

Lidar Remote Sensing of the Canopy Structure and Biophysical Properties of Douglas-Fir Western Hemlock Forests

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Scanning lidar remote sensing systems have recently become available for use in ecological applications. Unlike conventional microwave and optical sensors, lidar sensors directly measure the distribution of vegetation material along the vertical axis and can be used to provide three-dimensional, or volumetric, characterizations of vegetation structure. Ecological applications of scanning lidar have hitherto used one-dimensional indices to characterize canopy height. A novel three-dimensional analysis of lidar waveforms was developed to characterize the total volume and spatial organization of vegetation material and empty space within the forest canopy. These aspects of the physical structure of canopies have been infrequently measured, from either field or remote methods. We applied this analysis to 22 plots in Douglas-fir/western hemlock stands on the west slope of the Cascades Range in Oregon. Each plot had coincident lidar data and field measurements of stand structure. We compared results from the novel analysis to two earlier methods of canopy description. Using the indices of canopy structure from all three methods of description as independent variables in a stepwise multiple regression, we were able to make nonasymptotic predictions of biomass

and leaf area index (LAI) over a wide range, up to 1200 Mg ha⁻¹ of biomass and an LAI of 12, with 90% and 75% of variance explained, respectively. Furthermore, we were able to make accurate estimates of other stand structure attributes, including the mean and standard deviation of diameter at breast height, the number of stems greater than 100 cm in diameter, and independent estimates of the basal area of Douglas-fir and western hemlock. These measurements can be directly related to indices of forest stand structural complexity, such as those developed for old-growth forest characterization. Indices of canopy structure developed using the novel, three-dimensional analysis accounted for most of the variables used in predictive equations generated by the stepwise multiple regression. Published by Elsevier Science Inc.

INTRODUCTION

Characterization of structure in moderate to high biomass forests is a major challenge in remote sensing. While remote sensing has had considerable success in measuring the biophysical characteristics of vegetation in areas where canopy cover is relatively sparse, quantification of vegetation structure where leaf area index (LAI) exceeds 3 has been less successful (e.g., Sader et al., 1990; Spanner et al., 1990; Chen and Cihlar, 1996). High biomass forests, which generally have high LAI, occur primarily in the temperate and tropical regions. They cover only 25% of the Earth's terrestrial surface, yet account for 59% of terrestrial NPP and 89% of terrestrial biomass (Waring and Schlesinger, 1985). Given their prominent role in global biogeochemistry, better characterization of high biomass forests is desirable.

The need for wide-scale inventory of the amount

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and organization of forest biomass is especially pressing in the Douglas-fir/western hemlock [*Pseudotsuga menziesii*/*Tsuga heterophylla*] forests of the Pacific Northwest. These forests are among the most massive in the world, and can accumulate as much as 650×10^6 g C ha⁻¹ in above- and below-ground biomass pools (Grier and Logan, 1977; Harmon et al., 1986). Considerable research has been devoted to remotely measuring the structure and development of these forest stands (Cohen and Spies, 1992; Congalton et al., 1993). In addition, much effort has been devoted to measuring the distribution of carbon pools and fluxes on these landscapes (Cohen et al., 1996). Furthermore, the mechanisms and rates of succession in these forests have been the focus of intense scientific and management attention due to the association of at least two endangered species with the physical structure of old-growth stands (Franklin et al., 1981; Hansen et al., 1991). The ability to remotely sense both the total quantity and spatial organization of forest biomass would provide a way to meet the need for forest inventory. For instance, management of these forests' carbon balance and habitat conditions requires detailed knowledge of the total biomass and size class distribution of trees. Unfortunately, traditional optical and more recently developed radar remote sensing have achieved only limited resolution of structural conditions.

Scanning lidar (*light detection and ranging*) instruments, a new class of sensor, directly measure the vertical structure of forests using the principles of laser altimetry, and thus hold great promise for remotely sensing the quantity and spatial organization of forest biomass (Weishampel et al., 1996). Laser altimeters, a related but simpler class of instruments, estimate the distance between the sensor and a target through the precise measurement of the time between the emission of a pulse of laser light from the sensor and the time of detection of light reflected from the target. Scanning lidar systems (Blair et al., 1994; Harding et al., 1994; Dubayah et al., 1997) employ multiple measurements of both distance to and amount of energy reflected from the many surfaces of a geometrically complex target. When this distribution of return energy, the lidar waveform, is measured over a vegetation canopy, it records the vertical distribution of light reflected back to the sensor from vegetation and soil surfaces from the top of the canopy to the ground. For forests, relating these waveforms to conventional, primarily nonspatial, measurements of forest structure, such as aboveground biomass and stand basal area, has been a primary research goal (Lefsky, 1997; Lefsky et al., 1999; Means et al., 1999). In this study, we define a new system for the simplified description of three-dimensional aspects of canopy structure, and apply the measurements obtained with this system to predicting the total amount and structural complexity of forest biomass for Douglas-fir/western hemlock forests in western Oregon.

Canopy Structure

Canopy structure, defined as "the organization in space and time, including the position, extent, quantity, type and connectivity, of the aboveground components of vegetation" (Parker, 1995), contains much information about the state of development of forests. At the most basic level, differences in stand development are reflected in the mean and maximum height of the individuals of a stand (Lefsky, 1997; Lefsky et al., 1999; Means et al., 1999). However, even for stands of similar mean or maximum height, the physical structure of canopies can vary considerably, as a result of local differences in the importance of various mechanisms of forest succession, disturbance, and environmental factors (Spies and Franklin, 1991). The effects of these processes may be discernible from subtler features of canopy structure, such as the sizes of mid and lower canopy trees and subcanopy gaps.

Canopy structure changes dramatically after stand replacing disturbances in Douglas-fir/western hemlock forests. Young stands of closed canopy forest can have a high cover and little variability in tree size, usually resulting in a canopy that is a densely packed monolayer. The size and number of small gaps in these forests may be an indicator of the direction and speed of their development (Spies et al., 1990); such features should be observable with scanning lidar. In contrast to young stands, distinguishing characteristics of old-growth forests include the presence of large live trees, high diversity of diameters, relatively high species richness, as well as the presence of large standing snags and fallen logs. In the vertical dimension, the high diversity of tree heights and the presence of multiple canopy layers, or more specifically the continuous distribution of foliar surfaces from the top of the crown to near the ground, are key physical features of old-growth forests that separates them from the simpler canopies of younger stands (Franklin et al., 1981). These physical characteristics are a cause of the unique compositional and functional attributes of old-growth forests and provide a reliable means of discriminating between young, mature (an intermediate stage of development), and old-growth conditions (Spies and Franklin, 1991). These characteristics should have a measurable effect on the vertical distribution of the forest canopy. At a minimum, we should be able to distinguish young, mature, and old-growth stands on the basis of their physical structure. It would be desirable to relate continuous measurements of canopy structure to the key aspects of stand structure that distinguish these three age-classes.

Field Description of Canopies

The simplest approach to the description of canopy structure is measurement of the aggregate properties of the entire volume of the canopy, from ground level to the upper canopy surface, over some horizontal area.

Methods relying on measurements of the upper canopy surface will be referred to here as canopy surface height methods. The vertical extent of the canopy is height, usually measured either as the maximum stand height or the mean height of dominant and codominant trees; that is, those trees that are not overtopped and whose crowns are not immediately shaded by adjacent trees. Height can be an excellent predictor of the total mass of vegetation present in a stand (Lefsky, 1997; Lefsky et al., 1999; Means et al., 1999). Although the mean height of the upper canopy surface is a useful canopy description, it is not necessarily the most relevant variable for describing canopy function or structure. From a functional perspective, the variability of canopy heights strongly influences the average distance between the interior of the forest canopy and its outer surface, which strongly influences environmental conditions such as available photosynthetically active radiation (PAR) and humidity (Parker, 1995). From a structural perspective, differences in the average height of dominant and codominant trees in mature and old-growth Douglas-fir stands are small [<6 m, data from Spies and Franklin (1991) for stands in the vicinity of the H.J. Andrews Experimental Forest]; it is the greater variability of tree diameter and height that is most characteristic of old-growth forests.

The most common measurements of the horizontal extent of the canopy are percent cover (%), defined as the fraction of sky obscured by vegetation, and leaf area index ($\text{m}^2 \text{m}^{-2}$), defined as the ratio of the one-sided or, as in this article, the all-sided surface area of leaves to the projected ground area. Light gaps are perhaps the most significant component of horizontal variability. Light gaps are holes in the canopy which extend from the outer canopy surface into the interior of canopy, often to the forest floor (Watt, 1947; Canham et al., 1990; Spies et al., 1990). Both the temporal and spatial distribution of gaps vary within and between landscapes, directly affecting the composition and structure of forests. Gaps are significant because light and space resources are more available in gaps than in the surrounding forest. In the Pacific Northwest, where trees are relatively tall and narrow (<12 m in crown width but up to 85 m tall), the existence of a gap created by the death of a single tree does not alter the light environment as much as it does in forests with broader, shorter trees (Canham et al., 1990). Nevertheless, light environment and gap distribution have been found to be positively associated in an old-growth Douglas-fir/western hemlock forest (Parker, 1997).

Gaps can be considered a property of the uppermost (or outer) surface of the canopy, which has been mapped in several studies (Leonard and Federer, 1973; Ford, 1976, Miller and Lin, 1985). Few studies have quantified the importance of micro-scale gaps within the forest canopy (Spies and Franklin, 1989) as an influence on forest composition and structure. The outer surface of the can-

opy can be very regular, for instance, in plantations, or can have complex topography, with emergent crowns, canyons between adjacent crowns, and deep gaps. Complex canopy surfaces are generally characteristic of older stands. In such stands the surface area of the canopy can be greater than the ground surface below (Ford, 1976; Miller and Lin, 1985; Parker et al., 1992). The canopy hypsograph is a potentially useful tool for understanding the three-dimensional aspects of the canopy's upper surface. Hypsometry is a technique for relating the distribution of surface area to elevation originally developed for use in geomorphology (Strahler, 1952), but recently adapted to the study of canopy structure (Leonard and Federer, 1973; Parker, 1993). The canopy hypsograph is a plot of the proportion of the canopy surface that is above a given elevation, for all elevations from the forest floor to the highest point of the upper canopy.

The vertical distribution of material within the canopy may be measured as the foliage height profile (MacArthur and Horn, 1969), recently adapted for use with lidar remote sensing as the canopy height profile (Lefsky, 1997). Analysis of these profiles has focused on qualitative changes in canopy structure as a result of stand dynamics (Aber, 1979; Parker et al., 1989). One quantitative approach (Parker et al., 1989; Lefsky et al., 1999) calculates a height profile weighted mean height. Two studies (Aber et al., 1982; Lefsky, 1997) have tabulated the amount of foliage in each profile by height interval, and used the resulting bins as independent variables in multivariate statistical analysis of stand structure attributes. The vertical position of individual stems can also be estimated qualitatively using crown position (dominant, codominant, midstory, etc.).

A simple but useful system for canopy description involves the use of the binary presence or absence of layers of canopy material to characterize both the horizontal and vertical distribution of the canopy. Parker (1995) divided the canopy into three vertical strata and measured the presence or absence of foliage in each layer in a 3-ha stem-mapped plot located in southwestern Virginia, United States. He then calculated the relative abundance of each of the eight possible states of the three canopy layers. The classical vegetation gap, with foliage missing from all three strata was rare, accounting for 2.9% of the site, while 22.9% of the forest had foliage missing from two of the three layers. A more complex, but qualitative, system for recording canopy structure is the canopy profile diagram (CPD), a technique pioneered by Davis and Richards (1933) for use in tropical forests. These diagrams are based on detailed measurement of the position and dimensions of all crowns within a narrow transect (10–20 m wide), projected onto both a side and top view of the canopy. Canopy profile diagrams have been used primarily in documenting the canopy structure of various cover types and age classes in both tropical and temperate forests (Richards, 1983; Kuiper, 1988).

