Selbyana 21(1,2): 79–87. 2000.

Canopy Topography of an Old-Growth Tropical Rain Forest Landscape

John F. Weishampel*

Department of Biology, University of Central Florida, Orlando, FL 32816-2368, USA.
E-mail: jweisham@mail.ucf.edu

J. Bryan Blair

Laser Remote Sensing Branch, Code 924, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Ralph Dubayah

Department of Geography, University of Maryland, College Park, MD 20742, USA

David B. Clark

Department of Biology, University of Missouri-St. Louis, St. Louis, MO 63121-4499, USA

Robert G. Knox

Biospheric Sciences Branch, Code 923, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Abstract. The surface topography of a forest canopy is complex. Like the Earth's surface, it has a morphology that consists of hills and valleys but punctuated by gaps. The study of the surface of the forest canopy has been limited, largely by access. Recent advances in remote sensing (i.e., scanning laser altimetry) are beginning to provide broader views of this key interface between the atmosphere and the terrestrial biosphere. Our analysis of canopy topography across a 1 km^2 area of old-growth tropical rain forest in La Selva, Costa Rica—derived with laser altimetry—details patterns based on measures of depth to canopy surface from a given elevation and height to canopy surface above the ground. Spatial autocorrelation patterns of canopy height, disregarding influences of ground topography, were isotropic and significantly positive at scales < 50 m. The fractal dimension of canopy heights across the landscape was 1.96, indicative of a nearly random distribution of peaks and troughs. In contrast, with the inclusion of ground elevation, canopy patterns exhibited anisotropy and had a fractal dimension of 1.78. At the sensor scale, the steepness of ground slopes was unrelated to canopy height measures.

Key words: fractal dimension, laser altimetry, remote sensing, spatial autocorrelation

Introduction

Forest canopy structure is comparable to a fractal sponge—a volume of spaces and phytomass between two (as found with a planar object) and three (as found with a solid object) dimensions. By ignoring fine resolution spaces, our analysis was able to depict the outer surface or forest canopy hull. This virtually unbuffered surface experiences dramatic changes in microclimate (wind, temperature, humidity) and is in part sculpted by erosional forces. The forest canopy hull is dynamic and subject to phenological changes (leaf abscission and flowering) and to longer term ecological changes (resulting from competition and mortality). Its shapes and textures embody the history of the forest mosaic. Forming this mosaic are different tree species, age classes, underlying soils, ground topography, and disturbances (both endogenous, such as treefalls, and exogenous, such as wind throw).

Though perhaps belittling the complexity of a dairy product, forests are not just Swiss cheese, as stated by Lieberman et al. (1989); they are not merely a random distribution of gaps (or holes) of different sizes. The forest canopy surface can be highly organized into wavelike (Satō & Iwasa 1993) or multifractal formations, fractals embedded within fractals (Solé & Manrubia 1995, Drake & Weishampel 2000), where the gap size distribution follows a power law. Such emergent properties, useful in categorizing forest types, also affect canopy-atmosphere interactions (e.g., energy and mass exchange and transport) and ecological processes (e.g., recruitment, growth, and competition). The unevenness

* Corresponding author.

