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The canopy surface and stand development: assessing forest canopy structure and complexity with near-surface altimetry

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Abstract

A first-return laser rangefinder deployed from a low-flying helicopter provided inexpensive, repeatable, and high-resolution measurements of the shape of the outer forest canopy in stands of four successional stages on the Maryland coastal plain. The traces of canopy height in these stands revealed structural characteristics such as cover, maximum and mean heights which were consistent with corresponding ground measurements. Differences in the statistics on canopy structure corresponded to general developmental trends in these stands, including the development of maximum height and surface rugosity. Furthermore, some of the outer canopy statistics related to measures of internal organization, such as the shape of the foliage height profile and the leaf area index. These observations suggest that such measurements could be used readily to classify stand structure and developmental stage, and to deduce some aspects of internal organization of vegetation.
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Keywords: Complexity; Forest structure; Fractal dimension; Laser altimetry; Leaf area density; Leaf area index; Outer canopy; Rugosity

1. Introduction

Though much is known about how forests change in the number and size and identity of their stems (e.g., Oliver and Larson, 1990), scant information is available on the dynamics of canopy internal structure (see Aber, 1979; Brown and Parker, 1994) and almost nothing is known of the development of the outer forest canopy—the layer of leaves immediately adjoining the atmosphere (Parker, 1995). This is regrettable since: (1) the outer canopy is the portion of forests ‘‘viewed’’ by remote sensing instruments, and (2) numerous functional characteristics of forests are linked to developmental stage (e.g., Waring and Schlesinger, 1985). Thus, lack of information on the development of the outer canopy precludes the prediction of some stand functional characteristics from remote information.

The shape of the outer canopy is important for several reasons. This portion of the forest is the interface of atmospheric interactions. The extent and shape and disposition of this surface has implications for the distribution of illuminated foliage, the penetration of heat, and the extent of turbulent mixing, among other properties. Furthermore, the shape of the outer canopy necessarily constrains some aspects of the internal structure included below that surface. Consequently, changes in the outer canopy reflect the development of the forest.

The main objective of this study was to determine if airborne laser altimetry could measure the structure of

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the outer forest canopy readily and inexpensively. Another goal was to know whether stand stature and complexity could be deduced from those measurements, and if so, whether they are related to measures of internal canopy structure and complexity. The final aim was to discover if the pattern in stature and complexity changed in ways consistent with stand development.

2. Methods

2.1. Study sites

The forests chosen for this study were plots in different stages of the Tulip poplar association, which is both common and important in the mid-Atlantic region (Brush et al., 1980) and well-studied in the vicinity of the Smithsonian Environmental Research Center, SERC (Parker et al., 1989; Brown and Parker, 1994). We focused on local examples of four developmental stages including young (called "Nancy's plot"), intermediate ("KPH2a+ b"), mature ("Tower-creek") and old-growth stages ("Cedar Park"). All of the representative stands were located within 10 km of each other on similar soil types.

Table 1
General characteristics of the study stands, referring to all living stems over 2.0 cm DBH

Stand	Age (years)	Stem density (ha^{-1})	Basal area ($m^2\ ha^{-1}$)	Biomass ($Mg\ ha^{-1}$)
Young	12	21800	25.3	63.6
Intermediate	59	2090	51.0	349.9
Mature	95	1409	36.2	266.6
Old-growth	200+	1115	39.4	297.0

Ecological characteristics were measured in marked plots in each of the four stands, but not always in the same year as the altimetry observations. Stems greater than 2.0 cm DBH were censused in plots of sizes proportional to stand stature. In the 1.56 ha mature plot, estimates of density, basal area and biomass were corrected for the area of roads (ca. 5%). Stand age was estimated from ring counts from 10 large stems in each site, except for the old-growth, which was estimated to be more than 200 years old, from land-use history. Relative foliage height distributions were