Lidar Remote Sensing

Lidar is an established active remote sensing technology used to obtain accurate high resolution measurements of surface elevations from airborne and Space Shuttle platforms (Krabill et al., 1984; Bufton et al., 1991). The first generation lidar sensors for vegetation studies were designed to record the distance to the first reflective surface intercepted by a laser pulse over a relatively small sampling area, or footprint, usually less than 1 m in diameter (Schreier et al., 1984; Arp et al., 1982; Ritchie et al., 1992; Weltz et al., 1994). The first return of energy from the top surface of a forest canopy was combined with subsequent measurements of distance to the forest floor, obtained through gaps in the forest canopy, to infer the height of dominant trees. A later, more sophisticated technique involved recording the distance to the first and last reflective surface for each footprint, giving a direct height measurement for each observation. Such techniques have proven useful for predicting canopy height, timber volume, and forest biomass (Maclean and Krabill, 1986; Nelson 1988, 1997, 1998; Naesset, 1997), percent canopy cover (Ritchie et al., 1993; Weltz et al., 1994), and aerodynamic roughness length (Menenti and Krabill, 1986). However, the relatively small geographic area covered in these data sets, challenges in analyzing the data, and the lack of standardized methods for their geolocation have limited the use of conventional lidar sensors within the ecological community.

A new generation of lidar instruments developed at NASA's Goddard Space Flight Center (Blair et al., 1994; Harding et al., 1994; Dubayah et al., 1997) and similar instruments developed elsewhere (Aldred and Bonnor, 1985; Hyypa and Hallikainen, 1996; Nilsson, 1996) have alleviated these barriers to a wider application of the technology (Weishampel et al., 1996). Whereas earlier devices used a small footprint and most often measured the distance to the first reflective surface, the newer devices, termed scanning lidars, send out a laser pulse over an approximately 5–25 m diameter footprint, and record the timing and power of backscattered light over the full height profile (Harding et al., 1994). By recording the time-varying power, rather than the distance to a single height, information from beneath the tallest canopy surface is obtained. Although the power of the return signal falls off as the signal is intercepted by canopy surfaces, an identifiable return of energy from the ground is recorded in nearly all footprints, which allows an estimate of the total height of the stand, and indicates that some energy is available for the detection of understory foliage. Using an algorithm developed by Drs. D. Harding and M. Lefsky for use with the SLICER scanning lidar instrument (Lefsky, 1997), the lidar waveform can be transformed to estimate the bulk canopy transmittance and the vertical distribution of reflective canopy surfaces. Two recent studies have demonstrated that these new li-

dar devices can make accurate measurements of stand height, aboveground biomass, and basal area in deciduous forests of the eastern United States (Lefsky et al., 1999) and Douglas-fir/western hemlock forests in the Pacific Northwest (Means et al., 1999). In both of these studies, one-dimensional measurements of average height were used to predict variables such as aboveground biomass. The capability of lidar to characterize the full three-dimensional aspects of canopy structure has not been addressed previously.

OBJECTIVES

Existing methods of ground-based canopy description were designed so that they could be rapidly measured in the field. As a result, they characterize a subset of the total complexity of three-dimensional canopy structure. Existing remote sensing methods can rapidly collect information over a wide area, but until now have lacked detailed information on the canopy's three-dimensional distribution. With the availability of scanning lidar sensors, we have an instrument that can rapidly measure the total three-dimensional distribution of vegetation canopies over broad geographical areas. New systems of canopy description are necessary to describe and visualize the data from these new instruments. Our objectives were:

1. Measure the canopy structure of closed-canopy Douglas-fir/western hemlock forests using the SLICER surface lidar system and interpret the resulting data using two established canopy structure description techniques, the canopy height profile, and canopy surface height methods.
2. Develop a novel technique to characterize the three-dimensional aspects of canopy structure.
3. Relate attributes of all three systems of description (two established, one novel) to field-based measurements of forest stand structure and composition.

METHODS

SLICER Data Collection

Lidar waveforms were collected by the SLICER (Scanning Lidar Imager of Canopies by Echo Recovery) instrument in September 1995. SLICER is a modified scanning version of a profiling laser altimeter developed at Goddard Space Flight Center (Blair et al., 1994). The SLICER system digitizes the entire height-varying return laser power signal, resulting in a waveform that records the reflection of light from multiple canopy elements (foliage and woody structure) over a large (5–25 m diameter) footprint, at the wavelength of the transmitted pulse (1064 nm). The lidar waveforms used in this work were collected with a nominal footprint diameter of 10 m, taken in a 5 footprint swath. Georeferencing of lidar

footprints is accomplished by combining laser ranging data with aircraft position, obtained via kinematic GPS methods, and laser pointing, obtained with a laser-ring gyro Inertial Navigation System mounted on the SLICER instrument (Blair et al., 1994). Georeferencing of the SLICER data used in this study was done at Goddard Space Flight Center using software developed by J. Bryan Blair. During the period in which these measurements were taken, the vertical resolution of the waveforms collected by SLICER was set at 11 cm, which when combined with the 600-sample-wide waveform, limited the waveform to a maximum height of 66 m. Due to additional constraints in the waveform processing software, all waveforms greater than 63 m have been truncated to 63 m. Examination of the lidar and associated field data suggests that the truncation problem affects about 3% of the waveforms used in these analyses. Ground returns on several footprints of old-growth plots had to be set by hand due to loss of the ground return as a consequence of the truncation error. Ground return positions were set based on the characteristics of adjacent footprints and independent estimates of topography (Means et al., 1999).

Study Area and Field Measurements

Field data used in this study were collected in and near the H.J. Andrews Experimental Forest, located on the west slope of the Cascade Range in Oregon (Van Cleve and Martin, 1991). Twenty-six 0.25-ha field plots were established under existing SLICER transects; each plot was associated with a 5×5 array of SLICER waveforms. For this analysis, 22 plots representing young, mature, and old-growth forest were used; sites dominated by herbaceous and shrub vegetation were excluded. Stands were classed as young, mature, or old-growth, based on stand age and condition information from the Willamette National Forest and a classified TM image (Cohen et al., 1995). For these analyses the young class was split into two subsets, young stands under 20 m in height (very young), and young stands greater than 20 m (young). Although these last two classes are based on a structural attribute (height), the four classes will be referred to here as age-classes.

In each stand the slope angle was determined and a 50×50 m plot was laid out with dimensions corrected for slope angle. The intensity of field sampling was a function of the type of stand sampled. On old-growth plots all trees greater than 1.37 m tall were measured. On other plots where density of trees was high, all trees greater than 1.37 m tall were measured on selected subplots. Initially, tree diameters were measured on three or five subplots. The field crew then estimated the number of additional subplots needed to include at least 30 dominant and codominant trees and measured trees on 5, 9, or 13 subplots, regularly spaced to cover the full

extent of the plot. In each subplot, for all trees greater than 1.37 m in height, species, diameter at breast height (1.37 m DBH) and crown ratio (the proportion of the bole with live crown) was recorded. Total aboveground biomass was estimated from DBH using allometric equations (Means et al., 1994).

LAI of trees was estimated from allometric equations on sapwood cross-sectional area, except for small conifers and the relatively few hardwoods. Methods for the calculation of LAI follow those in Means et al. (1999) for the prediction of leaf biomass, but omitting the transformation from LAI to leaf biomass. In addition, the estimates were corrected for the degree to which the cross-sections of conifer needles deviate from planar, and the percent of leaf mass in petioles for hardwoods species (Gholz et al., 1976). To predict LAI for conifers, we first regressed sapwood cross-sectional area for cored trees on DBH separately for each of the common species, and used these equations to estimate sapwood cross-sectional area for all trees. We then calculated tree leaf area using published sapwood area to leaf area ratios (Waring et al., 1982). For western redcedar it was necessary to compute a mean leaf biomass: sapwood area ratio using a published data set of sapwood thickness and DBH and a published allometric model of leaf biomass as a function of DBH [see Means et al. (1999) for details]. Leaf biomass was then converted to LAI using a value of specific leaf area determined using data from six of our field plots. For small conifers we used published equations to estimate leaf biomass from allometric equations on DBH (Gholz et al., 1976; Helgerson et al., 1988), and converted leaf biomass to total leaf area using published values of specific leaf area for most species (Gholz et al., 1976); and the specific leaf area value from our data for western red cedar. For the relatively few hardwood trees, we used published, species-specific, allometric equations to predict leaf biomass from DBH (Gholz et al., 1976; Helgerson et al., 1988). We converted leaf biomass to total leaf area using published values of specific leaf area for the species or a closely related species (Gholz et al., 1979; Burton et al., 1991; Eschaback and Kappen, 1996).

Mean values for nine stand structure attributes, tabulated using four age classes, are presented in Table 1. Douglas-fir is the dominant species in these stands, contributing between 90% of all basal area in very young stands, and 64% in old-growth stands. Western hemlock is the second most important species, and occurs mostly in later succession, contributing 29% of total basal area in old-growth stands. Other variables distinguishing younger and old-growth age-classes included the number of shade-tolerant stems greater than 40 cm DBH, mean and standard deviation of DBH, and the number of stems greater than 100 cm DBH. The maximum values obtained for these attributes (i.e., biomass of 1329 Mg

Table 1. Mean values for Plot Attributes, from Field Data, by Age-Class

Variable	Very Young n=4	Young n=5	Mature n=4	Old-Growth n=9
1. Total above-ground biomass (Mg ha ⁻¹)	157.0	224.6	551.0	965.2
2. Total basal area (m ² ha ⁻¹)	16.2	33.7	61.4	91.6
3. PSME basal area (m ² ha ⁻¹)	21.4	26.4	57.0	59.6
4. TSHE basal area (m ² ha ⁻¹)	1.1	2.8	3.5	24.7
5. Shade tolerant stems greater than 40 cm (ha ⁻¹)	0.0	7.8	1.0	76.4
6. Mean DBH (cm)	10.1	11.1	36.7	28.6
7. Standard deviation of DBH (cm)	9.4	8.6	18.9	31.9
8. Stems greater than 100 cm (ha ⁻¹)	0.0	0.0	0.0	33.3
9. LAI (m ² m ⁻²)	5.1	6.7	7.9	9.1

ha⁻¹, LAI of 12.1 m² m⁻², basal area of 132 m² ha⁻¹) approach the highest recorded for Douglas-fir forests.

SLICER Data Analysis

Three approaches were employed for the description of canopy structure, each implemented using data from the SLICER instrument. Data for these analyses were taken from the 5×5 array of waveforms associated with each field plot. The most basic method, the canopy surface height measurements, only used the instrument's height measuring capability. A second set of measurements were made by transforming the raw waveform data into an estimate of the vertical distribution of the canopy—the canopy height profile (CHP). A third set of measurements was derived from a novel system for the measurement of canopy structure, the canopy volume method (CVM), which summarizes the total volume and spatial organization of filled and empty space within the canopy. Figure 1 provides a conceptual comparison of the results of each method, compared with a canopy profile diagram from Spies et al. (1990). For all methods ANOVA tests, using Scheffé's method of *post hoc* analysis, were used to test whether indices describing canopy structure varied significantly between age-classes.

