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**Canopy structure of some mixed deciduous forests at the Fernow Experimental Forest, West Virginia, observed with ground-based LIDAR measurements**

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## Introduction

The structure of the forest canopy is important to a variety of critical forest functions. However, obtaining the measurements of canopy structure that are necessary to understand these forest functions has been difficult. Most available techniques provide poor spatial resolution and are at scales not linked to the footprints of canopy functions. Consequently, progress in understanding canopy structure-function relationships has been slow. LIDAR remote sensing shows promise for yielding the desired resolution, particularly in the vertical dimension (Lefsky et al. 2002). However, most remote altimetry sensors are either very expensive or are currently in a development phase and are not available to support field research. In this project we used a portable laser range-finding system to make dense measurements of the location of canopy elements and assembled these into high-resolution views of structure in three dimensions. We focused here on the relationship between canopy structure and stand management history.

## Methods

Study Areas

In July of 2011 we took measurements of canopy structure in three forests in the northeastern portion of the Fernow Experimental Forest in the Monongahela National Forest near Parsons WV (Tucker County). The forests in this region were completely logged between 1903 and 1911 (Kochendorfer 2006). Sampling of canopy structure was conducted on 4 perpendicular transects at each of 7 locations in each of three well-studied watersheds (Kochendorfer 2006). Watershed 3 (WS3) was logged at various times in the 1950's and 1960's and been acidified with ammonium sulfate applications since 1989. Watershed 4 (WS4) has been untreated since the epoch of logging and serves as the reference case for this study. Watershed 7 (WS7) was clear-cut and herbicided in sections in the 1960's – since 1969 it has been allowed to recover naturally. Consequently, stand ages follow the order WS4 > WS3 = WS7. The locations within each watershed are a subset of study plots installed by Gilliam (W. Peterjohn, personal communication). The geometry of the sampling at each location is given in the figure below.

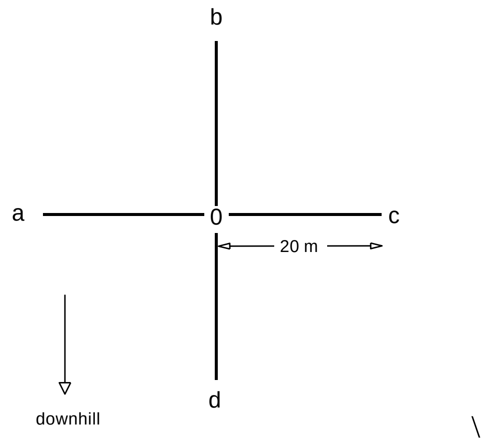


Figure 1. Field sampling layout. At each site four 20-m transects were sampled: from point a to the center (data file labeled a0), from the center to point c (0c), from point d to the center (d0) and from the center to point b (0b).

LIDAR measurements

We used a Riegl LD90-3100VHS-FLP laser rangefinder (operating in first-return mode at 890 nm and 2 kHz, laser safety class I) mounted to the front of a frame at 1 m above the ground and pointed upward. The frame was carried by a person, attached with a hip-belt and harness. Power for the laser was supplied from a 12V battery. The laser made 2000 measurements per second. The data were transferred through a serial cable to a small notebook computer (Asus EEE PC700), also mounted on the frame. The assembly, use, and biases of this system are described in Parker et al. (2004). The location of each range measurement was estimated from its sequence in the data file, assuming a constant walking speed. Distances between measurements were typically less than 1 cm - the spot size of the laser beam is 4-6 cm at the ranges measured.

The data files were edited to identify out-of-range values (such as when penetrating through canopy openings to the sky) and to remove spurious values. The edited files were processed through a customized program to group the ranges horizontally, calculate the vertical profiles using the method of MacArthur and Horn (1969), estimate the surface area density using the overlap transformation (Parker and Lefsky, in preparation), and assign coordinates to each estimate. Here we used bins that were 1 m in the horizontal and 1 m in the vertical. The resulting estimates refer to cube-shaped voxels of 1x1x1 m in the x, y and z dimensions, respectively.

Representations

To view the resulting three-dimensional estimates, we made height sections from the transects. These are presented as contour plots of surface area density, where the abscissa is horizontal distance along the transect and the ordinate is height above ground. The raw estimates were not interpolated for these presentations; however the contours were smoothed with a cubic spline. To understand the overall vertical structure in each sampled area we extracted the mean surface area density for each height and present these as bar graphs.

