product is derived from all seven bands of the Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor onboard NASA's Terra satellite. The continuous classification scheme of the VCF product may depict areas of heterogeneous land cover better than traditional discrete classification schemes. While traditional classification schemes indicate where land cover types are concentrated, this VCF product shows how much of a land cover such as "forest" or "grassland" exists anywhere on a land surface (Hansen et al. 2003). The tree cover estimates in this dataset are calculated using an automated algorithm for images acquired from the MODIS sensor over a one year period (October 2000– December 2001). This dataset is available online from the University of Maryland's Global Land Cover Facility (GLCF) at http://glcf.umiacs.umd.edu/data/modis/vcf/.

With waveform lidar, the relative strength of the canopy and ground returns provides information on canopy closure (Harding et al. 2001). In the case of LVIS, the relevant variable is the fraction of laser illumination that is returned to the sensor from the ground—the ground return (Lefsky 1997). Initial processing of the cover metric involves the calculation of a simple ground-return ratio of canopy energy to total energy in the lidar waveform (see Eq. 14.1). This ground-return ratio provides an approximation of the degree of canopy closure (Drake 2001).

$$CC = C_e / (C_e + G_e) \quad (14.1)$$

Where CC = canopy closure; C_e = total energy of canopy (in photon counts); G_e = total energy of ground (in photon counts) (Hofton et al. 2000).

14.4.2 Ground-Based Approaches

Visual estimations of canopy cover are point samples that typically determine the overhead presence or absence of canopy cover in the observed site. Sighting tubes (e.g. Cajanus tube) can help to ensure the verticality of the observation and improve the accuracy of results with suitable sample sizes (i.e. >100 points; Korhonen et al. 2006). Line-intercept sampling extends the concept by recording horizontal distances covered by live crown along a line-transect. Accuracies using these methods are generally high. While typically more time intensive than other methodologies, the line-intercept method is appropriate if more detailed information on layering and species is required (Fiala et al. 2006).

Various inexpensive hand-held devices (e.g. Moosehorn densiometers) can add additional rigor to visual estimates by calculating percentage cover at each sampled location. The Moosehorn, for example, uses an upward looking mirror with a grid that allows for the measurement of area for a given canopy. The recorder notes the number of open sky versus vegetation observations for a point field visible within the instrument viewer. Relative cover for the plot is the mean of the number of readings. This technique has been used to validate lidar metrics at the level of individual footprints (Hyde et al. 2005). Fiala et al. (2006) recommend the use of Moosehorn sampling for obtaining rapid, efficient estimates of vertically projected canopy cover.

Spherical densiometers are most frequently used for estimating canopy closure, but these estimates may have low accuracy and low precision (Strickler 1959). Although such problems can be reduced by use of a tripod, this does not eliminate the subjectivity involved in using these instruments. With their intermediate angle of view, densiometers are perhaps most accurately viewed as a hybrid estimate of cover and light, making them most useful where wide angle cover is the desired attribute to quantify (Fiala et al. 2006).

Another point sample method for measuring canopy cover and canopy closure is the upward looking imaging of a canopy using a camera with a hemispherical lens. The resultant image is a circle in which the center of the image is the zenith and the distance from center relates to view angles. When oriented and interpreted properly, these images can provide robust estimates of canopy cover, canopy closure, and canopy light interception as well as daily and yearly estimates of understory light, when overlaid with solar charts. Repeated measurements over time yield very detailed measurements of canopy closure and crown competition. When used with photon sensors this method can provide very accurate estimates of canopy light interception and when used with a robust sampling strategy, a useful estimate of total canopy cover through the gap fraction index and LAI (see below). Fiala et al. (2006) caution, however, that much hemispherical photography is really an estimate of light penetration, and is more appropriately used as a measure of angular canopy openness, rather than canopy cover.

Korhonen et al. (2006) and Fiala et al. (2006) provide recent comprehensive reviews and comparisons of ground-based approaches to estimation of canopy cover and closure and associated literature.

14.5 Leaf Area Index

Leaf area index (LAI) is one of the most challenging forest canopy structural metrics to quantify accurately, owing to large spatial and temporal variability and to measurement limitations inherent in all current methodologies. Numerous comprehensive reviews of theory, methodology, and instrumentation exist in the literature (e.g. Norman and Campbell 1989, Welles 1990, Fassnacht et al. 1994, Welles and Cohen 1996, Chen et al. 1997, Gower et al. 1999, Breda 2003, Jonckheere et al. 2004). A synthesis by Asner et al. (2003) provides some insight into the range in LAI observations globally across biomes, and the effect of more precise definition and improved measurement methodology on LAI estimation.