Existing Methods for the Description of Forest Canopies {Objective 1}

Canopy surface height measurements: These are the simplest class of measurements, which use only the height measurement capability of the sensor. The height of each waveform in the 5×5 array of waveforms associated with each field plot was measured as the vertical distance between the elevation of the first return energy and the average elevation of the ground return. The elevation of the first return energy is the point at which the power of the reflected light exceeds a threshold value; passing this threshold triggers the sensor's waveform recording process. By comparing the total number of digitizer counts of the return energy in an average waveform to the total surface area over which a waveform is collected, we estimate that less than 1 m² is needed to cause the digitizer to exceed the threshold value. The position of

the mean ground return is calculated as the height at which the peak of the ground return is found by the IMH (interactive MacArthur–Horn) waveform processing software (Lefsky, 1997).

Canopy surface height data were summarized by five indices. Four indices of height have been calculated directly from the 5×5 array of waveforms, including 1) maximum height (calculated as the maximum of the heights of the 25 waveforms), 2) the number of waveforms whose height exceeded 55 m, 3) mean height (calculated as the mean of the heights of the 25 waveforms), and 4) the range of canopy surface heights. The range of canopy surface heights was calculated as the difference between the maximum and minimum of the 25 canopy surface heights. An equation from (Means et al., 1999) was used to predict the mean height of dominant and codominant trees (5) from the mean canopy surface height. Canopy surface heights were also summarized graphically as canopy surface hypsographs. In Figure 1B the *y*-axis is the height above the ground elevation, while the *x*-axis is the fraction of the 5×5 block of waveforms (and therefore the canopy surface measured at the resolution of the waveform footprint) taller than the corresponding height on the *y*-axis. In this work, average hypsographs have been calculated and presented, along with error bars. Average hypsographs (and associated errors) were calculated by first ranking the 25 height measurements associated with each plot. To create average hypsographs, all of the height measurements with the same rank from each plot were averaged, for each rank from tallest to smallest.

Canopy height profile measurements: The second approach to canopy structure description is based on the CHP which is a modification of the foliage height profile or FHP (MacArthur and Horn, 1969). The FHP quantifies the distribution of foliage surface area as a function of height. Because SLICER cannot distinguish woody surface area from foliage surface area, we define the CHP as the distribution of both foliar and woody surface area as a function of height (Fig. 1C). While some investigators have measured the FHP directly, through stratified clipping (Fujimori, 1971) or point quadrat tech-

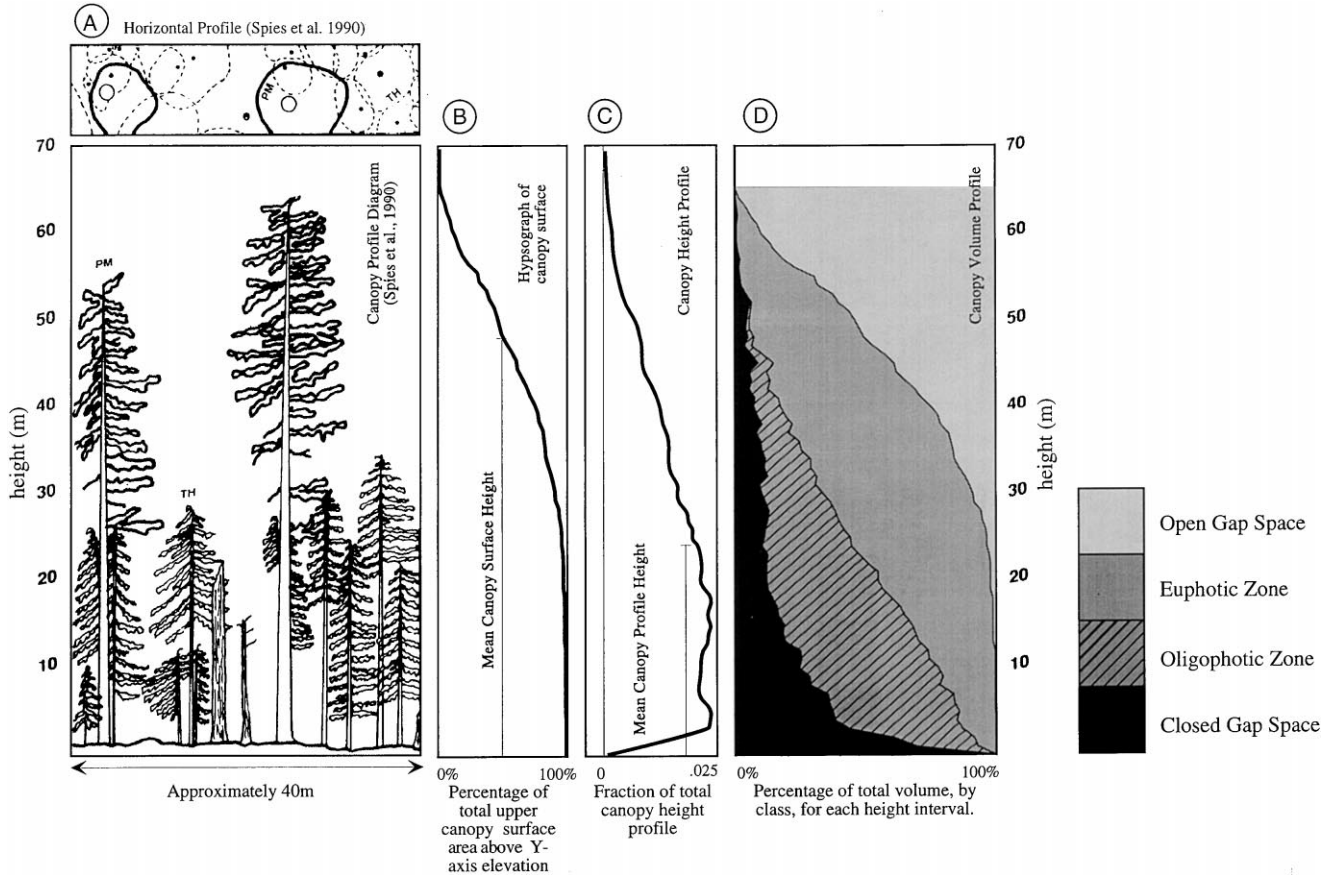


Figure 1. Conceptual comparison of three canopy description methods. Figures 1A is a canopy profile diagram prepared by Spies et al. (1990) after the methods of Davis and Richards (1933). Figure 1B is a canopy surface hypsograph, showing the vertical distribution of the upper canopy surface. Figure 1C is a canopy height profile, showing the relative vertical distribution of foliage. Figure 1D is a canopy volume profile, showing the vertical distribution of four classes of canopy structure.

niques (Warren-Wilson, 1958; 1965; Miller, 1967; Ford and Newbold, 1971), these methods have largely been supplanted for cross-site comparisons by MacArthur and Horn's (1969) method. Using their method for measuring the FHP, optical point quadrats are established and multiple observations of vertical distance to first leaf intersection are made using a camera equipped with a fixed-focal length telephoto lens. This distribution is used to estimate the cumulative percent cover of foliage as a function of height. These estimates of cover are transformed into the vertical distribution of foliage using a method that assumes that leaf angle remains constant with height and that the horizontal distribution of leaves is random. Given these assumptions, an equation [Eq. (1)] derived from the Poisson distribution can be used to relate percent cover to the amount of foliage:

$$\text{FHP}_c(h) = -\ln(1 - \text{cover}(h)), \quad (1)$$

where $\text{FHP}_c(h)$ is the cumulative one-sided leaf surface area (or LAI) expressed as a fraction of projected ground area above height h , and $\text{cover}(h)$ is the fraction of sky obscured by foliage above height h . The FHP is calculated from $\text{FHP}_c(h)$ by calculating the increment of LAI

at each height interval, with respect to that below it. The theory behind the original application of this technique is found in MacArthur and Horn (1969), and a validation of the method is presented in Aber (1978). Aber concluded that this method provides a simple and accurate method for measuring the relative canopy height profile in an eastern deciduous forest, but not its total LAI. The FHP can be calculated as relative (with the total vector scaled to sum to 1), or absolute (with the total vector scaled to sum to the total leaf or plant area index of the canopy). In this work relative canopy height profiles are used exclusively.

We used the SLICER system and IMH processing software to characterize the CHP, using methods that have been validated for an eastern deciduous forest (Lefsky, 1997). We hypothesized that the power of the back-scattered laser illumination is subject to the same process of occlusion observed in the field measurements of height to first intersection, and modified the MacArthur-Horn method to apply this approach to the SLICER return energy waveforms. After removing background noise created by the sensor's digitizer, the critical step in

the modification of the MacArthur–Horn routine was the separation of the portion of the waveform returned from the ground surface (the “ground return”) from the balance of the waveform. The ratio of the power of the ground return to the total signal power is inversely proportional to the total canopy cover, but, to estimate canopy cover, the ratio must be adjusted to account for differences in ground and canopy reflectance at 1064 nm. The total horizontal canopy cover at each height increment can then be calculated, which allows the use of the MacArthur–Horn equation. In Lefsky (1997) the processing routine that implements this algorithm was tested using coincident CHPs measured with the field-based optical-quadrat and remotely sensed SLICER methods at four dissimilar deciduous stands at the Smithsonian Environmental Research Station, located near Annapolis, Maryland, USA. A two-sample, uneven sample size, Chi-square goodness-of-fit analysis was performed to determine if there were statistically significant differences between field and SLICER-derived CHPs. The CHPs measured in the field and from SLICER were statistically indistinguishable, when the CHPs were smoothed to account for differences in the vertical resolution of the two methods. While the canopy height profile measurements have not yet been rigorously validated in a coniferous forest, mean canopy height profiles from the SLICER system have been compared to profiles inferred from a mean PAR transmittance profile measured by G. G. Parker at the H.J. Andrews Experimental Forest (Parker, 1997). These profiles matched very well at a coarse grain, but the transmittance-based profile shows more small scale variability than the SLICER-based estimate. This was expected, as the field observations are averaged over a much smaller area than the SLICER data set. Estimates of canopy cover made with the SLICER instrument have been shown to be highly correlated with field measured canopy cover for this data set ($r^2=0.94$; Means et al., 1999).

For this study, two measurements of the average height of the CHPs were calculated, the mean canopy height and the quadratic mean canopy height (Lefsky, 1997). The mean canopy height is measured as the mean of the canopy height profile weighted by the height of each element. The quadratic mean canopy height is measured as the mean of the canopy height profile weighted by the squared height of each element, and has been shown to be valuable in the prediction of stand characteristics in an eastern deciduous forest (Lefsky, 1997). These two variables differ from those calculated using the canopy surface height method, because they reflect the average height of all canopy surfaces, foliar and woody, not the total height of the canopy. Aerial cover of each field plot was calculated as Eq. (2):

$$Cover = 1 - \frac{K * GroundReturn}{CanopyReturn + K * GroundReturn} \quad (2)$$

where the ground and canopy returns are the total power reflected from the ground and canopy, respectively. The ground return power of the waveform is multiplied by K to account for differences in the albedo of ground and foliage (about a twofold difference) so K was set to 2.0. Values of these indices for the 25 canopy height profiles associated with each plot were averaged to obtain each single plot-level measurement.

A Novel Method for the Description of Forest Canopies {Objective 2}

In addition to the established techniques described above, we developed a novel technique, the CVM, to describe the three-dimensional geometry of forest canopies. This method is explicitly volumetric as it uses a 5×5 grid of contiguous lidar waveforms to characterize the forest canopy as a three dimensional matrix. The conceptual basis for the CVM is illustrated in Figure 2, and Figure 3 shows the results of each step of processing for 25 waveforms associated with an old-growth plot, as an example. The cells of the matrix are 10 m in diameter and 1 m tall: They correspond to a 1 m vertical bin within a single waveform. Each waveform is processed to remove background noise created during the sensor’s digitizing process and the ground return (as in the CHP methods), and then classified using two rules. A threshold value is used to classify each element of the waveform into either “filled” or “empty” volume, depending on the presence or absence (in the waveform) of returned energy (Fig. 2A). A second step classifies the filled elements of the array into an “euphotic” zone, which contains all filled elements of the profile that are within the uppermost 65% of total energy returned from the canopy, and an “oligophotic” zone, consisting of the balance of the filled elements of the profile (Fig. 2B). The terms “euphotic” and “oligophotic” were suggested by Richards (1983), to refer to the zone in the canopy which intercepts the bulk of available light (euphotic) and the zone beneath it. The 65% threshold value is derived from a theoretical expectation for the fraction of energy returned from the first unit of leaf area index (LAI), assuming an extinction coefficient of 1.

