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# Lidar Remote Sensing of Forest Canopy Structure and Related Biophysical Parameters at H.J. Andrews Experimental Forest, Oregon, USA

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## ABSTRACT

Scanning lidar remote sensing systems have recently become generally available for use in ecological applications. Unlike microwave and conventional optical sensors, lidar sensors directly measure the distribution of vegetation material along a vertical axis and can be used to provide three-dimensional characterizations of vegetation structure. Ecological applications of scanning lidar have previously used uni-dimensional indices of canopy height. A new, three-dimensional, approach to interpreting lidar waveforms was developed to characterize the total volume of both vegetation and empty space within the forest canopy, and their spatial organization. These aspects of the physical structure of canopies have been infrequently measured, either from field or remote methods. Applying this approach to 21 plots with coincident lidar measurements and field surveys, we were able to predict both biomass and leaf area index from the volumes of four classes of canopy structure. These predictions were non-asymptotic over a wide range, up to 1200 Mg $ha^{-1}$ of biomass and an LAI of 12, with 90 % and 88 % of variance explained, respectively.

## INTRODUCTION

Characterization of forest structure in moderate to high biomass systems is one of the key challenges in remote sensing. The need for wide-scale inventory of the amount and complexity of forest structure is especially pressing in the Pacific-Northwest where Douglas-fir [*Pseudotsuga menziesii*] forests are of particular interest. These forests are among the most productive in the world, with primary old-growth stands having a total of as much as 650 x $10^6$ g C/ha in aboveground and belowground pools [1]. Differences in the physical structure of these forests at progressive stages in their development have been the focus of intense scientific and management attention due to the dependence of at least two endangered species on the physical structure of old-growth stands. The ability to remotely sense both the total quantity and complexity of forest structure of these forests would provide one way to meet the need for forest inventory in support of research and management of both carbon balance and habitat conditions.

The SLICER (Scanning Lidar Imager Of Canopies By Echo Recovery) instrument is one of a new generation of systems that augment traditional first-return laser altimetry with a surface lidar capability [2,3]. Laser altimeters measure 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. In surface lidar, the power of the entire return laser signal is digitized, resulting in a waveform that records the vertical distribution of the backscatter of laser illumination from all canopy elements (foliar and woody) and the ground reflection, at the wavelength of the transmitted pulse (1064 nm, in the near-infrared). The use of relatively large footprints (5-15 m) is optimized to recover returns from the top of the canopy and the ground in the same waveform, yet be small enough to be sensitive to the contribution of individual crowns. Details of the technical aspects of SLICER can be found in [4,5]

## METHODOLOGY

Lidar waveforms were collected by the SLICER instrument in September, 1995. SLICER was configured to measure five waveforms cross-track, with each waveform covering a footprint 10 m in diameter. Geo-referencing of laser footprints was performed 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 [4]. 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. Waveforms with this problem were hand corrected by J. Means [6] based on independent estimates of topography and field data, to eliminate the truncation error.

Field data for this study were collected from the vicinity of the H.J. Andrews Experimental forest, located on the west side of the Cascade Range in Oregon, USA. Twenty-one 0.25 ha field plots have been established under an existing

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SLICER transect, with each plot associated with a 5 by 5 array of waveforms. In each plot, trees with height greater than 1.37 m were identified by species, measured for diameter at breast height (DBH) to the nearest cm, and evaluated for crown ratio (the proportion of tree height which is canopy) to the nearest 10 %. Total aboveground biomass was estimated from DBH using allometric equations [7]. Leaf area index values were calculated using allometric equations relating stem DBH to sapwood cross-sectional area as found in [8]. Sapwood area was converted to all sided leaf area using the species-specific coefficients in [9].

Waveforms were processed using the canopy volume profile algorithm (Fig. 1). Following the procedures in [10], the waveform was transformed into an estimate of the canopy height profile (CHP), the relative distribution of the canopy as a function of height. A threshold value was then used to classify each element of the CHP into either "filled" or "empty" volume, depending on the presence or absence (in the waveform) of returned energy. A second step classifies the filled elements of the matrix into an "euphotic" zone [11], which contains all filled elements of the profile that are within the uppermost 65 % of canopy closure, and an "oligophotic" zone, consisting of the balance of the filled elements of the profile. These two classifications were then combined to form three classes; empty volume beneath the canopy- (ie. closed gap space), filled volume within the euphotic zone, and filled volume within the oligophotic zone.