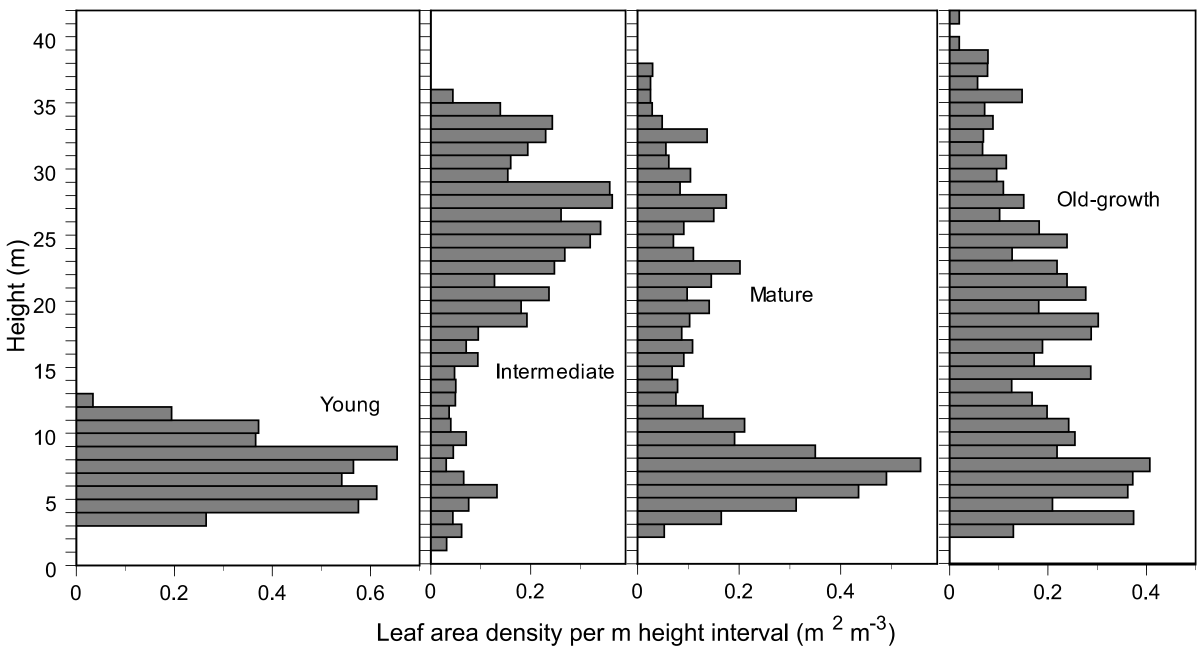

Fig. 1. Vertical distribution of foliage area in the canopies of the study sites, from ground-based optical observations and litterfall measurements.

measured using the method of optical point quadrats (Parker et al., 1989); leaf area index (LAI, $m^2\ m^{-2}$) was calculated from measurements of autumnal litterfall (Brown and Parker, 1994); and biomass was estimated from the equation of Monk et al. (1970). The leaf area density (LAD, $m^2\ m^{-3}$) for each meter of canopy height is the product of LAI and the proportion of leaf area at the level; the mean LAD is the ratio of LAI and maximum canopy height. The height above ground at which the cumulative downward LAI sums to 1 is termed the closure height. Important characteristics of the study stands are compared in Table 1. The vertical distribution of foliage in the stands is given in Fig. 1.

2.2. Laser altimetry

Sampling transects were identified for each stand by reference to local (Anne Arundel County, MD) topographic maps in areas that were relatively flat (slopes ranged from 2° to 8°). The intended flight paths were surveyed on the ground and small helium balloons were deployed at the top of the canopy to mark the ends of the flight paths. Altimetry transects, flown in the summer of 1997, were replicated with three roughly parallel lines in all stands except the old-growth (two lines).

A two-seat bubble-top helicopter (Hughes Aircraft Company, model H269C) was used as the sensing platform. A first-return laser rangefinder (Riegl Laser Measurement Systems, model LD90-3100HS) gave ranges at the rate of 200 Hz, where each range was the mean of five distances taken at 1000 Hz. The resolution of these averaged values was 1.0 cm. Video images of the canopy were taken with a camcorder focused at the laser target (Sony Corporation, model CCD-TR5). The laser and camcorder were placed in a cushioned box mounted to a searchlight bracket on the side of the helicopter. The laser was powered by a battery pack and the raw data were recorded on a laptop computer. Together these components cost about USD 12,000.

The helicopter flew at a nearly constant speed (about $2.2\ m\ s^{-1}$) and always at altitudes below the maximum range of the instrument (130 m). The start and stop times of all transects were noted. The mean along-track spacing (range 1.0–1.3 cm) was approximated from the total transect distance and the number of shots recovered.