The first two classifications (filled vs. empty, euphotic vs. oligophotic) are then combined to form three canopy structure classes: empty volume within the canopy (i.e., closed gap space), filled volume within the euphotic zone (i.e., euphotic zone), and filled volume within the oligophotic zone (i.e., oligophotic zone) (Fig. 2C). These classes are then computed for each of the 25 SLICER waveforms in a 5×5 array. The waveforms are then compared, and a fourth class is added; “open” gap volume is defined as the empty space between the top of each of the waveforms and the maximum height in the array (Fig. 2D). At this point, the total volume of each of the four canopy classes can be tabulated for the 5×5 array of waveforms associated with each plot.

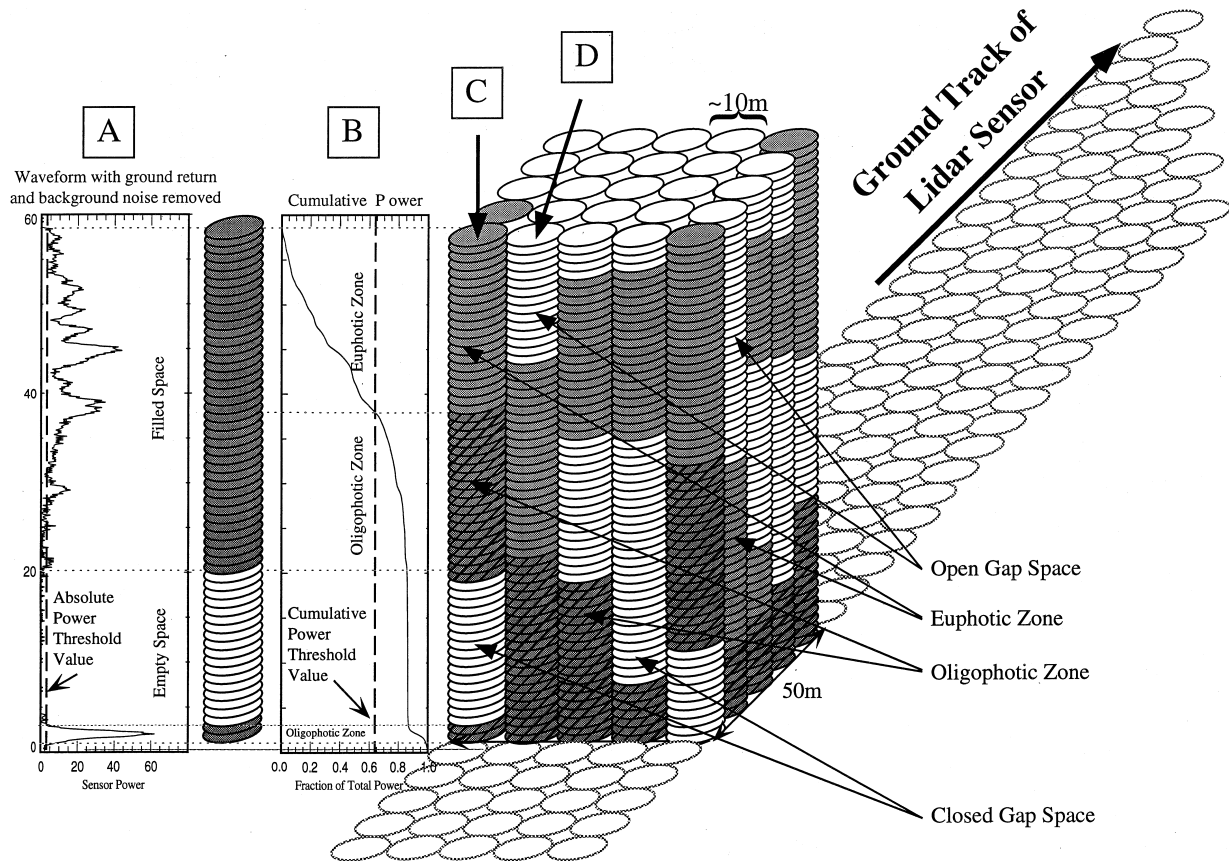


Figure 2. Conceptual basis for the CVM. The cells of the matrix in Figure 2 are 10 m in diameter and 1 m tall: They correspond to a 1 m vertical bin within a single waveform. Each waveform is processed to remove background noise (Fig. 2A), and a threshold value is used to classify each element of the waveform into either “filled” or “empty” volume. The cumulative top-down distribution of the waveform (Fig. 2B) is used to classify filled elements of the matrix into an “euphotic” zone, which returns the majority of energy back to the sensor, and an “oligophotic” zone, consisting of the balance of the profile. These two classifications are then combined to form three canopy structure classes: empty volume within the canopy (i.e., closed gap space), the euphotic zone, and the oligophotic zone (Fig. 2C). “Open gap” volume is then defined as the empty space between the top of each of the waveforms and the maximum height in the array (Fig. 2D). See text for details.

Three unit designations for these tabulations are possible. The first is the volume of each class per plot (m^3 per plot). The second is the volume of each class per unit area ($\text{m}^3 \text{m}^{-2}$), dividing the total volume by the plot area. The third approach visualizes the volume of each class as they would be if the individual elements of the waveform of that class were rearranged into a single layer of uniform depth. In this way, the algebraic simplification of $\text{m}^3 \text{m}^{-2}$ to m^1 can be more easily understood. The resulting height is numerically identical to the volume of each class per unit area. The last two designations are adopted in this work. When referring to the total quantity of a canopy structure class, it is natural to speak of the volume of each class. However, when referring to the physical dimensions of the same canopy structure, it is natural to refer to its height or depth. Because the numeric values are the same, the volume and either height or depth designations can be used interchangeably.

Figure 3 more fully illustrates the steps involved in

these calculations, and the development of the canopy volume profile. In panel A the 25 waveforms from field plot 8 are shown, in random order, with only the presence or absence of foliage indicated by dark and light shading (respectively). In panel B, empty spaces have been divided into those areas below foliage (closed gap space), and those that are above the top of the canopy for that waveform (open gap space). Panel C shows the separation of filled spaces into those near the top of the canopy and those further down in the canopy (euphotic and oligophotic zones). The final step (Fig. 3D) is the tabulation of the volume of each forest structure class as a function of height, resulting in the canopy volume profile (CVP). It should be noted that the canopy volume profile is just one possible technique for visualizing the results of the more general canopy volume method.

Two things should be considered when interpreting canopy volume profiles. First, they are derived from binary presence and absence (of return energy from can-

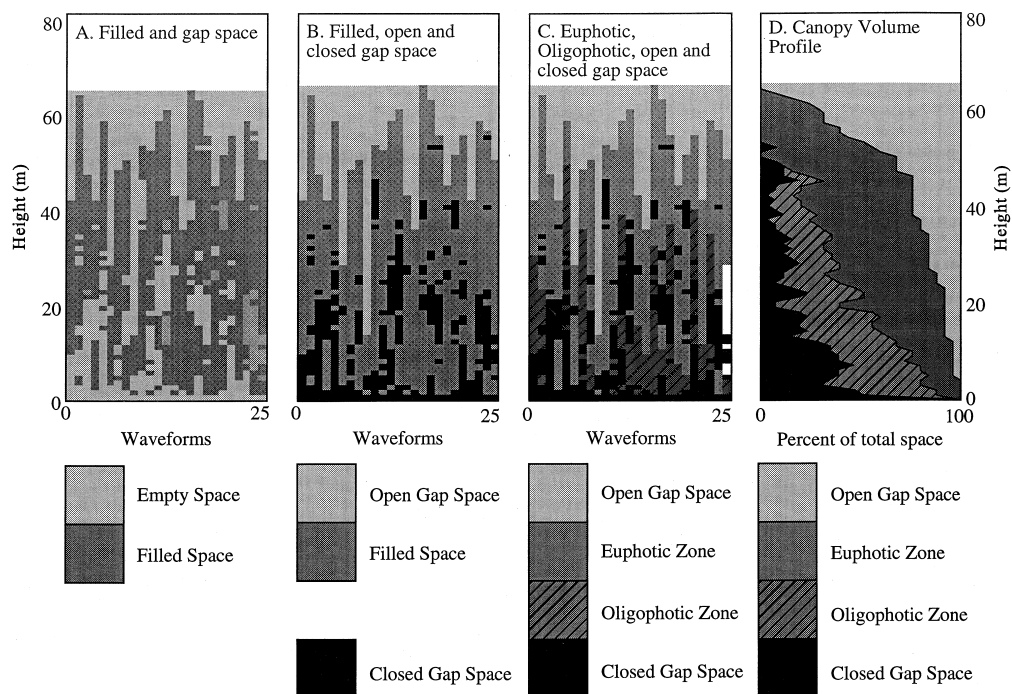


Figure 3. Example results of individual steps in the calculation of the canopy volume method and profile. See text for details.

opy structure) data for discrete elements in the array of waveforms. As a result, a larger volume of filled space is *not* necessarily indicative of a greater leaf area index (although, as we will show, on average it is); for example, a given leaf area could be distributed in a larger total volume, and would therefore be at a lower density. Second, the total volume of canopy structure classes at each height is calculated independently and presented, for each height interval, in the same order (from left to right): closed gap, oligophotic zone, euphotic zone, and open gap space. As a result, there is no information about the spatial covariance of classes along both the horizontal and vertical planes in this diagram. The order of presentation reflects the typical rank of each canopy structure type in the vertical axis. It is tempting, for instance, to view the entire volume of euphotic zone as a continuous space. However, it is not necessarily true that, within the 5×5 array of SLICER waveforms, the highest elevation of the oligophotic zone occurs beneath the highest elevation of the euphotic zone (although we might expect both values to positively covary).

Along with the four basic canopy structure classes (euphotic zone, oligophotic zone, open gap space, closed gap space), some useful combinations of these basic types can be defined. Some of these combinations overlap with those defined earlier as canopy surface height measurements. When such an overlap exists, the index will be treated as a canopy surface height variable. The total height of all four canopy volume classes is equivalent to the maximum stand height, and the sum of the

heights of the euphotic and oligophotic zones and the closed gap space is equivalent to the mean height of the canopy surface. This can be visualized as if the individual elements of the waveform of each class were rearranged into single layers of uniform depth. Filled canopy volume is equal to the total volume of euphotic and oligophotic zones and represents the total volume of "filled" canopy. It has no commonly used equivalent. Maximum and mean canopy surface height will be treated in this work as canopy surface height measurements, while filled canopy volume will be treated as a canopy volume measurement. Canopy volumes are also calculated as percentages of maximum height. Leaf area density (LAD) is calculated as the LAI of each plot, as derived from the field data, divided by the filled canopy volume. Finally, the average number of each of the four canopy structure classes (open and closed gaps, oligophotic and euphotic zones) occurring at each height was calculated for each plot, to measure the degree of the classes' vertical interspersions.