LAI is broadly defined as the amount of functional (green) leaf area in a canopy per unit ground area. Asner et al. (2003) describe four common measures of LAI that appear in the literature (Table 14.1). Of these, the most widely used is one-half the total green leaf area per unit ground surface area (definition 2, Chen and Black

Table 14.1 Leaf area index definitions (as reported in Asner et al. 2003)

1	Total	Total outside area of the leaves, taking leaf shape into account, per unit of horizontal ground area below the canopy
2	One-sided or one-half	One-half the total LAI (hemi-surface area or HSA), even if the two sides of the leaves are not symmetrical.
3	Horizontally projected	The area of 'shadow' that would be cast by each leaf in the canopy with a light source at infinite distance and perpendicular to the leaf surface, summed for all leaves in the canopy.
4	Inclined, projected	The projected area of leaves while accounting for leaf inclination.

1992) or the hemi-surface area (HSA, Gower et al. 1999). This definition is the most general measure for all leaf shapes, and is the appropriate parameter for radiation transfer models upon which indirect LAI measurement methods rely (Chen and Black 1992, Gower et al. 1999). This definition is most widely used in current literature and is the definition used in this chapter's discussion of approaches for estimating LAI.

The major methodologies for estimating LAI utilize either 'direct' approaches, such as destructive sampling, allometry, litterfall collection, and point contact sampling, or 'indirect' approaches involving optical instruments combined with modeling.

14.5.1 Direct Measurement

These approaches, particularly litterfall collection and destructive harvest, are commonly used as reference for evaluation or calibration of the more rapid, indirect methods and, in all cases, are best suited for estimation of maximum LAI. All direct methods involve determination of leaf area using either a leaf area meter (projected leaf area) or a specific relationship of dimension to area. For conifer species, projected leaf area must be adjusted by a coefficient related to the needle cross-sectional area (Chen and Black 1992, Chen et al. 1997).

In all cases green foliage area is measured on a sub-sample of leaves and related to dry foliage mass using dry weight to species-specific leaf area ratios, leaf mass per unit area (LMA, g/cm^2). The total dry mass of leaves collected within a known ground surface area is converted to LAI by multiplying the dry weight of each species by its species-specific LMA. The most critical step is accurate or representative determination of species-specific LMA, which varies vertically with the light environment in vegetative canopies, as well as in both space and time in response to resource availability. Rather than assessing LMA only from litterfall samples, LMA should be assessed on a site-specific basis from green leaf samples collected from several heights in the canopy (see "Foliar Chemistry" section for a method for LMA determination).

Harvest methods are the most accurate for direct estimation of LAI and involve destructive sampling and measurement of the area of all leaves within a delimited area. Harvest methods are most widely used in agricultural systems or those dominated by annual or small stature vegetation. In perennial, large stature systems such as forests, this method is challenging to implement and, in any case, precludes long-term study of LAI dynamics over time in a particular location. Most often destructive harvest methods in forests are used to develop site-specific allometric equations.

Allometric methods are based on physical dimensions, such as stem diameter at breast height (DBH) or sapwood area, using species-specific or stand-specific relationships derived from detailed destructive measurements of sub-samples of leaves, branches, and stems. As LAI is both spatially and temporally dynamic, allometric estimators of LAI are quite site specific and in any case cannot be used to capture temporal dynamics. Gower et al. (1999) advocate the development of site-specific allometric equations when accurate estimates of LAI are needed, particularly as reference for indirect methods used at the same site in the same period. Caution is advised when using existing allometric equations if site-specific equations cannot be developed, with particular attention paid to matching plant species and size when selecting such equations (Gower et al. 1999).

Point contact methods, which determine LAI from the mean contact number of a thin probe or plumb line that passes through the canopy (Warren-Wilson 1959), are accurate but are generally impractical in forest stands because of the tall stature of individuals and the often high density of leaves. A number of indirect optical methods have been developed based on this concept.

Litterfall collection is perhaps the most widely used non-destructive, direct method employed in forest ecology studies. Litterfall is typically collected in traps of known area distributed below the canopy before seasonal leaf fall. Collected litter is oven-dried and weighed to determine the litter dry weight (g m^{-2}). Leaf dry mass is converted to leaf area by multiplying the collected biomass, usually per species, by the species-specific LMA. Leaf area index is the accumulated leaf area over the period of leaf fall, which is sometimes seasonal but, more typically, the accumulated litterfall over one year. In deciduous systems, yearly litterfall (including small twigs, flowers, fruit, and seeds) is often used as an equivalent to yearly canopy production, minus herbivory. For a recommended approach, see Litterfall Methods in Aboveground Fluxes section (Bernier et al., this volume).