2.3. Data processing

Range values obtained before and after the actual transect (e.g., while hovering in place before or after the desired section) were edited from the data. The ground contacts were identified by inspecting the plot of surface height versus horizontal distance. The procedure for identifying ground contacts was checked by comparison with ground elevation transects extracted from topographic maps. Using these values, the shape of the ground surface below the outer canopy was estimated by cubic spline interpolation (Press et al., 1992). Ranges missing due to poor target reflectivity (1.2% overall), were linearly interpolated. The height of the local outer canopy was the difference between the first and the ground surface for each shot.

2.4. Statistics

Simple summary statistics were calculated for each canopy height series using the SAS system (SAS Institute Inc., 1990a,b). The standard deviation of canopy height is termed “rugosity” here, to distinguish it from the particular meaning associated with other descriptors, such as “roughness” (Leonard and Federer, 1973; Ritchie et al., 1993; Menenti and Ritchie, 1994). The cumulative distribution of canopy heights is termed the “hypsograph”. Such a representation has been used in the description of landform surfaces and their development (e.g., Strahler, 1952, 1957). Other measures of spatial covariance of the surface were calculated, including the fractal dimension, D (Burrough, 1981, 1983)—derived from the semivariogram of canopy height versus transect distance (e.g., Isaaks and Srivastava, 1988), and the integral scale, the integral of the autocorrelation function through $r = 0$ (e.g., Tennekes and Lumley, 1992). Differences in the derived descriptors of structure between plots were tested with analysis of variance using the GLM procedure (SAS Institute Inc., 1990b).

As a measure of the relative shape of the canopy from altimetry observations, we used the elevation-relief ratio, E (Pike and Wilson, 1971), defined as

$$E = \frac{h_{\mathrm{mean}} - h_{\mathrm{min}}}{h_{\mathrm{max}} - h_{\mathrm{min}}},$$

where h_{mean}, h_{min}, and h_{max} are the mean, minimum, and maximum canopy heights, respectively. This ratio reflects the degree to which outer canopy surfaces are in the upper $(E > 0.5)$ or in the lower $(E < 0.5)$ portions of the height range.

3. Results

3.1. Stand structure from ground observations

The stands in this developmental sequence thin rapidly when young and stabilize in density, basal area, and biomass after the first few decades (Table 1). Leaf area index increases throughout the sequence but the volumetric packing of leaves (LAD) is greatest in the youngest stand (Table 2). Note that the intermediate plot is high in basal area and biomass—it is a vigorous and well-stocked stand, in which nearly all the stems are *Liriodendron tulipifera*. Fig. 1 shows the differences in canopy internal structure among the plots and illustrates patterns typical of forest development in this region. Following land abandonment or large-scale disturbance, a dense short canopy quickly develops (e.g., young) and expands over the next decades in both height and depth (intermediate). In later stages there are smaller increments in stand maximum height, but large changes in internal organization of foliage. A distinct understory develops after about 50 years, producing a bimodal foliage distribution (mature). Later still, shade-tolerant dominants arise and reach the mid-canopy. This and the appearance of canopy gaps of different ages produce a foliage profile more vertically uniform in the oldest stands (old-growth). The elaboration of lower canopy surfaces is reflected in a reduction in the mean foliage height (Table 2).

Table 2
Measures of canopy structure derived from optical observations and litterfall measurements made within the stands

Stand	LAI[a] ($m^2\,m^{-2}$)	Mean LAD[b] ($m^2\,m^{-3}$)	Mean height (m)	Closure height (m)
Young	4.18	0.373	6.2	7.5
Intermediate	5.10	0.143	23.1	30.5
Mature	5.92	0.144	13.6	23.5
Old-growth	7.03	0.171	16.5	28.5

[a] Leaf area index.
[b] Leaf area density.

3.2. Canopy surface from altimetry

The canopy-height sections differed among the forest plots. The young forest (12 m maximum height) had a rather smooth outline, with very few contacts with the ground (0.15% within 10 cm of the ground). The intermediate stage forest was much taller (maximum height 42 m) with a more jagged surface area and more ground contacts (0.36%) than the young stand. The mature forest had even more variation in heights (0.24% ground contacts). The canopy of the old-growth stage had several distinct ‘‘valleys’’, a very jagged surface, with many laser shots penetrating to the ground (0.53%) and intermediate depths. Representative transects for each of the four stands are given in Fig. 2.