Predictions of Stand Structure {Objective 3}

To assess the ability of the canopy structure indices to predict ground based measures of stand structure, stepwise multiple regressions were performed. The three classes of canopy structure measurements (canopy surface height, canopy height profile, and canopy volume method) contain a total of twenty canopy structure indices (Table 2A, 1–20). Eleven of these indices were used as independent variables in stepwise multiple regres-

Table 2A. Mean Values for Canopy Structure Indices, by Age-Class

Variable	Very Young n=4	Young n=5	Mature n=4	Old-Growth n=9
Canopy surface height measurements				
1.° Maximum height (m)	14.0	25.6	51.3	61.2
2.° Number of waveforms >55 m tall (#)	0.0	0.0	1.5	6.7
3.° Mean canopy surface height (m)	13.1	22.0	39.9	46.6
4.° Canopy surface range (m)	4.3	12.4	26.5	39.2
5.° Mean height of dominant and codominant trees (m)	14.4	20.4	36.5	42.7
CHP measurements				
6.° Mean canopy profile height (m)	6.0	10.1	24.5	22.7
7.° Quadratic mean canopy height (m)	6.9	11.3	26.8	26.6
8.° SLICER predicted cover (%)	53	63	75	77
CVM measurements				
9. Euphotic zone volume (m ³ m ⁻²)	10.3	13.4	19.4	23.2
10. Oligophotic zone volume (m ³ m ⁻²)	1.3	5.5	12.4	14.3
11.° Open gap volume (m ³ m ⁻²)	1.8	5.2	10.8	15.0
12.° Closed gap volume (m ³ m ⁻²)	1.5	2.5	9.7	9.8
13.° Filled canopy volume (m ³ m ⁻²)	11.7	18.9	31.8	37.5
14.° Canopy classes per unit height (#)	1.6	1.8	2.4	3.0
15. LAD (m ² m ⁻³)	0.445	0.352	0.249	0.243
CVM heights as a percentage of maximum height				
16. Euphotic zone volume (%)	70	51	38	37
17. Oligophotic zone volume (%)	10	20	24	23
18. Open gap volume (%)	8	19	21	24
19. Closed gap volume (%)	8	9	17	16
20. Filled canopy volume (%)	80	71	62	60

° Indicates variables used in stepwise multiple regression analysis.

sions, as indicated by the presence of an asterisk next to the variables name in Table 2A. Euphotic and oligophotic zone volumes are not considered as independent variables separately, but are considered together as filled canopy volume. The mean height of the dominant and codominant trees was not considered, because it is predicted directly from mean canopy surface height, which is considered. The LAD was not considered, as it is derived from a field measurement. The percent volumes of each of the four classes of canopy volume also were not

considered as independent variables, as the total volumes of each class, and the maximum height, were.

RESULTS

Existing Methods of Forest Canopy Description

Table 2 summarizes the values of each of the 20 canopy structure indices. Table 2A presents the average values of each index, tabulated by age-class. Tables 2B and 2C indicate whether the between age-class differences in each variable are statistically significant.

Canopy Surface Height Measurements

The value of all five canopy surface height indices (Table 2A, Entries 1–5) increase from the youngest to oldest stands, but only one—maximum height (1)—is significantly greater in the old-growth condition than in the mature condition (Table 2B). As stands increase in mean canopy surface height (3) and maximum height (1), the range of canopy surface heights in each plot (4) increases as well. This increase in the range of canopy surface heights also increases as a percentage of total height; the ratio of canopy range (4) to maximum height (1) increased from a mean of 31% (4.3 m/14 m) in very young stands, to a mean of 64% (39.2 m/61.2 m) for old-growth stands. Canopy hypsographs confirm that very young stands have a nearly uniform upper canopy surface (Fig. 4A), while the upper canopy surface of the stands in the

Table 2B. Significant Differences ($P < 0.05$): Canopy Surface Measurements and CHP Indices

	Very Young	Young	Mature
Young			
Mature	1, 3, 5, 6, 7	1, 3, 5, 6, 7	
Old-growth	1, 2, 3, 4, 5, 6, 7	1, 2, 3, 4, 5, 6, 7	1

Table 2C. Significant Differences ($P < 0.05$): Indices Derived from the Canopy Volume Method

	Very Young	Young	Mature
Young	14		
Mature	9, 10, 11, 12, 13, 14, 15	9, 10, 12, 13, 14	
Old-growth	9, 10, 11, 12, 13, 14, 15	9, 10, 11, 12, 13, 14, 15	13, 14

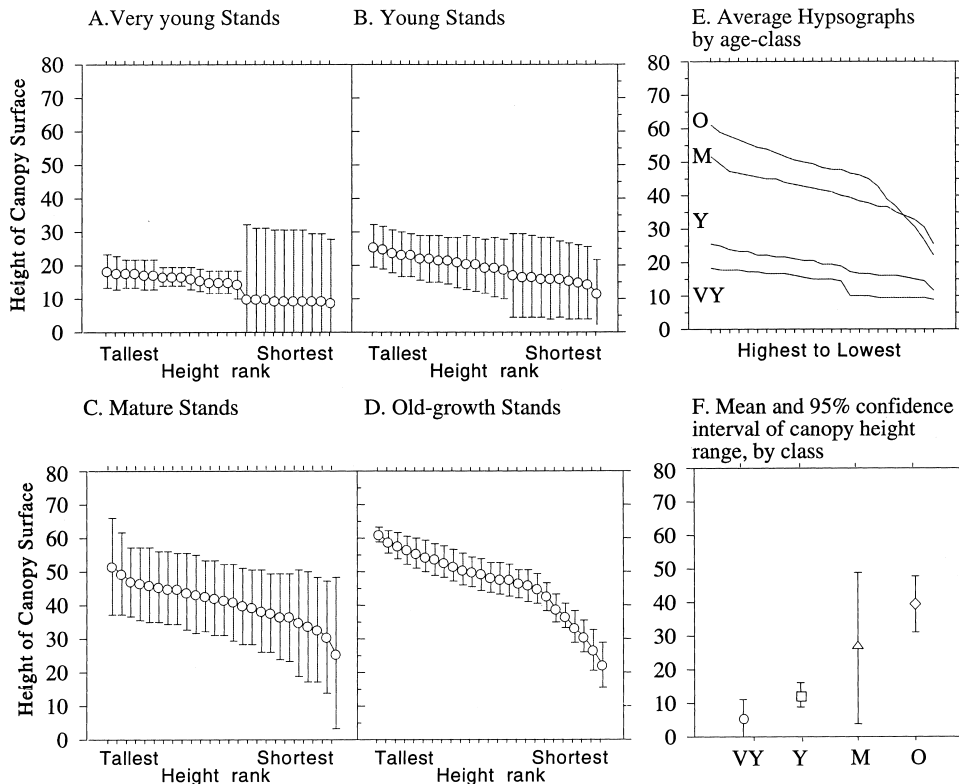


Figure 4. Mean hypsographs of canopy surface height, with standard errors shown as error bars.

other age-classes was more widely distributed (Fig. 4B–4D). Mature stands do not have a significantly greater height range (Table 2B) than the very young or young stands. However, mature and old-growth stands do have a significantly greater range than young stands when all young stands are considered a single class ($P < 0.05$). Increases in canopy range between mature and old-growth stands, averaging 26.5 m and 39.2 m, respectively (Table 2A, 4), were marginally nonsignificant ($P = 0.10$), due to the presence of one mature stand with a high range value (as indicated in Fig. 4F).

Canopy Height Profiles

Differences in the height and distribution of canopy structure were evident for each of the four age-classes. The very young stands (Fig. 5A), had a unimodal distribution of canopy surfaces that were nearly symmetrical vertically. In the young stands (Fig. 5B) the canopy height profile retains the symmetrical distribution, but the distribution is broader. Mature stands (Fig. 5C) generally have a weakly bimodal distribution of dense foliage near the upper canopy surface along with moderate density of foliage near the forest floor. The high standard deviations associated with the mature stand's canopy height profile (Fig. 5C) are due to the high diversity of maximum heights in the mature class relative to the other classes. Old-growth stands (Fig. 5D) had a more even distribution of foliage than mature stands, but had higher density of canopy surfaces near the lower half of the canopy height profile. As a consequence, the mean

and quadratic mean canopy height measurements of old-growth stands are slightly lower than those for mature stands (Table 2A, 6 and 7). Cover estimates for these stands increased as a function of age-class, but not significantly.

The Canopy Volume Method and Profiles

The CVM identified differences in the total volume (Table 2A) and spatial organization (Fig. 6) of canopy structure. Figures 6A–D show the canopy volume profile for four stands we considered typical of their age-class. On average, very young stands had 80% of their canopy volume filled (Table 2A, 20) consisting mostly of euphotic zone (Table 2A, 9 and 16). The evenness of upper canopy surface and a uniform canopy density result in a nearly level interface between the euphotic and oligophotic zones (Fig. 6A). Young stands (Fig. 6B) had a euphotic zone that was of approximately of the same depth (10 m for very young stands vs. 13.4 m for young stands, Table 2A, 9) as in the very young stands, but the average height at which it occurred rose by 10 m (Fig. 6B). This occurred because the average height of both the closed gap space and the oligophotic zone increased to a combined depth of 10.7 m (Table 2A, total of entries 10 and 11). The greater unevenness of the upper canopy surface caused open gap volume to increase from 1.8 m in very young stands, to 5.2 m (Table 2A, 11). As a result the percentage of filled volume in these stands decreased to 71%.

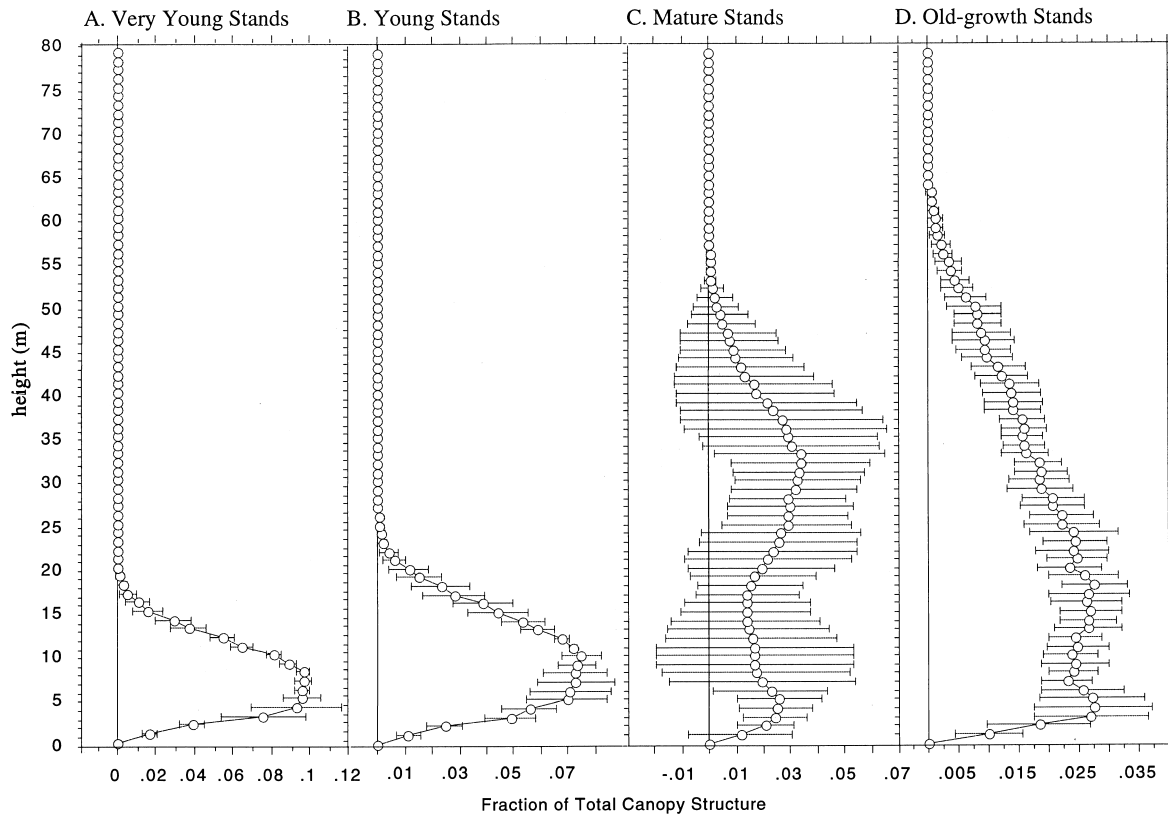


Figure 5. Mean and standard error of canopy height profiles, for all plots in each of the four age-classes.