With adequate spatial and temporal sampling, determining leaf area index by litterfall collection is most appropriate in deciduous stands, which shed a majority of foliage during a single season. In needle-leaved evergreen and mixed forests, estimation of LAI through litterfall collection is more problematic as needle fall is not as strongly seasonal as that of deciduous species nor related to new growth, but rather related to leaf lifespan and the cumulative climate conditions over the leaf life span. In these cases, needle-leaved litterfall is often multiplied by average leaf retention time to approximate needle-leaved mass in the canopy.

14.5.2 Indirect Measurement

As direct measurement of LAI in forest ecosystems presents many practical and logistical difficulties, much effort has gone into devising more rapid, indirect methods. Optical, indirect measures afford the opportunity to monitor seasonal dynamics of LAI that is either not possible or practical with most direct measurement approaches.

The most widely used methods are based on radiative transfer theory and rely on the dependency between canopy element distribution (i.e. angle and spatial distribution) and canopy gap fraction and size distribution to assess forest canopy parameters, especially LAI. All optical instruments used to estimate LAI measure light transmittance. Measures obtained with optical instruments are termed 'effective LAI' or L_e, because these measures, based on Beer's law, are calculated assuming a random spatial distribution of foliage, and represent solar radiation interception without the distinction between woody and photosynthetically active materials.

The assumption of random spatial distribution of foliage is often not met in forest canopies, and strategies (and instrumentation) to account for non-random foliage distribution, as well as the contribution of non-photosynthetic material (stem, branches), must be employed to convert L_e to LAI (see Kucharik et al. 1999, Gower et al. 1999, Chen et al. 1997). Non-randomness in foliage distribution, or foliage clumping, can occur at leaf, branch, and individual tree levels (Gower et al. 1999). In forests, L_e is generally only 30–70% of the true LAI because of foliage clumping (Chen and Cihlar 1995). The clumping index, which is derived from canopy gap size estimates, generally pertains to clumping at scales larger than the defined element size in the canopy. For needle-leaved species, this is the shoot, for broad-leaved species this is the individual leaf. Non-random distribution of needles on conifer shoots cannot be measured with remote optical instruments, but must be measured by direct methods if "within-shoot" clumping is to be considered in optical measurement "clumping" corrections (see Gower et al. 1999).

If no correction for woody material is employed the optically-based measures are most properly plant area index (PAI) or surface area index (SAI) rather than LAI. In many forests, proportion of wood area to the total plant area is small; however, this proportion can be up to 30% in cases where LAI is very low such as in the boreal forest (Chen et al. 1997). One notion is to use estimates of wood area to correct plant area estimates. For example, in deciduous forests, measurements could be obtained at a given site before and after leaf senescence and the wood area index (WAI) could be subtracted from the PAI to yield LAI. However, some evidence suggests leaves preferentially mask branches (Kucharik et al. 1998) so simply subtracting wood area from plant area is likely overcompensation. Further, several studies have indicated that branches intercept only a small amount of light in healthy forest canopies (e.g. Fassnacht et al. 1994, Kucharik et al. 1998). However, additional correction may be needed for some forests such as those with partially defoliated canopies or canopies that retain a large amount of dead branches.

Indirect estimates of LAI plateau between 5–6, caused by gap fraction saturation as LAI increases (Gower et al. 1999). Direct measurement is the only reliable approach for canopies with LAI > 6. However, the global mean LAI as reported by Asner et al. (2003) is 4.5 (SD = 2.5) with maximum values rarely exceeding 7.0, except in forest plantations.

Two broad categories of optical instruments are commonly used to measure LAI: those that sample the canopy hemispherically, with LAI estimation based upon canopy gap fraction analysis, and those that sample along transects, with LAI estimation based upon canopy gap size distribution analysis.

14.5.2.1 Canopy Hemispherical Sampling

This approach quantifies canopy gap fraction at multiple zenith and azimuth angles obtained simultaneously, and assumes random foliage distribution. Measurements with these instruments are most reliable when performed under diffuse sky conditions (such as occur at dawn and dusk or under uniformly cloudy conditions) to minimize direct scattering of sunlight off leaves and trunks. In all cases correction factors, i.e. "clumping" factors, to account for non-random foliage distribution are also required to accurately convert L_e to PAI. However, if the goal of measurement is simply to characterize the light environment, or to assess relative differences in L_e over time and between stands, correction factors may not be needed.