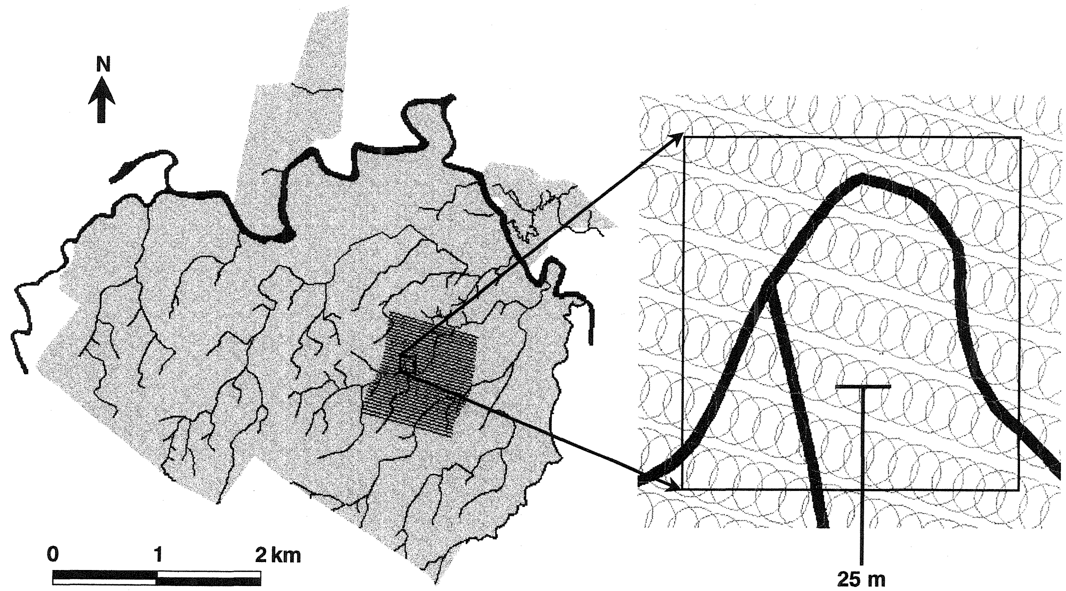

FIGURE 1. Portion of swath (≈1 km^2) of 2720 (80 × 34) overlapping LVIS footprints across a region of primary forest in La Selva, Costa Rica. The solid line in the inset is a tributary of the Puerto Viejo River. Circles represent the distribution of footprints.

of the top of tropical rain forest canopies may promote turbulent eddying of air, thereby enhancing transpiration, photosynthesis, and respiration (Leigh 1999).

Accurate mapping of forest canopy topography that depicts the spatial distribution of gap, dominant, codominant, and emergent crown elevations was deemed impossible 25 years ago (Leonard & Federer 1973). Though not impossible, such mapping remains difficult to obtain. Detailed canopy topography for the most part has been limited to areas a few ha in size, with canopy access provided by construction cranes (Parker et al. 1992, Parker 1993, 1995). Laser altimeters, originally designed to measure ground topography, produced results that were confounded by interfering returns from forest canopies (Arp et al. 1982). Laser altimeters adapted to focus on this signal are now capable of mapping canopy structure of forested landscapes (see Weishampel et al. 1996). We analyzed patterns of the canopy surface in a ca. 100-ha section of primary rain forest that were derived using the latest forest inventorying laser technology. Knowledge of such patterns is instrumental in developing radiative transfer and gaseous flux models.

METHODS

The Laser Vegetation Imaging Sensor (LVIS), see Blair et al. (1999), acquired canopy and ground measurements from La Selva Biological Research Station in Costa Rica (FIGURE 1), prior to the wet season in March 1998. LVIS flew aboard the NASA C-130 at altitudes ca. 8 km above ground level. LVIS is an imaging laser altimeter, similar to its immediate predecessor from the NASA Goddard Space Flight Center, called the Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) system (Blair et al. 1994, Lefsky et al. 1999a, 1999b, Means et al. 1999). It captures canopy structural patterns based on the reflectivity of component surfaces (such surfaces as leaves, branches, epiphytes, lianas, vines) from the canopy top to the ground. The resulting profile for a canopy is a waveform representing the vertical distribution of (approximately) nadir-projected surfaces. LVIS, unlike its predecessors which consisted of narrow transects of smaller laser footprints, is capable of mapping canopy landscapes (Weishampel et al. 2000). As programmed for this mission, it projected a 1-km across-track swath consisting of 80 overlapping, 25-m diameter laser footprints with a vertical resolution of 30 cm (FIGURE 1).

Canopy surface height measures differ, depending on whether height is measured from the ground up using traditional forest clinometer techniques (Avery & Burkhart 1994) or depth is measured to the upper surface of the canopy from above using a point drop technique (Miller & Lin 1985, Parker et al. 1992). The clinometer