Additional statistics

The Canopy Area Index (CAI) is the sum of surface area density across all levels in a column. The local outer canopy height (LOCH) is the maximum surface height in a column – across all columns together these define the outer canopy surface. The average value of this height is called the "mean outer canopy height" and its standard deviation is the "rugosity." The mean height weighted by the surface area density is called the "mean weighted height." The diversity of heights is measured with the natural-log Shannon-Weiner information index, "SWdiv," (equivalent for each column to the "foliage-height diversity") - the "SWequ" is the equitability of the index. As much of the canopy is open space, two sorts of porosity are recognized. The "internal porosity" ("PORint") is the fraction of voxels under the undulating outer canopy not occupied by surfaces; the "total porosity" ("PORtot") is the fraction of open space beneath the overall maximum canopy height. The gap fraction is the fraction of horizontal locations without any canopy surface area directly above (one minus the "cover").

## Results and Discussion

Example sections

The figures below give example height sections of canopy surface area density from the sampling points in each of the watersheds. All the figures are scaled the same for surface area but the vertical axis is higher for the taller watershed 4. In most cases, canopy surface area was distributed throughout the range of heights. Although not shown here, there was much structural variation among transects within watersheds.

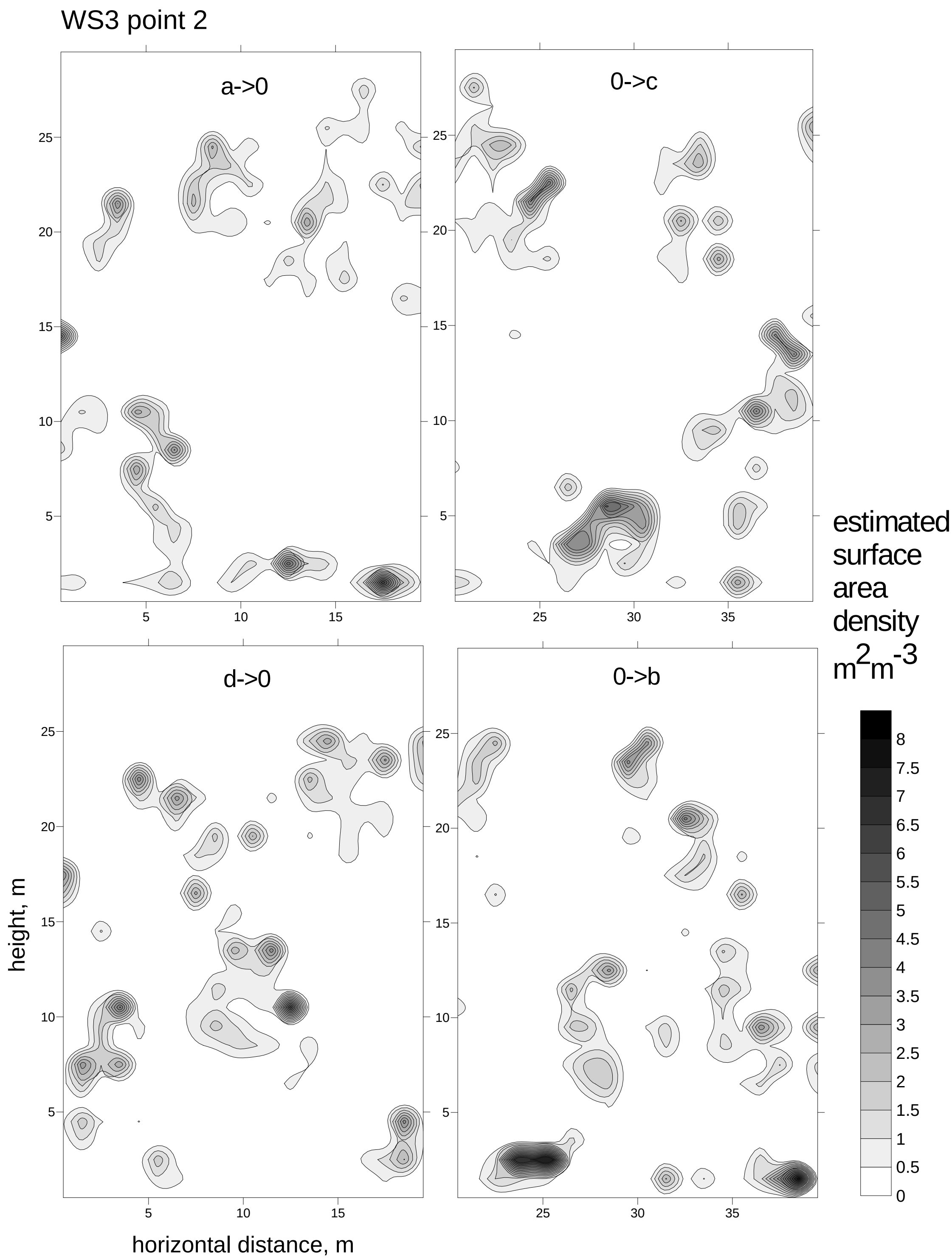


Figure 2. Example height section of canopy surface area density from Fernow Watershed 3, using sampling point 2.

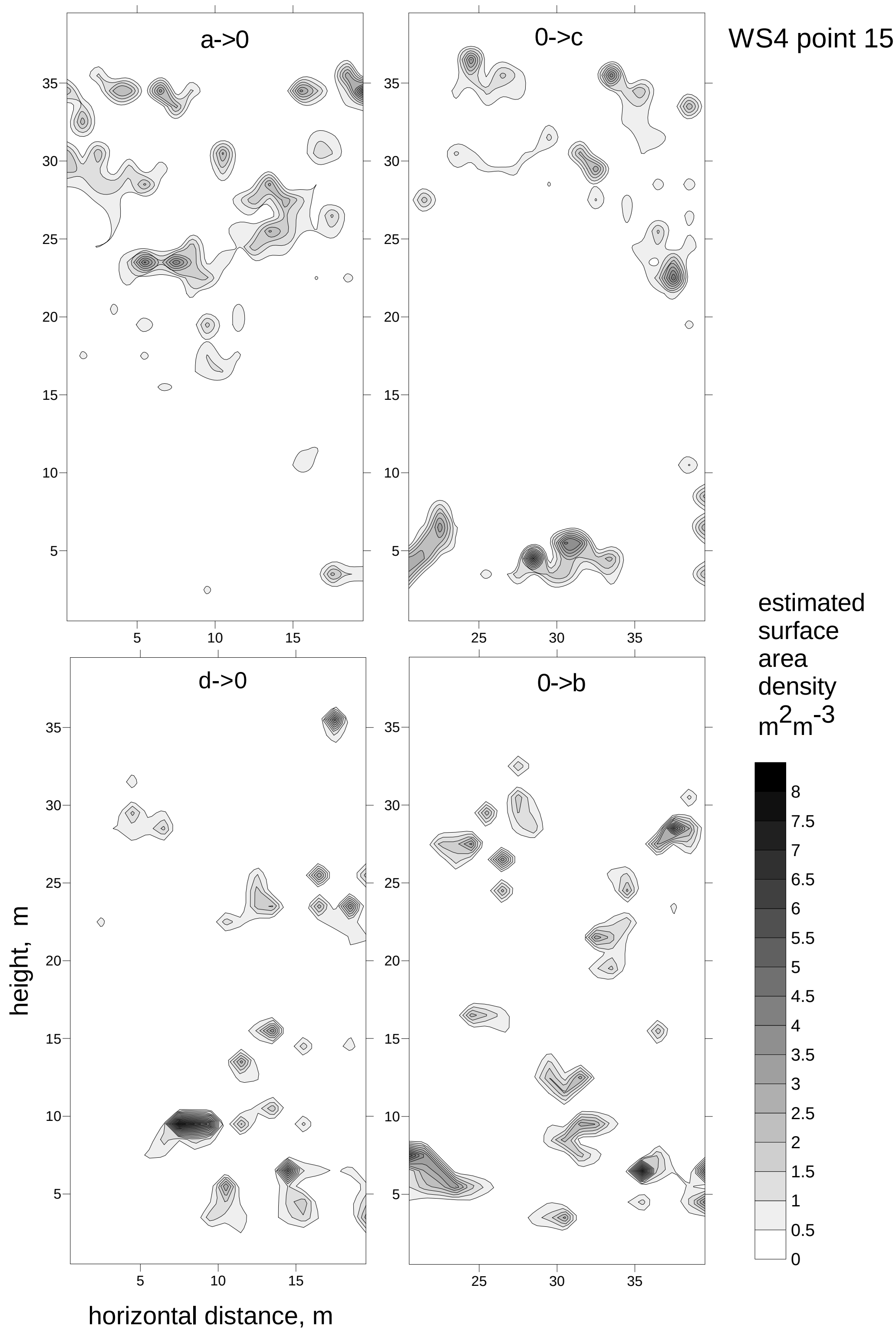


Figure 3. Example height section of canopy surface area density from Fernow Watershed 4, using sampling point 15.