The maximum canopy height rose from about 10 m in the youngest stand and stabilized at about 40 m in all the others. The mean heights of the outer forest canopy (Table 3) differed among the four plots (ANOVA: $F = 138.2$; $P < 0.0001$) and followed a trend with developmental stage. The young stand was shortest (3.9 m), but the intermediate had the highest average outer height (29.6 m); the mature and old-growth sites had progressively lower mean outer canopy heights (25.2 and 22.8 m, respectively), reflecting the influence of increasingly large and numerous gaps. The mean and maximum heights progressively diverged with stand age (Table 3). Canopy rugosity also differed significantly among plots (ANOVA: $F = 43.3; P < 0.0001$), increasing progressively, from 2.3 m (young forest), to 7.7 m (intermediate), to 9.4 m (mature), to 10.1 m (old-growth). The relative variability in canopy height (indicated by the coefficient of variation, the ratio of the standard deviation to the mean) decreased with developmental stage. Rugosity increased relatively more slowly than did mean outer canopy height with developmental stage.

All the measures of canopy complexity show that the outer canopy becomes increasingly elaborate with developmental stage. Of these, rugosity increased progressively through all stages (Table 4). The fractal dimension was generally larger in the older stands than the younger one, but the values were very closely clustered—the meaning to be associated with the differences found is unclear. The integral scale, which expresses the distance over which surface

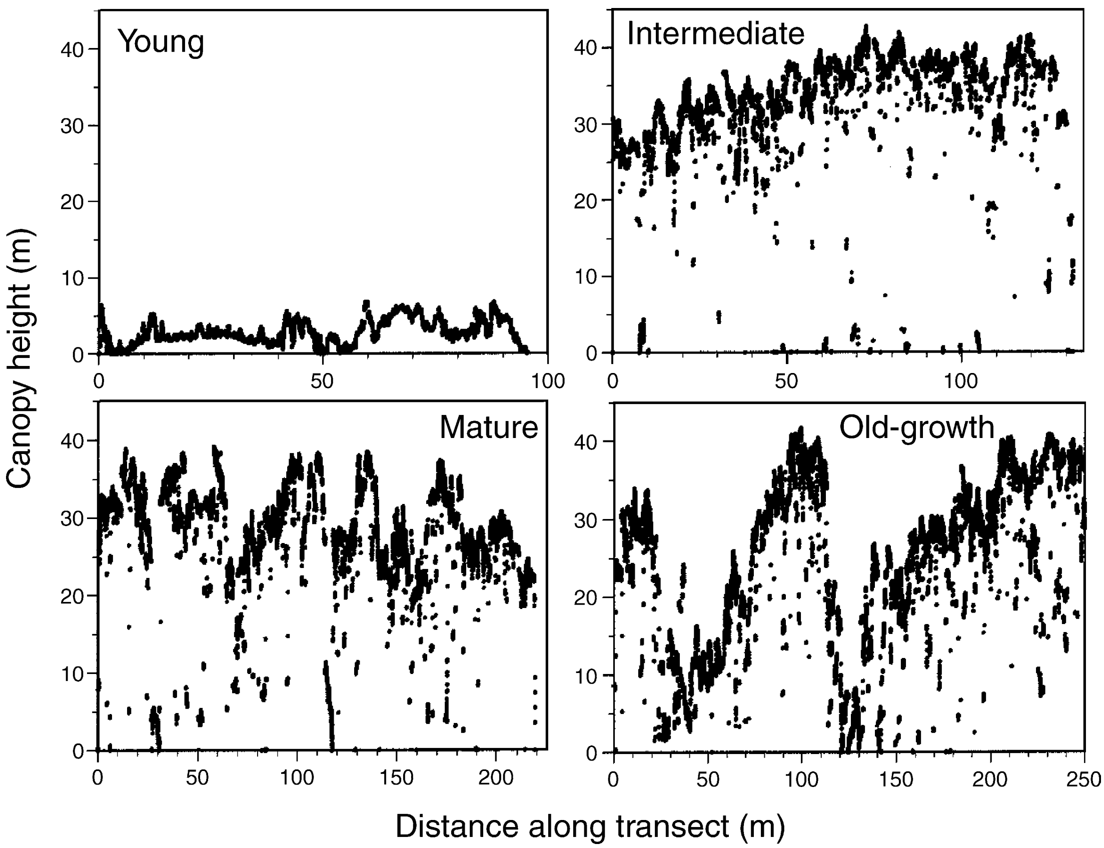

Fig. 2. Representative transects of local canopy height, measured with airborne laser altimetry, in the four study stands.

variations are correlated, agrees with the pattern of the fractal dimension. Thus, it appears that not only the variability of canopy shape but also the spatial scale of that variability increase with stand development stage.