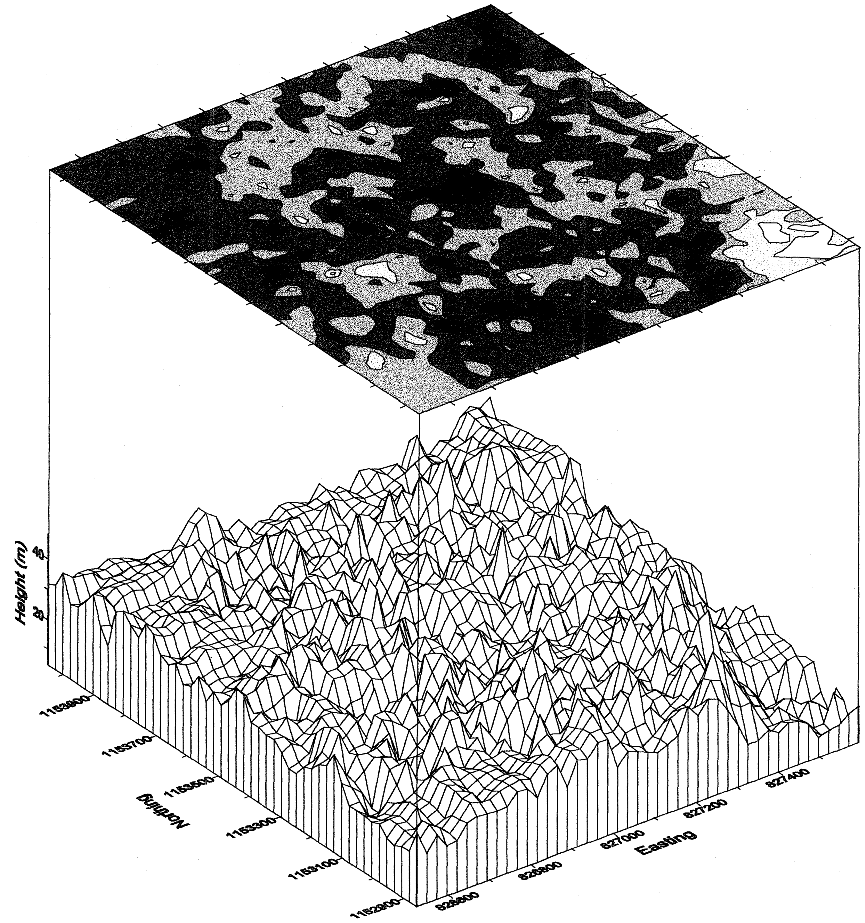

FIGURE 2. Contour and surface maps of canopy heights not including ground topography. Grey-scale intervals of 8 m range from 4 m (white) to 44 m (black).

method to measure tree height, typically does not account for differences resulting from fluctuations in ground elevation; it is equivalent to measuring the difference between the first and last laser return above the background noise from LVIS (FIGURE 2). The point drop method, analogous to bathymetric techniques, convolves ground and canopy elevations; it is equivalent to measuring the distance to the first LVIS return above the background noise (FIGURE 3). The clinometer method may be used for estimates of aboveground biomass or merchantable timber (Nelson 1997); whereas the point drop method may be more appropriate for canopy roughness measures affecting turbulent air flow (Groß 1993). Moreover, tree height and ground topography are often related; for instance, trees on sloped terrain tend to be shorter than trees on level terrain, and trees tend to decrease in size as elevation increases.

To compare topographic patterns of canopy height data derived using these two methods on the roughly 1 km^2 area of primary rain forest shown in FIGURE 1, we used several techniques. First, we followed a hypsometric approach rooted in geomorphology (Strahler 1952). Hypsometric methods, when applied to forest canopies (e.g., Leonard & Federer 1973, Lefsky et al. 1999a, G.G. Parker unpubl. data), depict the manner in which the canopy volume beneath the upper surface is distributed. These methods provide a graphical technique for comparing surface structure of canopied landscapes of different sizes and topographic relief. To directly assess the differences in the spatial distribution of heights, we used a multiple resolution goodness of fit