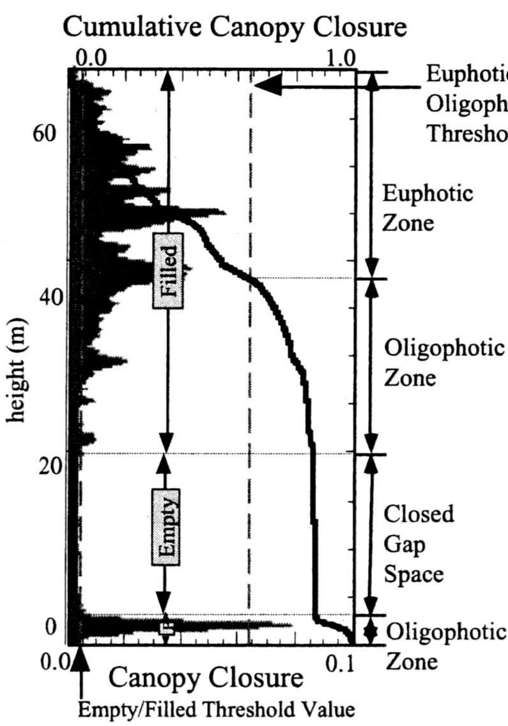


Figure 1: Canopy Volume Method

These same classes are then computed for each of the twenty five SLICER waveforms in the 5 by 5 array. The waveforms were then compared, and a fourth class was 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. At this point, the total volume of each of the four classes of canopy structure can be tabulated for each 5 by 5 array of waveforms.

To determine the ability of SLICER measured canopy structure indices to predict aboveground biomass and LAI , stepwise multiple regressions were performed using as independent variables the total volume of each of the four canopy structure classes and the total volume occupied by vegetation material, as measured by the combined volume of the euphotic and oligophotic zones.

## RESULTS

Fig. 2 presents canopy volume profile diagrams for representative young, mature and old-growth plots. These diagrams indicate, for each 1 meter vertical interval, the percent of each plot's 25 waveforms that belong to each of the four canopy structure classes. Young stands are characterized by short stature, a uniform canopy surface (as indicated by the height distribution of the interface between the euphotic zone and open gap space), and an absence of empty space within the canopy (ie. closed gap space). Mature stands are taller, but still are characterized by a uniform upper canopy surface. In contrast to young stands, mature stands have a large volume of closed gap space. Mature stands of Douglas-fir often have a high density of large trees with uniform DBH. The uniformity of size leads to the uniform canopy surface height, and the interception of light and other resources by these trees results in the absence of canopy material at lower levels. Old-growth stands are distinguished from mature stands by their uneven canopy surface, and the wide vertical distribution of each of the four canopy structure classes. Whereas stands from earlier stages in stand development have canopy structure classes in distinct vertical layers, in the old-growth stands each canopy structure class occurs throughout the height range of the stands. The continuous distribution of canopy surfaces from the top of the canopy to the ground has been cited as a key physical feature of old-growth forests distinguishing them from the simpler canopies of young and mature stands (Spies and Franklin, 1991)

Scatterplots of predicted vs observed stand structure attributes are presented in Fig. 3. The strength of the relationships developed here are very strong in comparison to other remote sensing techniques, and compare favorably with allometric equations relating complementary aspects of individual tree geometry. Examination of the scatterplots indicates that the predicted values of aboveground biomass and