In mature stands the average depth of the euphotic zone was 19.4 m, the average depth of the oligophotic zone increased to 12.4 m, and the volume of closed gaps in the canopy averaged 9.7 m (Table 2A, 9, 10, 12). The volumes of each of the individual canopy structure classes (Table 2A, 9–12) are greater for old-growth stands than for mature stands. Though the individual differences are not statistically significant, the total filled canopy volume is significantly greater in the old-growth stands than in the mature stands (Tables 2A and 2C, 13). The vertical distribution of the canopy structure classes changes with age-class. In young and mature stands (Figs. 6A–C), there is a horizontal arrangement of layers, while in the old-growth stands each canopy structure class occurs at nearly all heights (Fig. 6D). The average number of canopy classes per unit height index (Table 2, 14) confirms that the old-growth stands have a significantly higher number of canopy structure types at each level (Table 2A, 2C, 14). Figure 7 documents that the average density of foliage in the filled volume decreases from the young stands to the mature stands, but is essentially the same for mature and old-growth stands.

Prediction of Stand Structure from Canopy Structure Indices

The relationships developed using stepwise multiple regressions explained a large percentage of the total variance in the stand structure attributes (Table 3, Fig. 8).

The estimates of stand structure attributes made from these models, with the possible exception of shade tolerant stems greater than 40 cm and mean DBH, show no asymptotic tendency, even at very large values (Fig. 8). Of the 11 independent variables available in the stepwise multiple regression, three variables were not selected for any equation: SLICER predicted cover, canopy surface range, and the quadratic mean canopy height. The two conventional indices of canopy height were used in one equation each: maximum canopy height to predict standard deviation of DBH, and mean canopy surface height to predict Douglas-fir basal area. In comparison, the filled canopy volume variable was used as the primary variable in three equations. As far as we know, filled canopy volume has been defined only within the canopy volume method. Closed and open gap volumes were used in two and four equations, respectively, and the number of waveforms greater than 55 m was used in five. The number of canopy classes per unit height variable is used once, in the prediction of LAI.

The basal area of the main shade-intolerant (Douglas-fir) and tolerant (western hemlock) species respond similarly to maximum height; as we might expect, taller stands have higher basal area of both species (Fig. 9A). However, for those stands with a maximum height greater than 40 m tall, the basal area of Douglas-fir is negatively associated with the open gap volume, while the basal area of western hemlock is positively associated

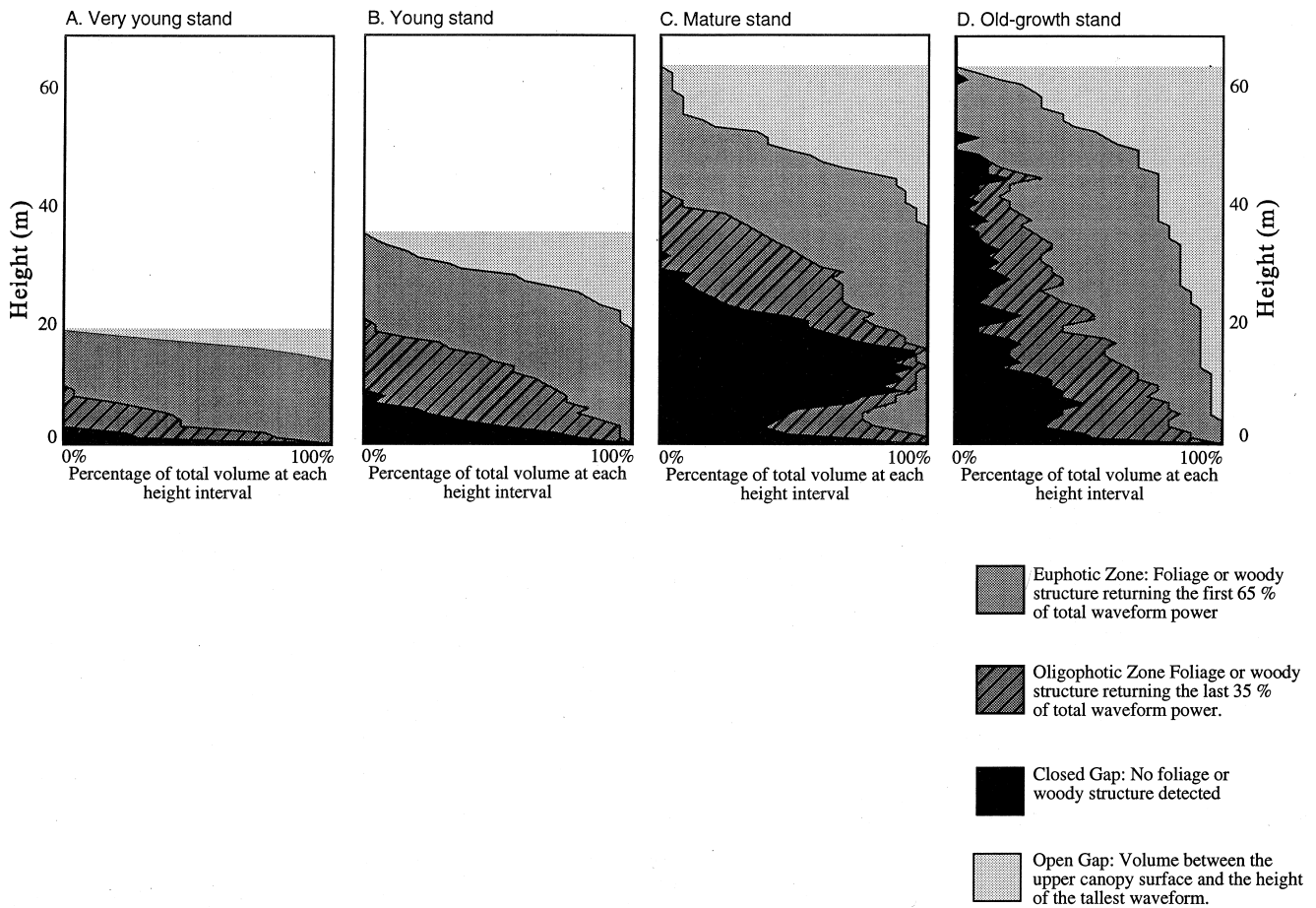


Figure 6. Typical canopy volume profiles for plots in each of the four age-classes.

with it (Fig. 9B). It is this difference between the two species that makes possible the statistically independent prediction of western hemlock basal area.

DISCUSSION

SLICER Data Analysis

Canopy Surface Height Measurements

Due to the small sample size in this study, it is useful to know how representative the sample is of surrounding

Douglas-fir/western hemlock stands. Canopy surface height measurements represent the only indices in this work that have been generally collected by other researchers, and therefore the only indices whose values can be compared to the literature. Two variables, maximum height and mean height of the dominants and co-dominants, were compared to values found in Spies and Franklin (1991) for the Oregon Cascades region. Comparison of our values to the literature was important because the maximum heights had been truncated to 63 m, due to the data collection limitation described earlier. There are numerous possible sources of disagreement between the values found in Spies and Franklin (1991) and in this study's height related estimates for three successional age-classes—young (including young and very young stands), mature, and old-growth. The first source of disagreement is the “truncation” of all waveform heights greater than 63 m (due to the instrument data collection error). A second source is differences in criteria for the selection of field sites, and a third is measurement error in the field. To estimate the importance of the truncation error, height indices for the Spies and Franklin data set were recalculated with all trees in the data set greater than 63 m tall truncated to 63 m, as in the SLICER data set. Mean height of dominant and co-

Figure 7. Mean and stand errors of LAD for plots in each of the four age-classes.

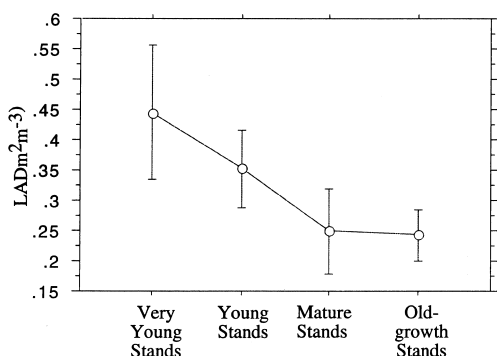


Table 3. Results of Stepwise Multiple Regression of Stand Attributes^a against Canopy Structure Volumes, and Associated Indices^b

	Adjusted R^2 (%)	Canopy Surface Height Indices			CHP Index ^c	Canopy Volume Method Indices			
		Maximum Canopy Height (m)	Mean Canopy Surface Height (m)	Number of Waveforms taller than 55 m		Mean CHP ^c Height (m)	Filled Canopy Volume ($m^3 m^{-2}$)	Closed Gap Volume ($m^3 m^{-2}$)	Open Gap Volume (m^3)
Total biomass ($Mg ha^{-1}$)	91	-155.3		32.9 _B		22.8 _A			
Total basal area ($m^2 ha^{-1}$)	87	-6.5		1.8 _B		2.2 _A			
PSME basal area	79	-1.6	1.9 _A					-2.1 _B	
TSHE basal area	78	-3.1		1.1 _C				2.2 _A	
Shade tolerant stems > 40 cm	52	-17.6						-1.5 _B	5.3 _A
Mean DBH (m)	61	-1.7			1.4 _A				
Stdev DBH (m)	85	1.8	0.36 _A						0.47 _C
Stems > 100 cm	85	1.0							
LAI	75	4.195		4.2 _A		0.35 _A		-0.26 _B	-1.97 _C

^a Additional independent variables used in these stepwise multiple regressions, but not used in any equation include canopy surface range, quadratic mean canopy height, and SLICER predicted cover.

^b $N=22$ for all regression models. Subscripted letters indicate rank of each variable, based on standardized coefficients, with A being the highest.

^c CHP = canopy height profile.

dominant stems were calculated for the SLICER data set using the equation of Means et al. (1999).

The heights measured for stands in this study were shorter than those in the data set used by Spies and Franklin (Table 4). For the young and mature classes, the truncation of the data from Spies and Franklin had little effect on the maximum or mean heights statistics, and we can conclude that the differences in the two data sets were related to the selection of sites. For the old-growth stands, all of the difference between the two data sets' maximum heights and half of the difference in the mean height of the dominants and codominants could potentially be assigned to the truncation effect (Table 4). This suggests that the truncation problem could have significant effect on our results for old-growth stands. However, the differences in class means may also be due to differences in field measuring technique and site selection. In addition, SLICER may not be registering the peak of each tree, because the horizontally projected surface of this portion of the tree may be too small to produce sufficient returned energy to the sensor to exceed the threshold value. Although the maximum height measurement was biased by the truncation error, it was a significant discriminant of mature and old-growth conditions. Correction of this error might result in more accurate estimates of stand structure attributes.