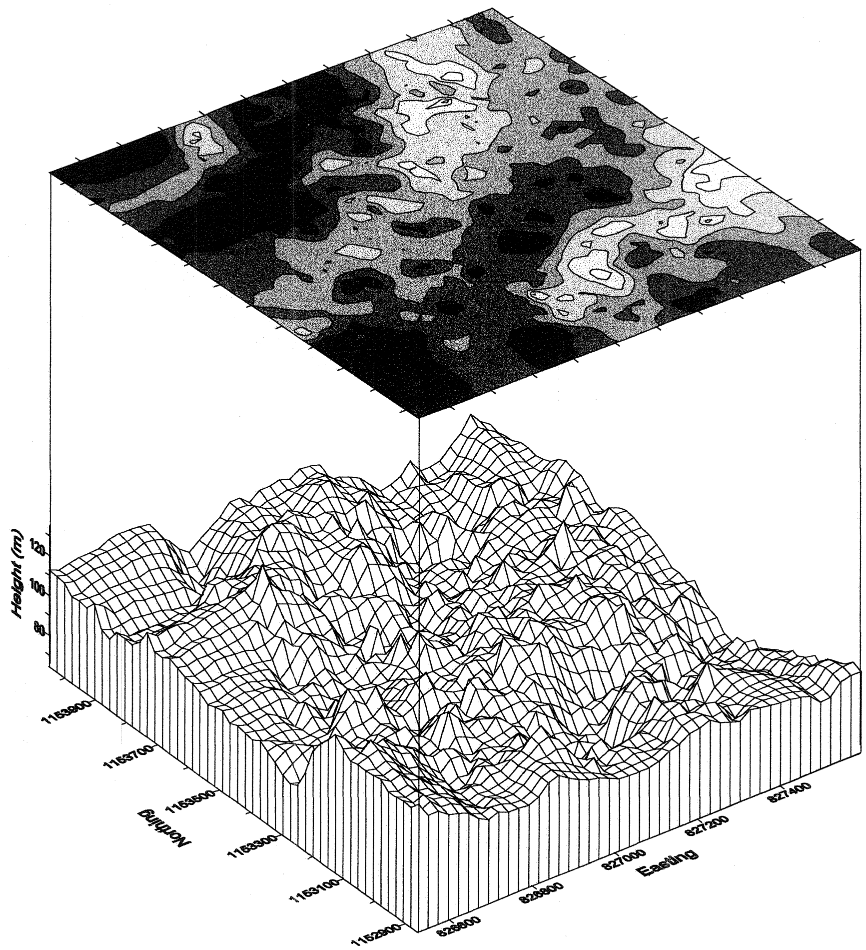

FIGURE 3. Contour and surface maps of canopy heights plus ground topography. Grey-scale intervals of 8 m range from 60 m (white) to 132 m (black).

procedure (Costanza 1989). For this procedure, heights were divided into quartiles and then treated as though they were unrelated categorical data. We then evaluated the number of height categories in windows of different sizes in corresponding locations from two maps. Autocorrelative patterns were calculated with geostatistical/fractal measures (Palmer 1988) and Moran's I (Legendre & Fortin 1989). Such measures have been used to quantify stand-level spatial patterns of measured (Ford 1976, Drake & Weishampel 2000) and simulated (Weishampel & Urban 1996) tree heights. To test for anisotropy, we examined autocorrelative properties from directions offset by 90°. Lastly, we evaluated the degree to which ground slope and tree heights were related. Vectors representing differences in laser-derived ground elevation were calculated (FIGURE 4). These show the direction and magnitude of slope which could be used to predict stream networks. Vector magnitudes at a given location were compared to canopy height measures.

RESULTS AND DISCUSSION

Both measures of canopy heights neared normal distribution (FIGURE 5). The mean aboveground canopy height for this section of old-growth forest was 29.3 m with a standard deviation of 7.2 m (FIGURE 5A). This is ca. 5 m taller than measured by Clark et al. (1996) at La Selva. Heights ranged 5.1–51.5 m. With the addition of elevation above mean sea level (msl), the mean height of the outer canopy surface was 99.1 m with a standard deviation of 9.9 (FIGURE 5B). These measures ranged 56.5–136.8 m, similar to what would be expected with published