Hemispherical (fish-eye) imaging is a technique to characterize plant canopies using images taken looking upward through an extreme wide-angle lens. Typically, an 180° 'fish-eye' camera lens coupled with a digital or film camera system is used to produce images of the projection of a hemisphere on a plane. The resulting circular image shows a complete view of all sky directions with the zenith in the center of the image and the horizons at the edges. These circular images record the size, shape, and location of gaps in the vegetation canopy from which such canopy structural parameters as openness, foliage inclination angle, and LAI may be calculated. Calculations of canopy metrics, such as leaf area index or canopy cover, depend on accurate measures of gap fraction as a function of zenith angle and azimuth. Advantages of an image approach include a permanent image which can be visually inspected and manually processed to accurately distinguish canopy elements, and which may be re-analyzed as methodologies develop.

Relatively inexpensive digital cameras are now available with a very large number of pixels that provide extremely high spatial resolution. Compared to photographic film, digital sensors have better radiometric quality and offer a number of practical advantages, not least among which is elimination of the expense and time involved with film processing and scanning, as well as the ability to preview images in the field to ensure image quality. Moreover, digital images have almost unlimited image treatment possibilities. Some caution should be used when employing typical "consumer-grade" digital cameras, as lens optics and dynamic range of such systems may introduce bias in canopy metric estimation (Frazer et al. 2001, Jonckheere et al. 2005).

An accurate estimate of LAI from digital hemispherical photography is best achieved when:

1. Exposure is controlled relative to above-canopy sky brightness (see Chen et al. 1991, Macfarlane et al. 2000, Zhang et al. 2005).
2. Images are corrected for the gamma function of the digital camera and its lens (see Leblanc 2005, Macfarlane et al. 2007).
3. The gap fraction distribution is corrected for foliage clumping (e.g. Chen and Cihlar (1995) and Lang and Xiang (1986) methods).

The LAI 2000 (LiCor, Lincoln, NB) plant canopy analyzer measures the gap fraction by comparing the radiation measured under the canopy at five zenith angles with simultaneous or near simultaneous above canopy incoming diffuse radiation, usually measured in a nearby opening. Where many under canopy measurements must be taken this can be a significant constraint if two instruments are not available. The LAI 2000 measures diffuse radiation simultaneously in five distinct angular bands, with central zenith angles of 7°, 23°, 53°, and 68°, by means of a fisheye light sensor. Chen et al. (1997) characterize the LiCor LAI 2000 as a more convenient and rapid version of hemispherical photography because image processing is not required. A built in optical filter blocks incoming radiation at wavelengths <490 nm to minimize canopy light scattering, maximizing contrast between the sky and canopy elements. The ratio of the two values gives the transmittance simultaneously for each sky sector and from which LAI is estimated. Calculations are performed automatically by internal software. Calculation assumptions include: foliage as an optically 'black body' which absorbs all light incident upon it; random distribution of canopy elements; canopy elements modeled using simple geometrical convex shapes; and, canopy elements assumed small relative to the angular bands of the instrument (Jonckheere et al. 2004). Advantages of this approach include its rapidity in continuous and homogeneous canopies. Disadvantages include the requirement of an above canopy reference; inaccuracy, mostly under-estimation, in clumped, discontinuous, and heterogeneous canopies; and, relatively coarse resolution, i.e. only five concentric rings using an immediate and automatic integration by the instrument in the field.

14.5.2.2 Canopy Transect Sampling

These approaches are typically line transect measurements of direct sunlight transmitted through canopy gaps yielding a profile of light that penetrates the canopy from which canopy gap size and distribution may be estimated. All require direct/full sunlight conditions for best operation. For gap fraction estimation, data collection over several hours is required to sample an adequate range of solar angles.

Demon (CSIRO, Canberra, Australia) is an optical instrument that is an extension of the point-quadrat method where direct beam radiation from the sun, measured through a directional narrow view angle, replaces the probe or plumb line (Lang 1990, Breda 2003). Filters are used to limit the spectrum of received light (≈430 nm) in order to minimize the effects of light scattering by foliage. A wide range of solar zenith angles is sampled by taking measurements, sampled via one or several line transects, over several hours and under bright sun-lit conditions to sample an adequate range of sun angles for gap fraction estimation. LAI is calculated from these data by model inversion and instrument specific averaging techniques (Dufrêne and Breda 1995).