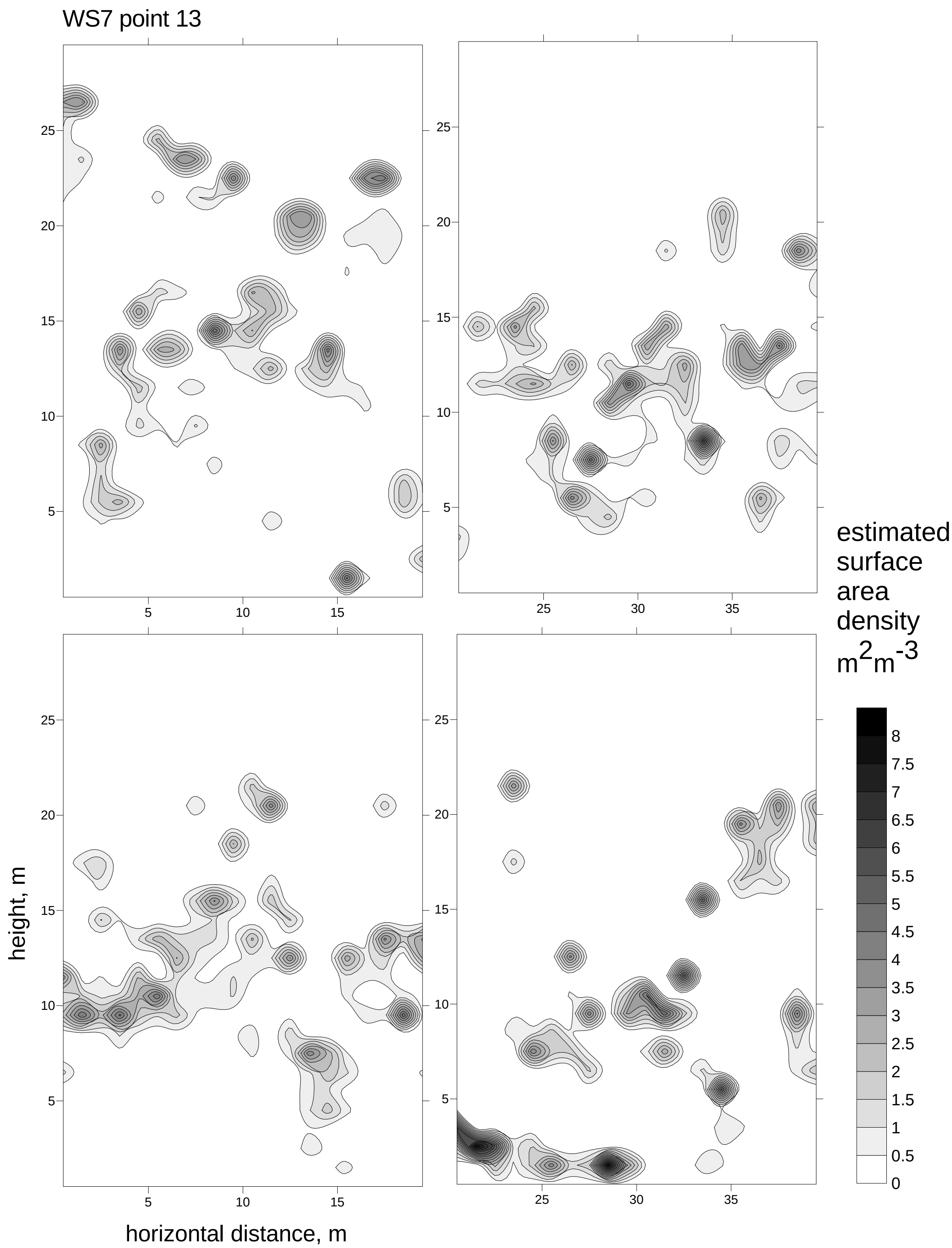


Figure 4. Example height section of canopy surface area density from Fernow Watershed 7, using sampling point 13.