The hypsographs differed among the plots but were similar among replicates within each stand (Fig. 3). The hypsograph is a nearly straight line in the youngest stand, with a very slight *y*-intercept. In the intermediate stands, it remains a straight line of about the same slope, but with a larger intercept. In the mature stand the hypsograph deviates from a straight line, with a curved section near the origin. This curvature is more pronounced in the old-growth stand. Not only does the maximum height change in stand development, but so also do the slope of the main portion of the curve and

Table 3
Simple statistics of the canopy heights of the four plots estimated from airborne altimetry[a]

Stand	Maximum height (m)	Standard deviation of height (m)	Mean height (m)	Elevation-relief ratio
Young	9.71 (2.61)	2.25 (0.43)	3.92 (0.92)	0.402 (0.092)
Intermediate	41.83 (1.50)	7.69 (0.04)	29.63 (1.51)	0.729 (0.019)
Mature	40.20 (0.95)	9.44 (0.75)	25.19 (1.21)	0.627 (0.064)
Old-growth	39.57 (3.10)	10.05 (0.21)	22.79 (1.14)	0.576 (0.005)

[a] Parenthetical values are standard deviations of each measure across replicate transects.

Table 4
Summary measurements of canopy complexity from airborne laser altimetry[a]

Stand	Rugosity (m)	Fractal dimension	Integral scale (m)
Young	2.25 (0.43)	1.78 (0.087)	5.2 (2.6)
Intermediate	7.69 (0.04)	1.93 (0.019)	3.5 (2.5)
Mature	9.44 (0.75)	1.89 (0.140)	16.4 (17.6)
Old-growth	10.05 (0.21)	1.94 (0.013)	15.8 (9.1)

[a] Values in parentheses are standard deviations of each measure across replicate transects.

the proportion of heights very close to the ground (Fig. 4).

Where directly comparable, the airborne altimetry measures and those taken from within the stand are consistent. For example, maximum heights are very similar for the optical (Table 2) and altimetric (Table 3) observations, but mean heights differ by method. This is because the optical measurements refer to all surfaces within the stand whereas the altimetric observations reflect only the topmost. Note nonetheless how both measures of height show the trend of rapid expansion followed by a decline with stand development.

Canopy cover derived from ground observations depends on the proportion of sky, while from the helicopter cover reflects the proportion of ground. Cover estimates are similar between methods but are always somewhat higher (>99%) from the downward-looking laser than those from the ground (ranging 93–97%). The bias is likely due to range-averaging by the laser (a ground observation requires five successive returns to be at the ground) and because there is some error associated with estimating the ground elevation from a fitted surface.

Some characteristics of canopy structure measured within the stand were related to others derived from laser altimetry. Surface rugosity was not related simply to the mean or maximum canopy height (since these showed a maximum in the intermediate developmental stage) but was related to the LAI, which typically increased during stand development, though