AccuPAR and Sunfleck Ceptometer (Decagon Devices, Pullman, OR) are linear sensors that measure the sun fleck fraction or quantity of transmitted photsynthetically active radiation (PAR). These measurements, over a range of solar zenith angles and combined with assumptions about foliage distribution, are used with supplied software to estimate PAI. Limitations of these instruments include large variability between measurements necessitating substantial numbers of measurements in order to derive reliable results. The technique is not suitable in coniferous forests due to penumbral effects in the sun fleck fraction (Jonckheere et al. 2004).

TRAC (Tracing Radiation and Architecture of Canopies) is an optical instrument that measures the photosynthetic photon flux density (PPFD) through a canopy.

Using a solar beam as a probe, it records, by means of three photosensitive sensors, the transmitted direct light at a high frequency (Chen and Cihlar 1995). Sunflecks that are projected onto the sensor where canopy gaps occur in the sun's direction are proportional to the gap sizes being measured. By walking the instrument under a canopy at a fixed speed, its gap fraction and gap size distribution can be computed (Leblanc et al. 2002). The gap fraction measured by TRAC is with respect to the solar zenith angle at time of measurement. To effectively measure gap fraction, TRAC measurements at multiple solar zenith angles must be undertaken, such as over the course of half a day.

Using supplied software, the clumping index is found by comparing the measured gap size distribution with a theoretical gap size distribution associated with a canopy with randomly distributed foliage elements (Chen and Cihlar 1995). The clumping index obtained from TRAC can be used to convert L_e to LAI. A practical scheme for combining TRAC and LAI-2000 measurements in varied forest cover types is presented in Leblanc and Chen (2001).

14.6 Recommendations

14.6.1 Canopy Height

Ground-based measurements of canopy height are obtained from individual tree height measurements on a per plot basis. Total height and height to the base of the live crown should be recorded for each individual. Each individual should be tagged (see Chapter 4, Biomass) and its location from plot center (distance and azimuth) recorded. Laser rangefinders, sonic hypsometers, or clinometers are the recommended instrumentation.

14.6.2 Canopy Cover and Closure, Leaf Area Index

Digital hemispherical image analysis is recommended for the quantification of canopy cover, closure, and leaf (plant) area index. Variables measured using this approach include cover (using zenith angles < 30°) and crown closure, as well as gap fraction, gap size distribution, and clumping index from which leaf area index may be derived.

Multiple images per plot should be obtained. Number of images is dependent on plot size. A grid or transect approach is recommended to capture spatial variability (e.g. Macfarlane et al. 2007, Jonckheere et al. 2005, Chen and Leblanc 2003).

The basic equation for obtaining LAI from optical measurements is (Chen 1996):

$$L = (1-\alpha)L_{e\gamma_E}/\Omega_E \qquad (14.2)$$

where L denotes LAI; α is the woody-to-total plant area ratio; L_e is the effective LAI; γ_E is the needle-to-shoot area ratio; and Ω_E is the foliage clumping element index. A foliage element refers to either a conifer shoot or a broad leaf.

In optical gap fraction measurements, all objects above the ground, including both leaves and woody materials, affect L measurement. If no correction is made using the woody-to-total area ratio, i.e. $\alpha = 0$, then the value obtained is plant area index (PAI) rather than LAI. Since the principal interest is in green leaves only, effects of woody materials require removal by incorporating α. Sources for α in the literature include Chen (1996) and Gower et al. (1999). This ratio may be computed directly using the ratio between PAI derived from optical sampling and the maximum LAI value derived from direct measurement approaches such as litterfall.

As discussed previously, the starting point for optical estimates of LAI are measurements of radiation transmission from which gap fraction is estimated based on an assumption of a random leaf spatial distribution. As the distribution is often not random, the effective LAI, as estimated by the optical instruments, typically differs from the 'true' LAI. Non-randomness or 'clumping' may occur at two levels: at the level of the canopy element (leaf or shoot) and at scales larger than the canopy element. In conifer stands, needles are grouped first in shoots, hence shoots of conifers are treated as the foliage element and a correction for this leaf grouping is made using the needle-to-shoot area ratio, γ_E. For broad-leaved stands, individual leaves are the element and no shoot-level correction is necessary, i.e. $\gamma_E = 1$. Measurement of needle-to-shoot area ratio is highly labor intensive, so a recommendation is made here for use of published values where possible. Sources for needle-to-shoot area ratios for many forest species may be found in Chen (1996) and in Gower et al. (1999). Clumping at scales larger than the shoot is quantified using the element clumping index, Ω_E, which can be derived from optical measurements of canopy gap size distribution derived from hemispherical images.