Mean Vertical Structure

The mean vertical pattern of average surface area density differs markedly among the watersheds. In watershed 7 the mode of maximum surface area density is pronounced and near the canopy top (“top-heavy”, Parker [1997]) whereas other watersheds have a “bottom-heavy” mean profile. The mean and maximum heights of the stands are consistent with the ranking of ages and biomass estimates reported in Kochendorfer (2006).

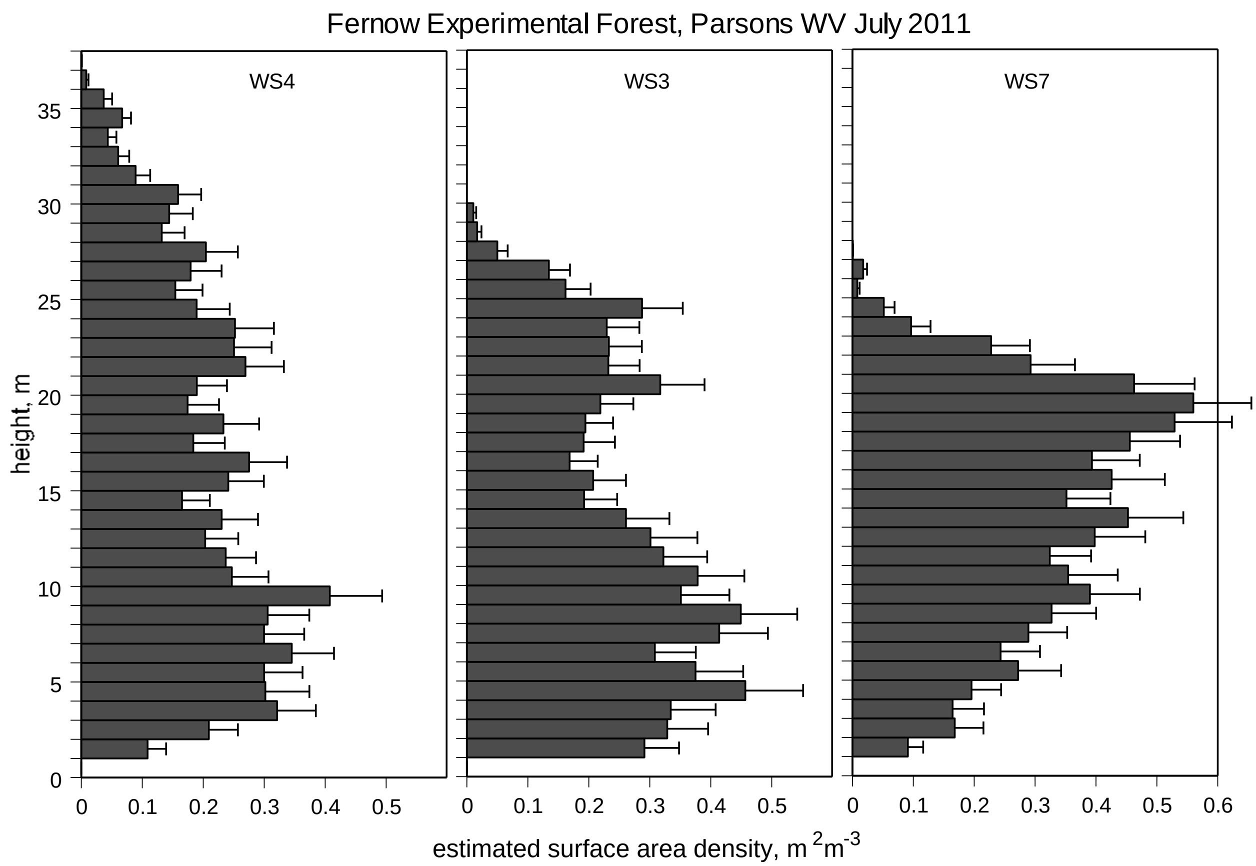


Figure 5. Mean vertical profile of canopy surface area in three watersheds of the FEF in 2011. Error bars are standard errors.

Summary statistics

Structural statistics, based on the 1-m horizontal bins, are tabulated below (Table 1) for each watershed and sampling site. These measures also show numerous differences between the sites. All the watersheds show a high degree of closure (very low gap fraction). Mean and maximum forest heights followed the sequence WS4>WS3>WS7, consistent with the canopy height profiles shown earlier (Figure 5). The highest degree of canopy variation ("rugosity) was in the older, taller forest of watershed 4. Total porosity was similar across watersheds but watershed 4 had a higher internal porosity. The Shannon-Weiner diversity index (equivalent to mean 'foliage-height diversity") and it equitability did not differ much across watersheds. Some metrics not presented here for space limitations include the surface-weighted canopy heights and the size-distribution of gaps.