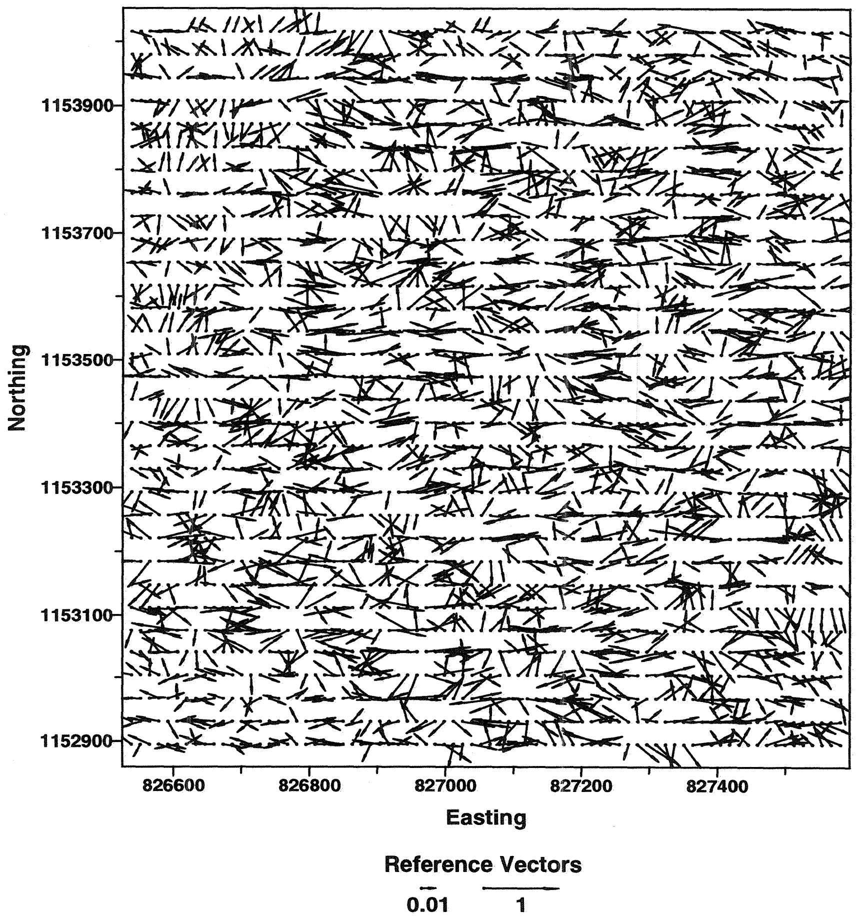

FIGURE 4. Vector map of ground topography depicting the direction and steepness of slopes.

ground elevation (Sanford et al. 1994). Thus ca. 34 m of canopy surface relief across this area could be accounted for by changes in ground elevation.

Both hypsometric curves (FIGURE 6) are similar. They are sigmoidal, indicative of normally distributed patterns. Their inflection points, which signify the transition point where the rate of decrease of canopy volume upwards changes from an increasingly rapid rate of decrease to a diminishing rate of decrease, occur approximately at the same location. The slope at the inflection point for the canopy heights without elevation is slightly less than that with elevation. This reflects the less jagged topography in canopies with elevation, as shown in FIGURES 2 and 3. This difference is also apparent in comparisons of the fractal dimensions (Zeide 1991, Pachepsky et al. 1997) of the different measures of canopy surface. Canopy topography without elevation had a fractal dimension of 1.96; that with elevation was 1.78. These dimensions mean that canopy topography without elevation was closer to random and occupied more of a two-dimensional area.

Though the multiple resolution goodness of fit between the two measures improved as window size increased (FIGURE 7), it always was less than expected with the random permutation maps of the quartile categories. The average fit (such as F_t from Costanza 1989), based on equal weighting of the window sizes, was 0.75 on a scale of zero to one, with one representing identical maps. This fit was significantly lower than that found with random quartile maps (F_t = 0.86). Thus at fine to coarse scales, essentially no correspondence was found between the height measures across the landscape.

Autocorrelative patterns for the two topographic measures were strikingly different. For