Numerous software programs, some free and some commercially available, have been developed to process images and produce canopy metrics, e.g. WinSCANOPY (Regent Instruments, Qué., Canada), SOLARCALC (Chazdon and Field 1987), Winphot (ter Steege 1996), HemiView (Delta-T Device, Cambridge, UK), Gap Light Analyzer (Frazer et al. 1999), DHP (Leblanc et al. 2005), Hemisfer (Schleppi et al. 2007) and others.

Estimates of LAI derived from hemispherical optical sampling may be compared with direct estimates derived from litterfall sampling (see discussion above and Chapter 7, Litterfall Sampling).

Literature Cited

Adams J, Zuchowski L (1997) Impulse 200 and Impulse 200LR User's Manual 4th edition. Laser Technology, Inc., Englewood CA

Asner GP, Scurlock JMO, Hicke JA (2003) Global synthesis of leaf area index observations: implications for ecological and remote sensing studies. Global Ecology and Biogeography 12: 191–205

Avery TE, Burkhart HE (1983) Forest Measurements (3rd edition). McGraw-Hill, New York
Blair JB, Rabine DL, Hofton MA (1999) The Laser Vegetation Imaging Sensor (LVIS): A medium- altitude, digitisation-only, airborne laser altimeter for mapping vegetation and topography. ISPRS Journal of Photogrammetry and Remote Sensing. 54: 115–122
Breda NJJ (2003) Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. Journal of Experimental Botany 54(392): 2404–2417
Bunnell FL, Vales DJ (1990) Comparison of methods for estimating forest overstory cover: differences among techniques. Canadian Journal of Forest Research 20: 101–107
Chazdon RL, Field C (1987) Photographic estimation of photosynthetically active radiation: evaluation of a computerized technique. Oecologia 73(4): 525–532
Chen JM (1996) Optically based methods for measuring seasonal variation in leaf area index of boreal conifer forests. Agricultural and Forest Meteorology 80: 135–163
Chen JM, Black TA (1992) Defining leaf area index for non-flat leaves. Plant, Cell, and Environment 15: 421–429
Chen JM, Cihlar J (1995) Quantifying the effect of canopy architecture on optical measurements of leaf area index using two gap size analysis methods. IEEE Transactions on Geoscience and Remote Sensing 33: 77–787
Chen JM, Rich PM, Gower ST, Norman JM, Plummer S (1997) Leaf area index of boreal forests: theory, techniques, and measurements. Journal of Geophysical Research 102 D24: 29, 429–29, 443
Chen JM, Leblanc SG (2003) Canopy structure measurements using optical instruments. In Fluxnet Canada Measurement Protocols 1.3. www.fluxnet-canada.ca
Chen JM, Black TA, Adams RS (1991) Evaluation of hemispherical photography for determining plant area index and geometry of a forest stand. Agricultural and Forest Meteorology 56: 129–143
Clark DB, Clark DA (2000) Landscape-scale variation in forest structure and biomass in a tropical rain forest. Forest Ecology and Management 137: 185–198
Cook JG, Stutzman, TW Bowers CW, Brenner KA, Irwin LL (1995) Spherical densiometers produce biased estimates of forest canopy cover. Wildlife Society Bulletin 23(4): 711–717
Donnelly DM, Johnson RR (1997) Westside Cascades Variant of the Forest Vegetation Simulator. WO-Forest Management Services Center. USDA Forest Service. Fort Collins, CO, 68 p
Drake JB (2001) Estimation of tropical forest aboveground biomass using large-footprint lidar. Ph.D. Thesis. University of Maryand, College Park, Maryland
Dubayah RO, Knox RG, Hofton MA, Blair JB, Drake JB (2000) Land surface characterization using lidar remote sensing In:. Hill MJ, Aspinall RJ (Eds.) Spatial information for land use management. Gordon and Breach Science Publishers, Australia. p.25–38
Dufrêne E, Breda N (1995) Estimation of deciduous LAI using direct and indirect methods. Oecologia 104: 156–162
Fassnacht KS, Gower ST, Norman JM, McMurtrie RE (1994) A comparison of optical and direct methods for estimating foliage surface area in forests. Agricultural and Forest Meteorology 71: 183–207
Fiala CS, Garman SL,Gray AN (2006) Comparison of five canopy cover estimation techniques in the western Oregon Cascades. Forest Ecology and Management. 232: 188–197
Franklin JF, Spies TA, Van Pelt R, Carey A, Thornburgh D, Berg DR, Lindenmayer D, Harmon M, Keeton WS, Shaw DC, Bible K, Chen J (2002) Disturbances and the structural development of natural forest ecosystems with some implications for silviculture. Forest Ecology and Management 155: 399–423
Frazer GW, Canham CD, Lertzman KP (1999) Gap Light Analyzer (GLA), Version 2.0: Imaging software to extract canopy structure and gap light transmission indices from true-color fisheye photographs. Copyright 1999: Simon Fraser University, Burnaby, BC, and the Institute of Ecosystem Studies, Millbrook, New York, (http://www.rem.sfu.ca/forestry/index.htm or http://www.ecostudies.org)
Frazer GW, Fourneir RA, Trofymow JA, Hall RJ (2001) A comparison of digital and film fisheye photography for analysis of forest canopy structure and gap light transmission. Agricultural and Forest Meteorology 109: 249–263