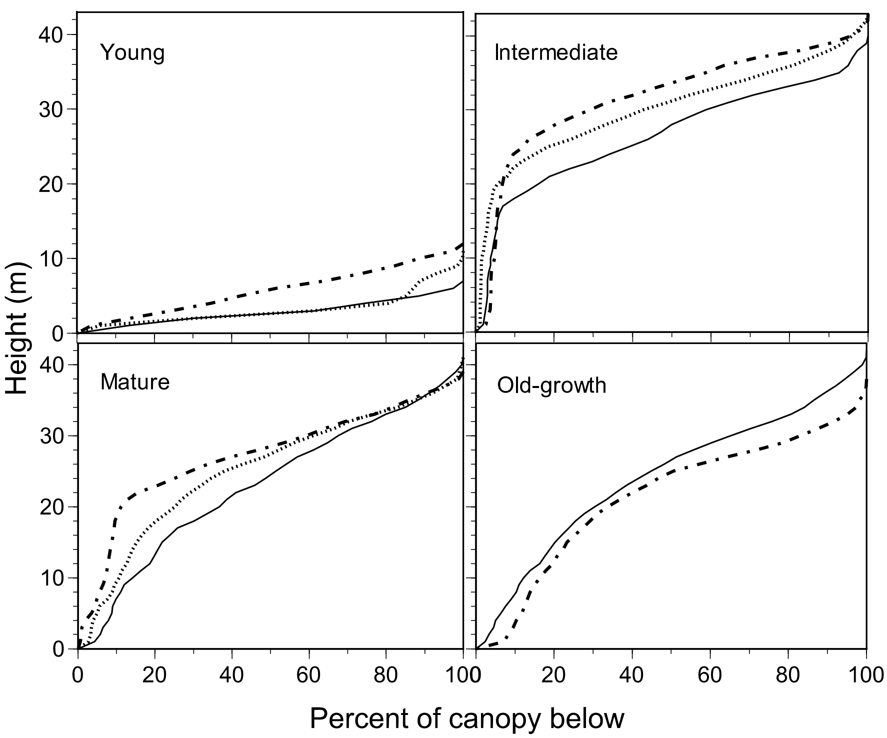

Fig. 3. Hypsographs derived from airborne laser altimetry for the separate transects in each study site.

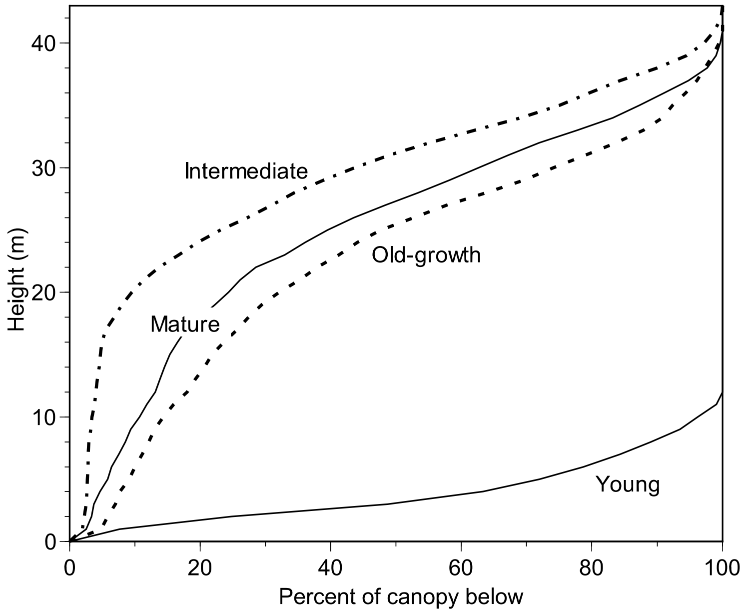

Fig. 4. Comparison of the mean hypsographs of each of the study sites.

asymptotically. Fig. 5 shows the relation between canopy rugosity and LAI, giving a curve describing the relation between them.

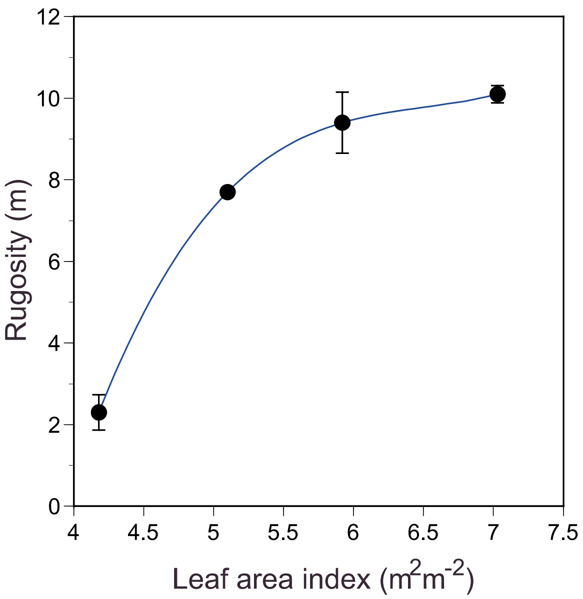

Fig. 5. Relation between surface rugosity and stand leaf area index (LAI) across the study sites. Error bars are standard deviations across replicate transects.

4. Discussion

This study was limited to 11 sample transects representing four stages in the developmental sequence of one forest association. Though replicate observations were performed in each plot, we recognize that the differences demonstrated here apply strictly to this set of plots, not to the general pattern of stand development in this forest type. Further, the consistency of the pattern presented may reflect the use of stands from a single forest association—it may not apply in another kind of forest or in mixtures of types. However, the trends we found are consistent with some other measurements and expectations and suggest broader applications. A full evaluation of this approach will require a more extensive observation set, with randomized allocation of stands and multiple replications within age/stage category.