Table 1. Summary metrics of canopy structure for each watershed and sampling point.

| WS | site | CAI | LOCH | rugosity | Hmax | SWdiv | SWequ | PORint | PORtot | gap fraction |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 02 | 7.08 | 18.2 | 7.5 | 27.5 | 1.67 | 0.73 | 36.20 | 59.28 | 0.0150 |
| 3 | 08 | 6.89 | 19.9 | 5.9 | 26.5 | 1.72 | 0.72 | 41.43 | 54.90 | 0.0236 |
| 3 | 09 | 7.48 | 17.2 | 7.6 | 29.5 | 1.40 | 0.69 | 46.82 | 69.67 | 0.0137 |
| 3 | 10 | 7.52 | 19.4 | 7.1 | 29.5 | 1.80 | 0.75 | 35.99 | 58.35 | 0.0137 |
| 3 | 13 | 7.59 | 13.4 | 7.4 | 27.5 | 1.43 | 0.71 | 30.91 | 68.15 | 0.0010 |
| 3 | 15 | 7.58 | 13.5 | 6.5 | 25.5 | 1.43 | 0.72 | 35.05 | 65.45 | 0.0029 |
| 3 | 06 | 7.37 | 20.8 | 6.8 | 29.5 | 1.63 | 0.75 | 49.79 | 64.40 | 0.0076 |
| **mean** | | **7.36** | **17.5** | **7.0** | **27.93** | **1.58** | **0.73** | **39.45** | **62.89** | **0.0111** |
| | | | | | | | | | | |
| 4 | 03 | 7.09 | 21.6 | 7.2 | 31.5 | 1.59 | 0.73 | 52.36 | 68.06 | 0.0241 |
| 4 | 04 | 7.09 | 24.8 | 7.7 | 34.5 | 1.64 | 0.75 | 56.78 | 69.08 | 0.0180 |
| 4 | 07 | 7.61 | 21.0 | 5.2 | 28.5 | 1.67 | 0.73 | 48.49 | 61.49 | 0.0022 |
| 4 | 10 | 7.26 | 15.4 | 7.4 | 28.5 | 1.35 | 0.68 | 43.20 | 70.34 | 0.0254 |
| 4 | 11 | 7.10 | 19.3 | 8.8 | 33.5 | 1.37 | 0.71 | 55.74 | 75.72 | 0.0075 |
| 4 | 13 | 7.54 | 21.4 | 10.2 | 36.5 | 1.55 | 0.71 | 48.94 | 71.64 | 0.0084 |
| 4 | 15 | 6.81 | 26.5 | 10.0 | 36.5 | 1.63 | 0.72 | 56.94 | 70.77 | 0.0413 |
| **mean** | | **7.21** | **21.4** | **8.1** | **32.79** | **1.54** | **0.72** | **51.78** | **69.59** | **0.0181** |
| | | | | | | | | | | |
| 7 | 02 | 7.47 | 17.4 | 5.4 | 25.5 | 1.47 | 0.72 | 50.58 | 65.07 | 0.0061 |
| 7 | 06 | 7.72 | 18.0 | 4.6 | 23.5 | 1.36 | 0.66 | 53.94 | 64.41 | 0.0030 |
| 7 | 08 | 7.70 | 17.0 | 4.4 | 23.5 | 1.40 | 0.67 | 47.58 | 62.08 | 0.0008 |
| 7 | 10 | 7.74 | 16.2 | 6.7 | 26.5 | 1.51 | 0.72 | 39.03 | 62.75 | 0.0020 |
| 7 | 12 | 7.45 | 17.7 | 5.0 | 27.5 | 1.62 | 0.71 | 37.13 | 55.09 | 0.0089 |
| 7 | 14 | 7.27 | 18.2 | 4.4 | 25.5 | 1.48 | 0.67 | 48.16 | 59.13 | 0.0200 |
| 7 | 13 | 7.17 | 15.3 | 5.7 | 26.5 | 1.40 | 0.71 | 44.58 | 64.81 | 0.0170 |
| **mean** | | **7.51** | **17.1** | **5.2** | **25.5** | **1.46** | **0.69** | **45.86** | **61.91** | **0.0083** |

## Associated data files

Space-delimited text data files of summary results from each transect in each stand of this study can be provided. There are two kinds of files containing separate results: the triplet file (usually "*.out") and a file summarizing a variety of additional statistics (typically "*.sta"). Each file has a prefix designating the site and transect and a file extension denoting the type of result. The coordinate system follows the cartesian convention, with z increasing vertically from 0 at the ground. Note that the value of the x-coordinate is constant for each transect (i.e., it is a placeholder).