Canopy Height Profile Measurements

The effect of stand development on the canopy height profiles in this study was similar to that observed in the eastern deciduous forest (Aber, 1979; Parker, 1995; Lefsky, 1997). The youngest stands have a unimodal distribution of canopy surfaces that is nearly vertically symmetrical. Mature stands have a bimodal distribution, and old-growth stands have a more even distribution of foliage. In old-growth stands, a greater relative density of canopy surfaces was found in the lower half of the canopy than has been found in eastern deciduous forests. This concentration of foliage in the lower canopy is due to several factors. Older stands often have a dense subcanopy of western hemlock that has been recruited into the stand after its initial establishment. (Kuiper, 1988). The maximum height of western hemlock is typically less than Douglas-fir (Waring and Franklin, 1979), which tends to maintain these trees in a lower position. Furthermore, western hemlock maintains a longer crown than Douglas-fir, because of its greater shade tolerance (Kuiper 1988), which tends to distribute foliage in the lower half of the individual tree crowns.

Canopy Volume Measurements

Canopy structure in these stands, as measured by the CVM, changed in a regular way with respect to age. Two CVM measurements of canopy structure were statistically significant in distinguishing between the four age-classes: filled canopy volume and the number of canopy classes per unit height. The canopies of very young stands had an even upper canopy surface, had canopies

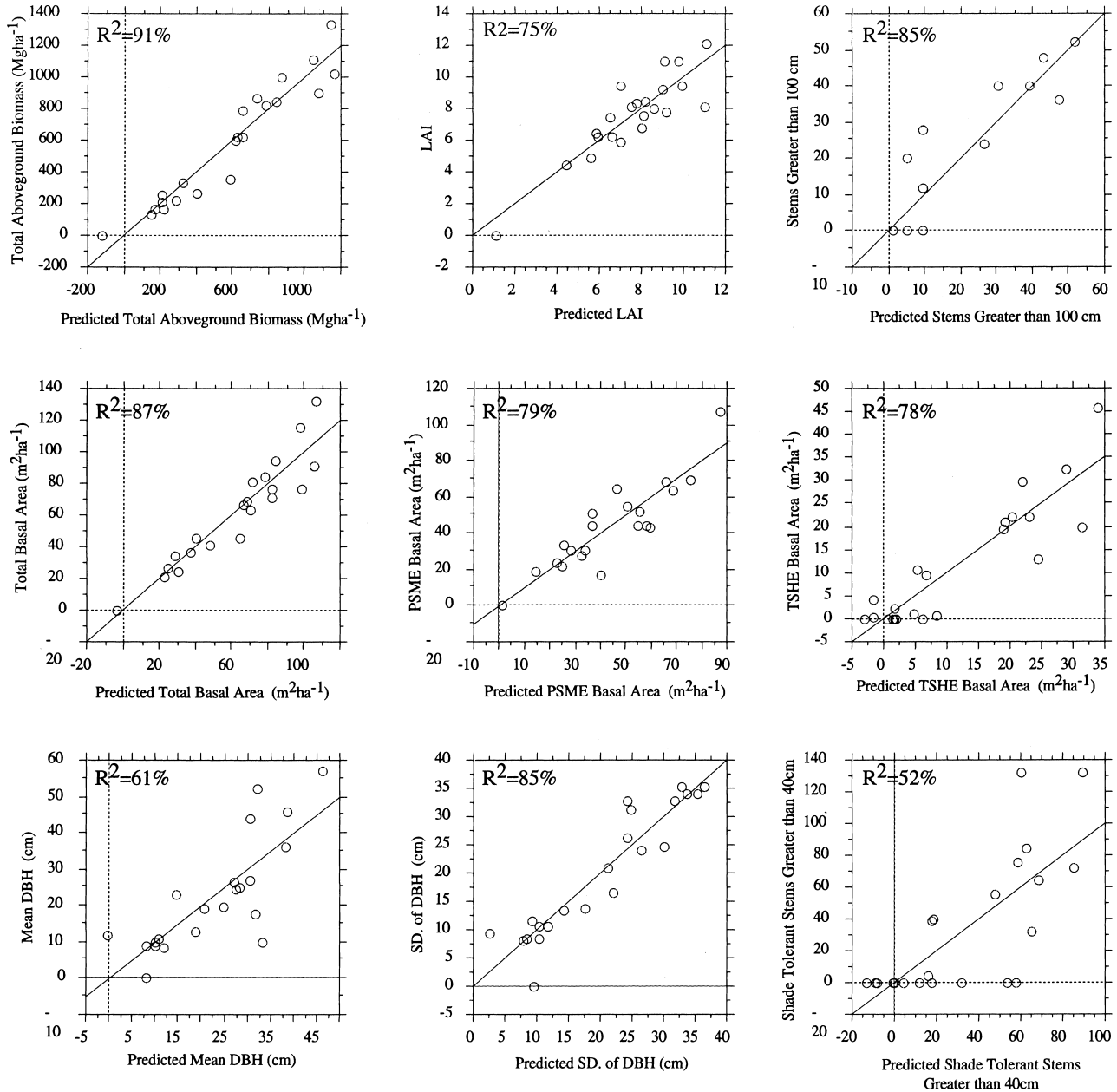


Figure 8. Scatterplots of observed stand attributes as a function of those attributes predicted using regression models.

comprised mostly of the euphotic zone, and had small volumes of empty space within them. Young stands had a less regular upper canopy surface, which resulted in a lower percentage of filled canopy volume. This may be due the creation of small gaps in the canopy because of the death of individuals as self-thinning proceeds. The volume of the euphotic zone in these stands was similar to that of the very young stands, but the volume of the oligophotic zone increased. The volume of closed gaps remained low.

The volumes of both the euphotic and oligophotic zones were higher for the mature stands than for young and very young stands, but the oligophotic zone was a

larger proportion of the total canopy volume in the mature stands. At this point in stand development, a large volume of space is present in which resources are insufficient to support additional foliage, as indicated by the large increase in the closed gap volume. This large volume of empty space within the canopies of mature stands is consistent with the observed canopy structure of mature even-aged Douglas-fir stands, which consist of similarly sized trees with tightly packed crowns, and little or no foliage beneath (Kuiper, 1988). Nevertheless, in this circumstance the lidar sensor probably overestimated the amount of empty space within the forest canopy, because it does not sense the boles of these trees

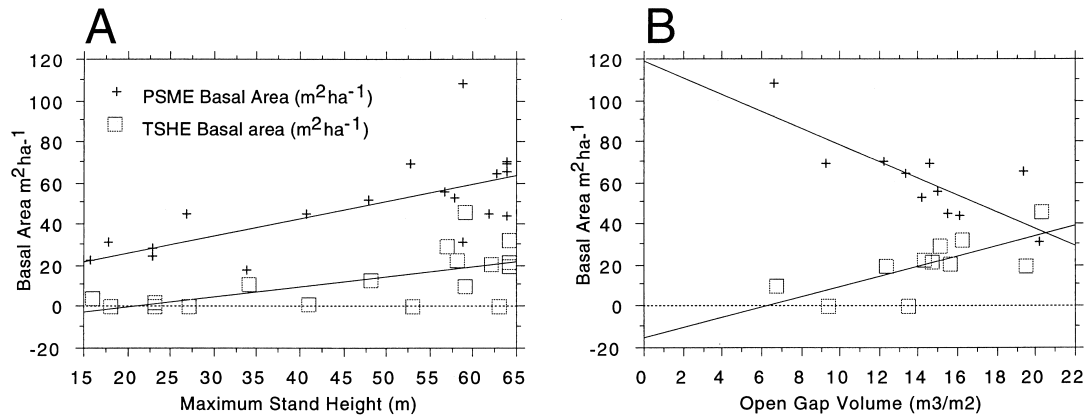


Figure 9. Basal area of Douglas-fir (PSME) and western hemlock (TSHE) as a function of A) maximum height and B) open gap volume.

which lie beneath the densest area of the crowns of individual trees. In the more developed mature stands, including the one pictured in Figure 6C, a layer of filled space is present beneath the zone where closed gap structure is dominant. This layer predominantly consists of foliage and woody tissues that have only empty space immediately above them, and therefore may be identified as a true understory, as opposed to foliage of taller individuals which extends to near the forest floor.

The old growth canopy volume profile (Figure 6D) showed a number of differences from the mature stand. The upper canopy surface in these stands is distributed from the maximum stand height down to near the forest floor (in the example of Figure 6D, a height of 4 m, on average to a height of 22 m). As a result, open gap space accounted for an average of 24% of the total canopy volume. Empty space of both kinds accounted for 40% of the total canopy volume. The volumes of closed and empty gap space are similar for the mature and old-growth stands, but again the vertical distribution of empty spaces is more uniform in the old-growth stands. The differences observed are due to the breakup of the canopy, as documented in several studies of old-growth

Douglas-fir forest (Oliver and Larson, 1990; Franklin and Spies, 1991; Spies and Franklin, 1991). The appearance of a more even distribution of canopy structure classes has been verified by the statistically significant increase in the average number of canopy structure classes at each height interval.

The filled canopy volume consistently and significantly increased from very young to old growth stands. An 171% increase in filled canopy volume between very young and mature stands is associated with an 55% increase in LAI (from 5.1 to 7.9) resulting in a 45% decrease in LAD. In contrast, the increase in LAI between mature and old-growth stands is proportionate to the increase in each stand's filled volume, so that the volumetric density of LAI remains constant. This increase in both filled volume and LAI between mature and old-growth stands suggests that old-growth stands have larger LAI values because their canopies are distributed in a similar fashion, but over a larger volume, not because of any difference in the distribution of foliage that might arise from the other differences in canopy structure documented here.

While the criterion for the distinction between "eu-

Table 4. Comparison of Height Statistics Calculated in This Work to Literature Values

	Young	Mature	Old-Growth
Average maximum height			
This study	20.4	51.3	61.2
Spies and Franklin (1991)	37.7	53.8	67.5
Difference	-16.6	-2.5	-6.3
Spies and Franklin-truncated	37.0	53.2	60.1
Average height of dominants and codominants			
This study	18.4	36.6	42.7
Spies and Franklin (1991)	29.4	44.6	52.2
Difference	-11.0	-8.0	-9.5
Spies and Franklin-truncated	29.4	43.1	47.9

photic" and "oligophotic" zones is related to the light extinction in the canopy, the criterion is applied to the extinction of the laser signal, not to sunlight. There are two key differences between the laser pulse and natural illumination at the same wavelength. The laser is always pointing at or near nadir, while sunlight is intercepted along a variable angle but never at 90° at our latitude (44°12'30"). In addition, scattered sunlight is an important component of the radiation budget of many forests (Montieth and Unsworth, 1990), and there is no analogous illumination in the lidar method.

Prediction of Stand Structure Attributes from Canopy Structure Indices

It is not surprising that canopy structure indices derived from SLICER data can predict stand structure attributes, given the emerging literature on the application of SLICER and similar devices (Lefsky, 1997; Lefsky et al., 1999; Means et al., 1999). Several points can be inferred from the stepwise multiple regression analysis. The relationship between canopy structure and stand structural attributes can be summarized in three main points. First, the filled canopy volume is the most important variable for predicting total aboveground biomass, total basal area and LAI (Table 3). Filled canopy volume can be thought of as a three-dimensional analog of cover, with cover being the fraction of surface area of the forest floor covered by canopy, and filled canopy volume being the volume of space occupied by the same canopy material. Field and remote methods of estimating LAI have been limited by the strongly asymptotic relationship between LAI and cover (Brown and Parker, 1994). As a result of this asymptotic relationship, the cover of canopies with an LAI greater than 2 or 3 is not considerably different from those with greater LAI. The projected horizontal space available for additional layers of leaves, in this sense, is fixed. In this work we have found that increases in LAI after canopy closure are associated with the distribution of that foliage over a larger volume, and that the total LAI is closely related to the volume of the filled canopy.