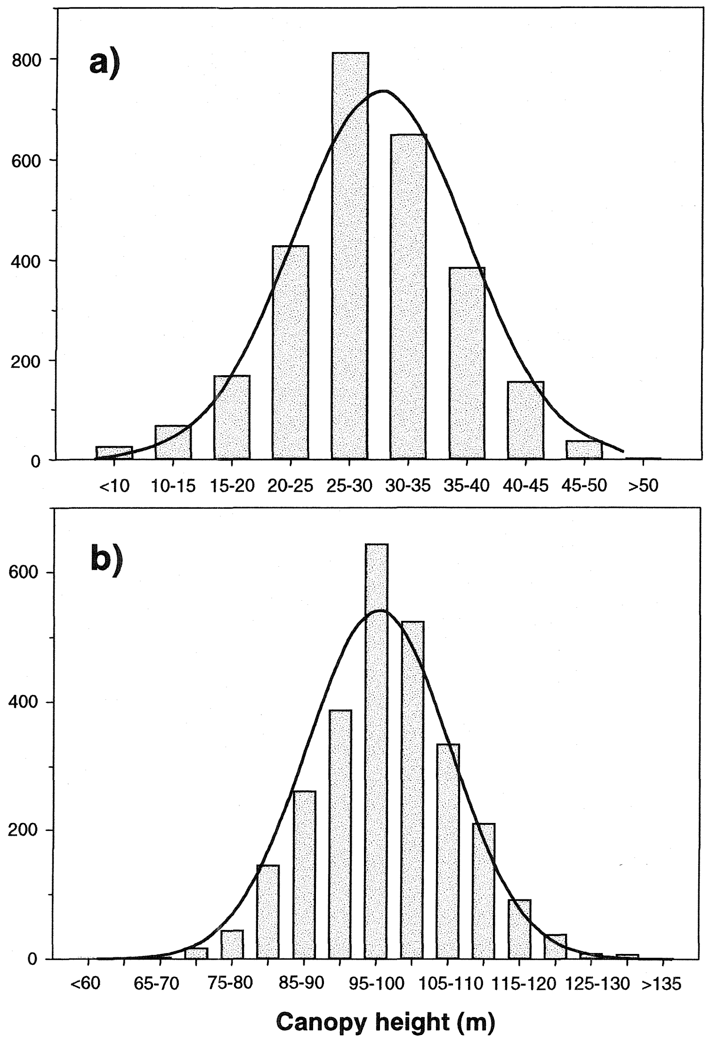

FIGURE 5. Distribution of canopy height measures derived from the laser altimeter: a) without ground topography and b) with ground topography. The solid lines are normal distributions from mean and standard deviation of measures.

canopy height measures alone, autocorrelation decreased to zero after 100 m (FIGURE 8), signifying randomness at these scales. This rapid decline and the absence of anisotropy (as designated by the similarity between 0° and 90° correlograms) are what would be expected from canopy height measures at La Selva (Clark et al. 1996) and from spatial gap model simulations near these latitudes (Weishampel & Urban 1996). For canopy height measures that included ground elevation, autocorrelation was initially higher and declined considerably up to 200 m. In addition, anisotropy was pronounced. Ground plus canopy topographic patterns exhibited periodic undulations at lags >600 m. The slight negative relationship found between slope steepness and canopy height was not significant.

CONCLUSIONS

Because ground topography accounted for more than a three-fold increase in average canopy surface height and a nearly two-fold increase in range, the two measures of canopy topography were not expected to be similar. Furthermore for this section of forest, ground elevation changes are relatively low and

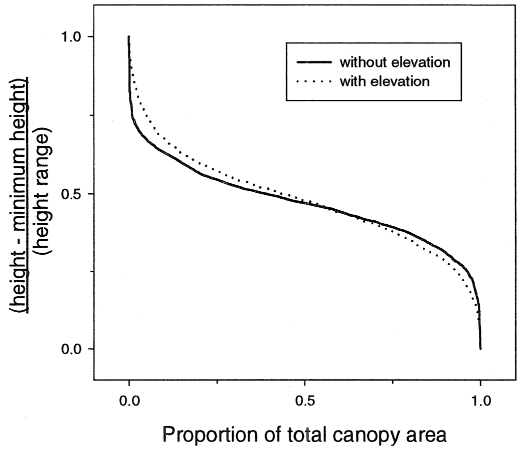

FIGURE 6. Hypsometric curves of canopy height measures.

should only minimally affect forest structure. Based on the hypsometric graphs, differences appeared to be slight, but they were most apparent when we examined autocorrelative properties. In these analyses, the underlying geomorphology revealed autocorrelation at distances well beyond that expected with simple measures of tree height. Additionally, the fractal measures showed canopy surface height without ground topography to have a rougher texture than when ground topography was included. Thus the vantagepoint of a bird flying above the canopy differs substantially from that of a monkey climbing from tree to tree within it.

At certain scales, closed canopy forests resemble a head of broccoli (H.H. Shugart pers. comm.); that is, they display self-similar fractal properties. Measures of canopy surface topography presently limited to a few areas soon will be available globally via remote sensing. The Vegetation Canopy Lidar (Dubayah et al. 1997) is a satellite mission scheduled to launch in 2002. It will provide transects of canopy surface height and below canopy ground topography data. This characterization of canopy properties will be used primarily for terrestrial ecosystem and climate modeling. It will provide a new means of classifying vegetated surfaces and more accurate parameterization of models that require information on canopy height. For carbon models that need better estimates of aboveground biomass, canopy height measures without topographic ground data will be available. For boundary layer airflow models that need better estimates of aerodynamic roughness or surface heterogeneities (Pielke et al. 1998), both measures of canopy surfaces may be utilized. Hence, measures of canopy structure once thought to be logistically impossible will be commonplace at landscape scales globally.