Gower ST, Kucharick CJ, Norman JM (1999) Direct and indirect estimation of leaf area index, fPAR, net primary production of terrestrial ecosystems. Remote Sensing of Environment 70: 29–51

Hansen M, DeFries R, Townshend JR, Carroll M, Dimiceli C, Sohlberg R (2003) Vegetation Continuous Fields MOD44B, 2001 Percent Tree Cover, Collection 3, University of Maryland, College Park, MD, 2001

Harding DJ, Lefsky MA, Parker GG, Blair JB (2001) Laser altimeter canopy height profiles. Methods and validation for closed-canopy, broadleaf forests. Remote Sensing of Environment 76: 283–297

Hemiview (Delta-T Devices) http://www.delta-t.co.uk/

Henning JG, Radtke PJ (2006) Detailed stem measurements of standing trees from ground-based scanning lidar. Forest Science 5291: 67–80

Hofton MA, Minster JB, Blair JB (2000) Decomposition of laser altimeter waveforms. IEEE Transactions on Geoscience and Remote Sensing 38: 1989–1996

Huang, C, Yang L, Wylie B, Homer C (2001) A strategy for estimating tree canopy density using Landsat 7 ETM + and high resolution images over large areas. USGS. EROS Data Center, Sioux Falls, South Dakota

Hyde P, Dubayah RO, Peterson BE, Blair JB, Hofton MA, Hunsaker C, Knox R, Walker W (2005) Mapping forest structure for wildlife habitat analysis using waveform lidar: Validation of montane ecosystems. Remote Sensing of Environment 96: 427–437

Jennings SB, Brown ND, Sheil D (1999) Assessing forest canopies and understory illumination: canopy closure, canopy cover and other measures. Forestry 72(1): 59–74

Jonckheere I, Fleck S, Nachaerts K, Muys B, Coppin P, Weiss M, Baret F (2004) Review of methods for in situ leaf area index determination. Part I. Theories, sensors and hemispherical photography. Agricultural and Forest Meteorology 121: 19–25

Jonckheere I, Nackaerts K, Muys B, Coppin P (2005) Assessment of automatic gap fraction estimation of forests from digital hemispherical photography. Agricultural and Forest Meteorology 132: 96–114

Kimes DS, Ranson KJ, Sun G, Blair JB (2006) Predicting lidar measured forest vertical structure from multi-angle spectral data. Remote Sensing of Environment 100: 503–511

Korhonen L, Korhonen KT, Rautiainen M, Stenburg P (2006) Estimation of forest canopy cover: a comparison of field measurement techniques. Silva Fennica 40(4): 577–588

Kucharik CJ, Norman JM, Gower ST (1998) Measurements of branch area and adjusting leaf area index indirect measurements. Agricultural and Forest Meteorology 91: 61–88

Kucharik CJ, Norman JM, Gower ST (1999) Characterization of radiation regimes in non-random forest canopies: theory, measurements, and a simplified modeling approach. Tree Physiology 19: 695–706

Kuusipalo J (1985) On the use of tree stand parameters in estimating light conditions below the canopy. Silva Fennica 19(2): 185–196

Lang ARG, Xiang Y (1986) Estimation of leaf area index from transmission of direct sunlight in discontinuous canopies. Agricultural and Forest Meteorology 37 (3): 229–243