4.1. General pattern with development

If the patterns we found from ground and airborne measurements are typical of stand developmental stages, they may be used to indicate the dynamic patterns of this forest type. The change in the

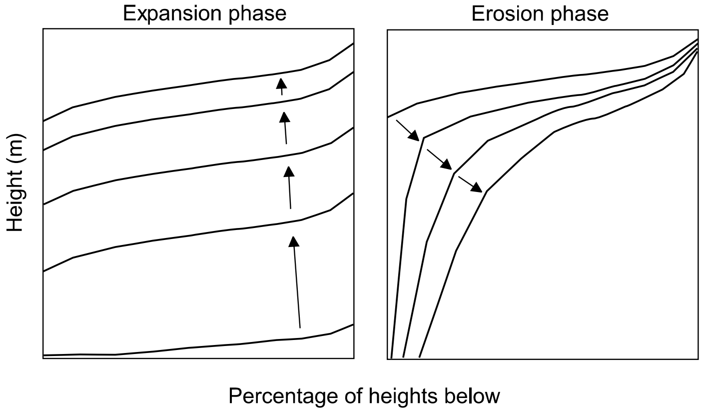

Fig. 6. Scheme depicting the two phases in outer canopy development, as reflected by changes in the hypsograph.

hypsograph illustrates some aspects of the developing outer canopy shape (Fig. 6). The youngest stage is short and uniform in surface. In succeeding decades the canopy grows rapidly in height, with relatively little increase in complexity. After reaching a maximum mean height (around 30 m in the intermediate stage) the outer surface begins to erode, with a slow decline in mean surface height, but a large increase in rugosity. As indicated by mean height, canopy volume peaked in the intermediate aged stands. This trend suggests that, if calibrated for a given type of vegetation, the trace of the outer canopy and some derived descriptors (such as the hypsograph) could be used to deduce developmental stage and/or surface complexity.

4.2. Quantifying effective canopy geometry

The hyspograph may be used to quantify intermediate-scale (tens to hundreds of meters) aspects of canopy structure that have proven difficult to define, such as the effective top, bottom, and depth. Most of the hypsographs have a linear central section, suggesting a well-behaved structure that might be simply described. These linear sections provide an estimate of the height of the effective top and bottom of the canopy, when extrapolated to the left and right vertical axes (0 and 100% of values). The difference between these is an estimate of effective canopy depth. Leonard and Federer (1973) used a similar approach in describing the surface of a red pine plantation. Unusually high leaves will be ignored by this approach. This approach is most appropriate for well-behaved outer canopies, such as in young or uniform stands. In older or heterogeneous stands, the canopy bottom may be undefined by this approach. Here we estimate the effective canopy top and bottom at 6 and 1 m, 40 and 21 m, 38 and 17 m, and 36 and 14 m, for the young, intermediate, mature and old-growth stands, respectively.

4.3. Surface topography and internal canopy structure

The rugosity of the outer canopy is related to measures of canopy internal structure. The topography of the outer canopy restricts the variation in the included structure. When rugosity is small, the canopy is potentially occupied with material at any level. However, when rugosity is high, implying height restrictions at many spatial locations, there will be a tendency for more foliage to be lower in the canopy (“bottom-heavy” structure in the sense of Parker, 1997).

The shape of the outer canopy is a guide to internal structure because it reflects and constrains that structure. It is reasonable that both the evenness of canopy internal structure (e.g., the vertical foliage distributions in Fig. 1) and total amount of foliage surface (e.g., the LAI) should be reflected in the complexity of the outer canopy (e.g., as measured by rugosity). The increase in LAI with increasing rugosity (Fig. 5) may be a response to the opportunity for allocating photosynthetic area at additional outer canopy surfaces such as at the edges of gaps.

5. Conclusion

This study tested a relatively inexpensive and straightforward method for measuring the general stature and structural complexity of the forest outer canopy. A laser rangefinder mounted on a small helicopter showed that the canopy surface varied not only in stature, but also in complexity in several forests of differing developmental stage. These changes were consistent with impressions gained from observations at the forest floor and with expected transitions in growth patterns and canopy events. These observations suggested two general phases of change in outer canopy structure during stand development (Fig. 6): a period of elevation of the canopy without elaboration (the ''expansion'' phase), followed by a period with a gradual decline in maximum canopy height and a concomitant increase in rugosity, caused by surface perforations, usually caused by the death of overstory trees (the ''erosion'' phase).

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