ACKNOWLEDGMENTS

We appreciate the assistance of Jason Godin, Michelle Hofton, and Nancy Casey-McCabe, and comments of two reviewers. This research was supported by a NASA Earth System Science Program (ESSP) award to the University of Maryland for the Vegetation Canopy Lidar

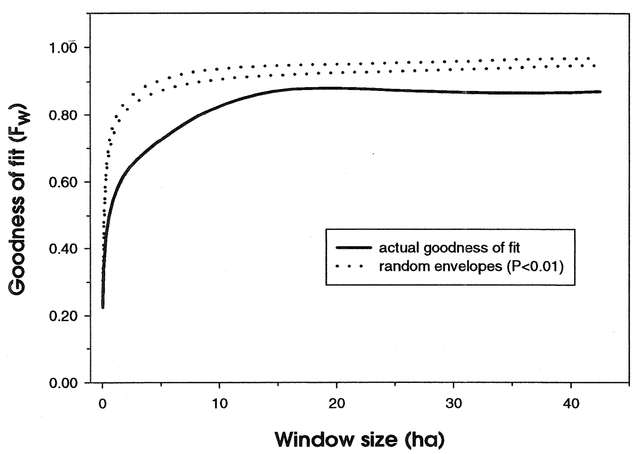

FIGURE 7. Goodness of fit versus window size for the canopy height surface measures with and without ground elevation. The dotted lines are the minimum and maximum values from 100 randomly permuted quartile maps.

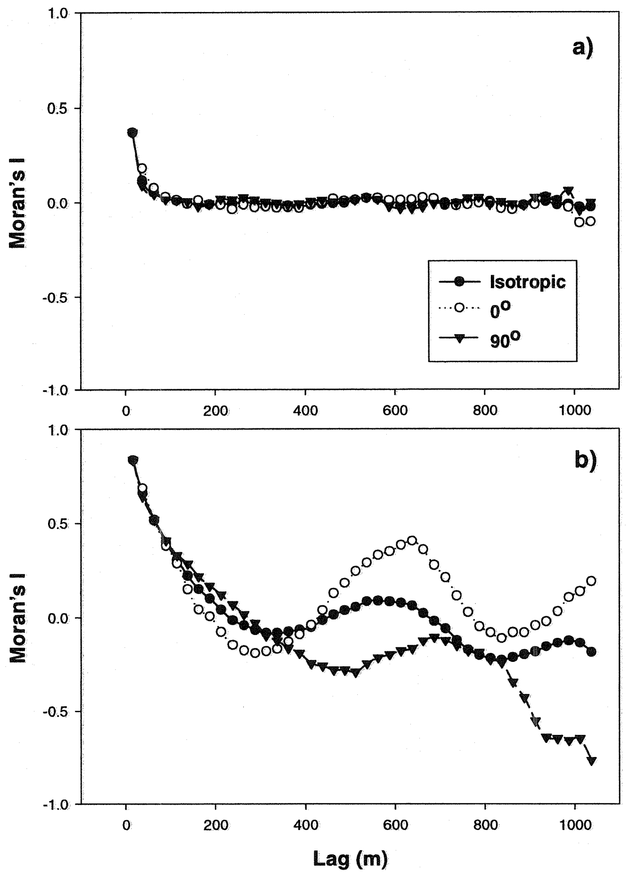

FIGURE 8. Autocorrelative properties of laser-derived canopy heights: a) without ground topography and b) with ground topography.

(VCL) mission subcontracted to the University of Central Florida (Z64 4403).

LITERATURE CITED

Arp, H., J.C. Griesbach and J.P. Burns. 1982. Mapping in tropical forests: A new approach using the Laser APR. Photogrammetric Engineering and Remote Sensing 48: 91–100.

Avery, T.E. and H.E. Burkhart. 1994. Forest Measurements. McGraw-Hill, Inc., New York.