Lang ARG (1990) An instrument for measuring canopy structure. Remote Sensing Reviews 5: 61–71

Leblanc SG, Chen JM (2001) A practical scheme for correcting multiple scattering effects of optical LAI measurements. Agriculture and Forest Meteorology 110:125–139

Leblanc SG, Chen JM, Kwong M (2002) Tracing Radiation and Architecture of Canopies TRAC Manual version 2.1.3. Natural Resources Canada

Leblanc SG, Chen JM, Fernandes R, Deering DW, Conley A (2005) Methodology comparison for canopy structure parameters extraction from digital hemispherical photography in boreal forests. Agricultural and Forest Meteorology 129: 187–207

Lefsky MA, Cohen WB, Parker GG, Harding DJ (2002) Lidar remote sensing for ecosystem studies. Bioscience 52(1): 19–30

Lefsky MA (1997) Application of lidar remote sensing to the estimation of forest canopy and stand structure. PhD. Dissertation. University of Virginia. Charlottesville, VA

LiCor http://www.licor.com/

Lovell JL, Jupp DLB, Culvenor DS, Coops MNC (2003) Using airborne and ground-based ranging lidar to measure canopy structure in Australian forests. Canadian Journal of Remote Sensing 29(5): 607–622

Macfarlane C, Coote M, White DA, Adams MA (2000) Agricultural and Forest Meteorology 107(2): 155–168

Macfarlane C, et al. (2007) Estimation of leaf area index in eucalypt forest using digital photography, Agricultural and Forest Meteorology. 143: 176–188

Norman JM, Campbell GS (1989) Canopy structure In: Percy RW, Ehleringer JR, Mooney HA, Rundel PW (Eds.) Plant physiological ecology: field methods and instrumentation. London: Chapman & Hall, pp. 301–325

Ollinger SV, Treuhaft RN, Braswell BH, Anderson JE, Martin ME, Smith ML (2007) The role of remote sensing in the study of terrestrial net primary production In: Fahey TJ, Knapp AK (Eds.).. Principles and standards for measuring net primary production. Oxford University Press, Oxford, pp. 204–237

Parker GG (1995) Structure and microclimate of forest canopies. In: Lowman M, Nadkarni N (Eds.) Forest canopies: a review of research on a biological frontier. Academic Press, San Diego, CA, pp. 73–106

Parker GG, Brown MJ (2000) Forest canopy stratification-it it useful? The American Naturalist 155(4): 473–484

Parker GG, Harding DJ, Berger ML (2004) A portable lidar system for rapid determination of forest canopy structure. Journal of Applied Ecology 41: 755–767

Schleppi P, Sedivy I, Thimonier A (2007) Correcting non-linearities and slope effects in the estimation of the leaf area index of forests from hemispherical photographs. Agriculture and Forest Meteorology 144: 236–242 (http://www.wsl.ch/wald/dl/hemisfer/index-en.php)

Strickler GS (1959) Use of the densiometer to estimate density of forest canopy on permanent sample plots. USDA Forest Service. Portland, OR PNW. Note PNW-180. 5 p

ter Steege H (1996) WINPHOT 5.0: a programme to analyze vegetation indices, light and light quality from hemispherical photographs.Tropenbos Guyana Programme, Tropenbos, Guyana. Rep. 95–2. Wagner 1998 (http://www.bio.uu.nl/~herba/Guyana/winphot/wp_index.htm)

Treuhaft RN, Asner GP, Law BE, Van Tuyl S (2002) Forest leaf area density profiles from the quantitative fusion of radar and hyperspectral data. Journal of Geophysical Research-Atmospheres 107: 4568

Turner DP, Ollinger SV, Kimball JS (2004) Integrating remote sensing and ecosystem process models for landscape to regional scale analysis of the carbon cycle. BioScience 54: 573–584

Warren Wilson J. (1959) Analysis of the spatial distribution of foliage by two dimensional point quadrats. New Phytologist 58: 92–101

Welles JM (1990) Some indirect methods of estimating canopy structure. Remote Sensing Reviews 5: 31–43

Welles JM, Cohen S (1996) Canopy structure measurement by gap fraction analysis using commercial instrumentation. Journal of Experimental Botany 302: 1335–1342

WinsCanopy http://www.regentinstruments.com/products/Scanopy/Scanopy.html

Zhang YQ, Chen JM, Miller JR (2005) Determining digital hemispherical photograph exposure for leaf area index estimation. Agricultural and Forest Meteorology 133(1–4): 166–181