These files provide no information on canopy structure below 1 m (even though the files have entries of 0.0 for various measures at the voxels centered at 0.5 m in height). Note that the values in these files are estimates, obtained with a procedure that has some instrument biases, positional uncertainties, and assumptions about the nature of the organization of canopy elements. How these sources of error affect the resulting estimates is a subject of current research. In fully-foliated forests the majority of surfaces targeted by this instrument are leaves. However, other tissues were also sometimes encountered, which is why we use the term "surface area density."

TRIPLET FILES (*.OUT)

These files give three items of information for each voxel. Following four descriptive header lines, each line has the following variables:

- x, y, z coordinates of the voxel center in meters
- d(z) number of laser hits in that [x,y,z] voxel
- fee(z) fraction of column surface area in this height bin (sums to 1 for a given [x,y] if there are any surfaces, to 0 otherwise)
- el(z) estimate of surface area density ($m^2m^{-3}$) within this voxel

GENERAL STATISTICS FILES (*.STA)

After several descriptive header lines these files yield three groups of results. The first block is a representation of the estimated surface area density as a function of height (across the page) and transect position (down the page) - it is a crude sideways version of the "curtain" contour plots we often present. The surface area density of a voxel occupies three horizontal spaces, where the value is hundredths of surface area units ($m^2m^{-3}$) as an integer: a value of 23 would indicate 0.23 $m^2m^{-3}$ and a value of 429 would indicate 4.29 $m^2m^{-3}$. Zeros indicate empty voxels. The next block gives summary metrics across height for each horizontal bin along the transects. These metrics are: the x and y coordinate of the horizontal bin, the Canopy Area Index (CAI), the maximum height (Hmax), the mean height (Hbar), the mean height weighted by surface area (Dconc), the Shannon-Weiner diversity index (SWdiv) and its equitability value (SWequ), the Simpson Index of similarity (simdx) from the current column to the next (the last row has a value of 0.0), the number of occupied voxels (occ), the number of open voxels below the local outer canopy (olo) and the number of open voxels below the maximum height (ohi), the interior porosity (PORint) and the total porosity (PORtot). The final block of results gives various statistics on surface area density for each 1m height class – these are used to produce canopy height profiles. Note there is no information on the 0-1 m height class, as this is below the laser height.

Data distribution

These results incorporate our best current method for estimating these aspects of canopy structure.  Note that we are continuing research on these methods and will likely refine the transformation procedures and the estimations of canopy structure.  Please feel free to contact me regarding any questions about the context, origin, transformations, and appropriate use of these data.


**Acknowledgements**

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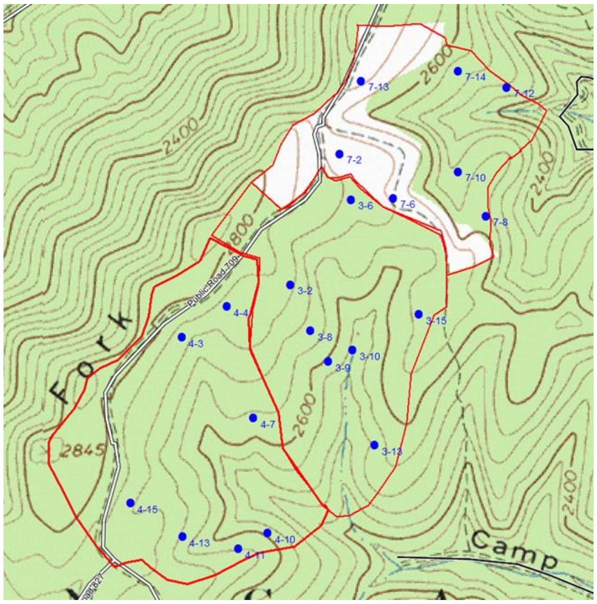
**Addendum:**

Map showing sample locations in Watersheds 3 (center), 4 (lower left), and 7 (upper right).




Photos showing the LIDAR system and its use by Dr. Parker.