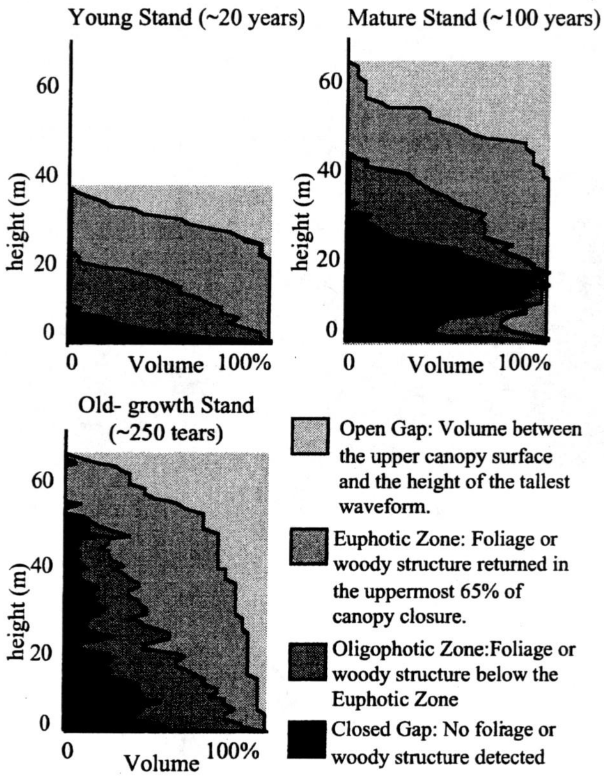

Figure 2: Canopy Profile Diagrams

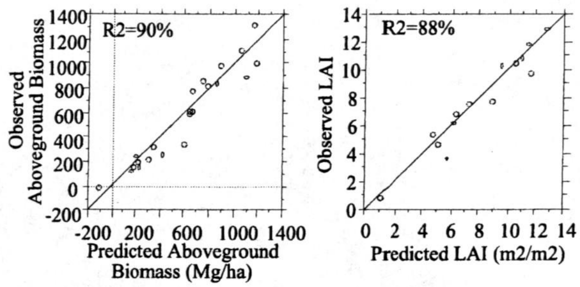

Figure 3. Observed vs. Predicted Stand Structure Attributes

LAI show no asymptotic tendency, even at extremely large values (1200 Mg/ha Biomass, LAI of 12). The equation predicting biomass involved positive correlations with the total filled volume, and the number of waveforms taller than 55m. The equation predicting LAI involved a positive correlation with the total filled volume and the open gap volume, and a negative correlation with the closed gap volume. This may be interpreted as suggesting that the all-sided surface area of leaves is proportional to the volume they are distributed in. Increases in the vertical range of the upper canopy surface tends to increase LAI, and the presence of empty spaces within the canopy tends to decrease LAI. Although both LAI and aboveground biomass use the total filled volume variable in their equations, scatterplots and regressions have shown that the predicted values of each variable are no more highly correlated with each other than the original data.

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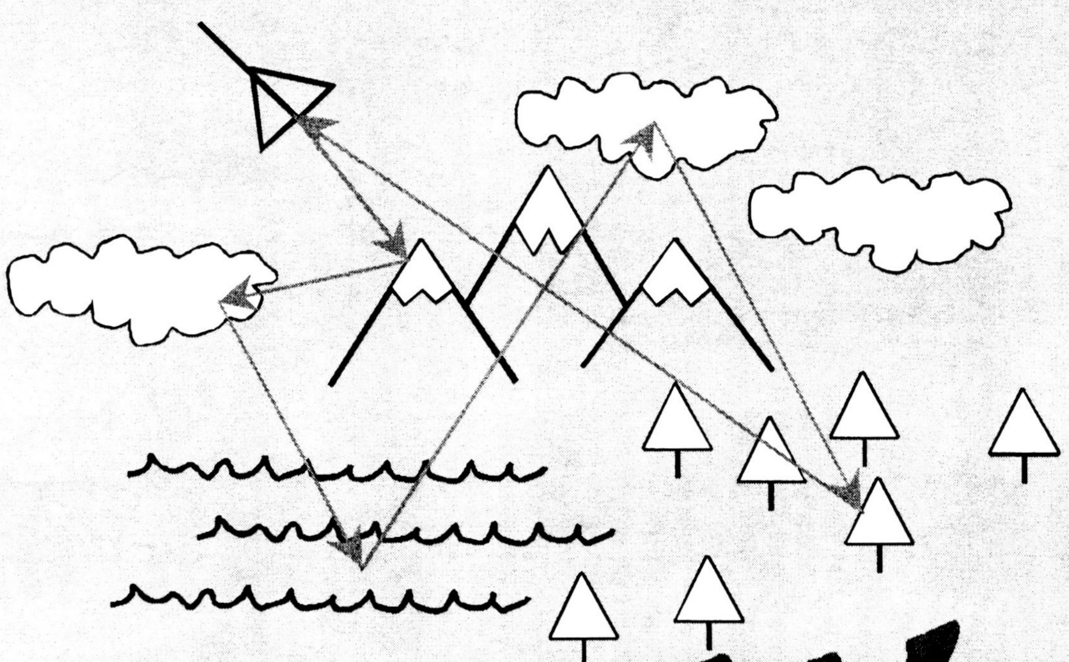

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