The second factor in the prediction of stand structure attributes is the role of open gap volume, which is the primary variable in two of the regression models (western hemlock basal area and number of shade tolerant stems greater than 40 cm). In mature and old-growth stands, the basal area of Douglas-fir is negatively correlated with the open gap volume, while the basal area of western hemlock is positively correlated with it (Fig. 9). This relationship is due to the differing shade tolerance of the two species. The typical mature stand in our study had an even canopy of large dominant Douglas-fir trees. As individuals in the mature stands die, gaps in the canopy structure increase the open gap volume. These small gaps are most often exploited by western hemlock, which

can better tolerate the high shade conditions that are predominant before, and to a lesser extent after gap creation. Western hemlock does not grow as tall as Douglas—and so the open gap volume in the canopy remains, possibly for centuries. Open gap volume may be useful in predicting indirectly a wide range of attributes associated with old-growth structure, such as the abundance of coarse woody debris and tree decadence.

The third main variable in the regression models is the number of waveforms taller than 55 m. This variable was highly correlated with the number of stems greater than 100 cm in diameter, which has been shown to be a good discriminant of mature and old-growth conditions in these forests (Spies and Franklin, 1991). The number of waveforms taller than 55 m was also important in predicting the standard deviation of DBH, and the total aboveground biomass and basal area. The role of this variable, which is related to the skewness in the distribution of the upper canopy surface, in predicting basal area and biomass suggests that the presence of larger stems has a nonlinear effect on the amount of basal area and biomass in the stand. This is similar to the findings of Lefsky (1997; 1999) that the relationship between the density of foliage and total basal area and biomass increased with height. More generally, the importance of this variable, and the other novel indices, suggests that a wide range of height related variables should be considered in any analysis relating canopy to stand structure.

It should be emphasized that the correlation coefficients reported for the relationships in this article are training accuracies; we expect that the strength of these relationships would have declined somewhat if they had been applied to an independent validation data set. Furthermore, field plots in this article had relatively uniform composition, at least within a given seral stage, and this also contributed to the high correlation coefficients. Finally, these results were obtained over fairly large footprints (50 m×50 m) and the integration of both field and lidar measurements over such a large area also tends to increase the strength of the relationships.

Comparison of Canopy Description Methods as Scene Models

The remote sensing problem can be defined as "inferring the order in the properties and distributions of matter and energy in the scene from the set of measurements comprising the image" (Strahler et al., 1986). The definition of a sensor used by Strahler et al.—a "device which measures the intensity of electromagnetic radiation"—does not adequately describe the capabilities of the surface lidar instrument used in this work, which records the intensity of electromagnetic radiation reflected from the target as a function of distance from the sensor. However, the data from lidar instruments fit within the conceptual framework established by Strahler et al. In

their framework, a “scene model” specifies the three-dimensional order of the scene and its interaction with the energy source used in sensing. These models are invertible when the identity and three-dimensional organization of the objects comprising the scene can be inferred from the remotely sensed image. Each of the three “canopy description” methods (canopy surface height, canopy height profile, canopy volume method) is, in effect, a scene model that defines the objects interacting with the sensor, contains certain assumptions about how these objects are distributed in three-dimensional space, and hypothesizes how the laser would interact with those objects. Although the measurements made by SLICER and other surface lidar systems are more directly related to the three-dimensional distribution of matter in the scene than most other types of remote sensing, the problem of model inversion remains. The assumptions used in the scene models determines what aspects of canopy structure can logically be inferred from each waveform. The validity of the assumptions is one factor determining the accuracy and utility of the resulting measurements of canopy structure.

The lidar waveform recorded by the sensor represents the power returned as the laser signal is reflected by a subset of the total canopy. We are currently unable to state with precision, for even a single forest type, the degree to which that sample is representative of the total canopy, or what the relationship is between the portion of the canopy sampled and the entire canopy. In that sense, the lidar measurements are currently noninvertible with respect to the total three-dimensional distribution of the canopy. One way to approach the problem of model inversion is to focus on those aspects of the waveform that can be most easily and reliably inverted. Simple characterizations of the waveform will involve the least complicated, and most reliable, scene models. One such model is the canopy surface height approach used in this article. It is a discrete L-resolution model (*sensu* Strahler et al., 1986) which assumes that each scene component is a single object with one attribute, height, and that the object’s size is equal to, or less than, the diameter of the footprint. The canopy surface height approach is the simplest of the methods considered, which by ignoring the relative power of the waveform, avoids any assumptions about the relationship between intercepted and total canopy surface area.

The canopy height profile model takes as its unit of analysis the individual elements of canopy surface area, which is mostly foliage, reflecting the laser pulse. The size of the objects being sensed are assumed to be small relative to the size of the waveform footprint, and they are not treated as individual objects; therefore, the canopy height profile model is a continuous L-resolution model, in which the sum of the interactions between each canopy surface and the lidar instrument are treated as a single unit of analysis. The canopy height profile

model does allow interpretation of more information contained in the waveform than the canopy surface height model. However, the assumptions necessary to do so may not be realistic for the forest described in this article. The canopy height profile method attempts to relate the power of the waveform to the total density of foliage at each height, and to do so, assumes that the increase in the cover of intercepted surfaces is caused by a layer of foliage uniformly distributed in the horizontal dimension. This implies that the density of canopy surfaces should be the same within and between individual crowns.

This assumption may be met (or nearly met) during the earlier stages of succession after canopy closure, when there is a high density of canopy surface area in closely packed crowns. However, in the old-growth stage, the actual distribution of canopy surfaces in these forests is characterized by a clumped distribution of canopy surfaces within crowns that are widely distributed. This leads to biases in estimating the vertical distribution of canopy surface areas. Simulation studies (Lefsky, unpublished) suggest that there may be considerable errors arising from these violations of the MacArthur–Horn assumptions, but these errors are difficult to characterize systematically. These errors are a result of the fact that the power of the energy backscattered to the sensor falls exponentially as a function of intercepted surface area. As a result, most energy returned to the sensor comes from near the local upper canopy surface. When that surface area is distributed uniformly in the horizontal plane, the energy is intercepted, and a uniformly reduced amount of energy is available to be intercepted in the next height interval. When the upper canopy surface is variable in height, the return energy at each height is a mixture of high power signal returned from the local canopy surface, and low power signal returned from occluded canopy surfaces at the same height. These same simulation studies suggest that when the high and low power signals are convolved, the resulting waveform is more indicative of the distribution of the upper canopy surface than the distribution of all canopy surfaces.

The canopy volume method is an L-resolution discrete model (like the canopy surface height model) that takes as its units of analysis each individual 1 m segment of the waveform. The model takes a conservative (compared to the canopy height profile) approach to what information on the obscured canopy structure can be inferred from that which is observed. It makes two assumptions, the first of which is reasonable: The presence of returned energy in any height interval indicates that there is some canopy surface area in that interval. The second assumption is more problematic: The absence of returned energy in any height interval indicates that there is no canopy surface area in that interval. It is possible that this assumption is violated in natural canopies, as in some mature stands in this study. In those

cases, the occlusion of foliage by that above it may be complete for some areas within the footprint. If that were the case, it is possible that foliage could be present beneath one of these areas, but not detected in the waveform (if occlusion were total across the entire footprint of the waveform no further energy, from either foliage or the ground surface, would be detected in the waveform). This may lead to an underestimation of filled volume and overestimation of the volume of closed gaps. Nevertheless, given that the horizontal distribution of canopy surface area is extremely nonuniform in Douglas-fir forests, inferences about the presence and absence of canopy surface area are more plausible than inferences about the total amount of surface area.

The canopy volume method can be thought of as a synthesis of the hypsograph and canopy height profile methods. The chief advantage of the hypsographic method lies in the unit of analysis, the area of the canopy above a given elevation, which allows a concrete physical structure to be inferred from the data. However, the standard hypsograph does not give information about the internal canopy structure. The chief advantage of the canopy height profile method is its ability to interpret information about the vertical structure of the entire canopy from the limited information obtainable with vertical intercepts. The chief weakness of the canopy height profile is its reliance on spatial averaging, which prevents any characterization of the horizontal distribution of canopy structure. As a result, it is impossible to distinguish horizontal layers that have a low density of evenly distributed canopy surface area from those which have a high density of canopy surface area, but restricted to one location. Another disadvantage of the CHP measurement is the inability to reliably assign a physical structure to its units. Without an independent measurement of LAI (as in Parker et al., 1989), the profile must be scaled to one, producing the relative canopy height profile. This leads to problems in interpreting the profiles, especially when considering profiles from short and tall stands in the same analysis. Combining the surface area units of the hypsograph, with the vertical profiling ability of the canopy height profile leads to the volumetric analysis of the canopy volume.

The canopy hypsograph and height profile are both attempts to describe canopy structure given limited resources. The development of systems for the description of canopy structure has heretofore been constrained by the inherent difficulty and expense of making observations in the vertical dimension. As a result, existing methods are a compromise between the needs of researchers and the resources available to them. While some observations of canopy structure over large plots (Parker et al., 1991), or over series of field plots (Aber, 1979; Aber et al., 1982; Parker, 1995) are available, they are not common. With the growing availability of both remote and field lidar measurement systems, new methods of de-

scription will be necessary to organize the measurements made with these systems, of which the canopy volume method is one example.

One critical aspect of future analyses of lidar data will be the footprint size of the imagery. In these analyses, footprints of 10 m diameter were used. A footprint size of 25 m will be used in the Vegetation Canopy Lidar (VCL) and Laser Vegetation Imaging Sensor (LVIS) programs (Dubayah et al., 1997). VCL is a satellite surface lidar system, developed as part of NASA's Earth System Science Pathfinder program and due to be launched in early 2000; LVIS is an airborne device being used for validation of VCL's capabilities. The smaller footprint size used in this work may be preferable for estimating canopy structure in the coniferous forest of the Pacific Northwest, because it is close to the crown diameter of the dominant individuals, which average from between 8 m (for young stands) to as much as 10 m for old-growth stands (Kuiper, 1998). The crown size of dominant individuals in a stand represents the upper limit of the optimal sampling resolution for capturing the variability of the upper canopy surface (Cohen, 1990), which we have shown can help characterize the seral stage of a stand. Lidar footprints wider than this size will result in an underestimation of the variability of the upper canopy surface if a canopy surface height model is applied to the data. One possible solution to this problem consists of a fourth model for the interpretation of lidar waveforms. We have seen that the canopy height profile method assumes that the canopy surfaces are uniformly distributed in the horizontal dimension, and thus attempts to measure the vertical distribution of all foliage. This assumption is probably incorrect, but, nevertheless, the canopy height profile can be a useful measurement in the Pacific Northwest (Means et al., 1999). A similarly incorrect, but potentially useful, assumption about the horizontal distribution of canopy surfaces would be that all the power returning to the sensor is reflected from near the upper surface of the canopies of each individual tree. If this was the case, the cumulative return energy waveform (accumulated from the top of the stand down) could be treated as the cumulative upper canopy surface distribution. In this way, estimates of the variability of the upper canopy surface could be made using single lidar waveforms, rather than using arrays of waveforms, as in this work.

CONCLUSION

The development of forest ecology applications of lidar remote sensing will depend on detailed knowledge of canopy organization. Systems for the simplified description of the complex three-dimensional structure of canopies will be needed to make that organization comprehensible. In this article, we have presented a method which explicitly quantifies the volume of filled and empty

space in the canopy and incorporates two simple distinctions—empty space versus filled space and euphotic versus oligophotic canopy zones. These simple distinctions are capable of quantifying aspects of canopy structure, such as multiple canopy layers, in ways previously not possible. In addition, our set of novel indicators of canopy structure appears to be more closely related to ecologically significant aspects of forest stand structure than the more conventional indices we examined.

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