Blair, J.B., D.B. Coyle, J.L. Bufton and D.J. Harding. 1994. Optimization of an airborne laser altimeter for remote sensing of vegetation and tree canopies. Pp. 939–941 *in* Proceedings of International Geoscience and Remote Sensing Symposium. Institute of Electrical and Electronics Engineers, Piscataway, New Jersey.

Blair, J.B., D.L. Rabine and M.A. Hofton. 1999. The Laser Vegetation Imaging Sensor (LVIS): A medium-altitude, digitization-only, airborne laser altimeter for mapping vegetation and topography. ISPRS J. Photogrammetry and Remote Sensing 54: 115–122.

Clark, D.B., D.A. Clark, P.M. Rich, S. Weiss and S.F. Oberbauer. 1996. Landscape-scale evaluation of understory light and canopy structure: Methods and application in a neotropical lowland rain forest. Canad. J. Forest Res. 26: 747–757.

Costanza, R. 1989. Model goodness of fit: A multiple resolution procedure. Ecol. Modeling 47: 199–215.

Drake, J.B. and J.F. Weishampel. 2000. Multifractal analysis of canopy height measures in a longleaf pine savanna. Forest Ecol. & Managem. 128: 121–127.

Dubayah, R., J.B. Blair, J.L. Bufton, D.B. Clark, J. JaJa, R. Knox, S.B. Luthcke, S. Prince and J. Weishampel. 1997. The Vegetation Canopy Lidar mission. Pp. 100–112 *in* Land Satellite Information in the Next Decade II: Sources and Applications. ASPRS, Bethesda, Maryland.

Ford, E.D. 1976. The canopy of a Scots pine forest: Description of a surface of complex roughness. Agric. Meteorol. 17: 9–32.

Groß, G. 1993. Numerical Simulation of Canopy Flows. Springer-Verlag, New York.

Lefsky, M.A., W.B. Cohen, S.A. Acker, G.G. Parker, T.A. Spies and D. Harding. 1999a. Lidar remote sensing of the canopy structure and biophysical properties of Douglas-fir western hemlock forests. Remote Sensing Environm. 70: 339–361.

Lefsky, M.A., D. Harding, W.B. Cohen, G. Parker and H.H. Shugart. 1999b. Surface lidar remote sensing of basal area and biomass in deciduous forests of eastern Maryland, USA. Remote Sensing Environm. 67: 83–98.

Legendre, P. and M.J. Fortin. 1989. Spatial pattern and ecological analysis. Vegetatio 80: 107–138.

Leigh, E.G. Jr. 1999. Tropical Forest Ecology: A View from Barro Colorado Island. Oxford University Press, New York.

Leonard, R.E. and C.A. Federer. 1973. Estimated and measured roughness parameters for a pine forest. J. Appl. Meteorol. 12: 302–307.

Lieberman, M., D. Lieberman and R. Peralta. 1989. Forests are not just Swiss cheese: Canopy stereogeometry of non-gaps in tropical forests. Ecology 70: 550–552.

Means, J.E., S.A. Acker, D.J. Harding, J.B. Blair, M.A. Lefsky, W.B. Cohen, M.E. Harmon and W.A. McKee. 1999. Use of large footprint scanning airborne lidar to estimate forest stand characteristics in the Western Cascades of Oregon. Remote Sensing Environm. 67: 298–308.

Miller, D.R. and J.D. Lin. 1985. Canopy architecture of a red maple edge stand measured by a point drop method. Pp. 59–70 *in* B.A. Hutchinson and B.B. Hicks, eds. The Forest-Atmosphere Interaction. Reidel Publ. Dordrecht, The Netherlands.

Nelson, R. 1997. Modeling forest canopy heights: the effects of canopy shape. Remote Sensing Environm. 60: 327–334.

Pachepsky, Y.A., J.C. Ritchie and D. Gimenez. 1997. Fractal modeling of airborne laser altimetry data. Remote Sensing Environm. 61: 150–161.

Palmer, M.W. 1988. Fractal geometry: a tool for describing spatial pattern of plant communities. Vegetatio 75: 91–102.

Parker, G.G. 1993. Structure and dynamics of the outer canopy of a Panamanian dry forest. Selbyana 14: 5.

———. 1995. Structure and microclimate of forest canopies. Pp. 73–106 *in* M.D. Lowman and N.M. Nadkarni, eds. Forest Canopies. Academic Press, San Diego.

Parker, G.G., A.P. Smith and K.P. Hogan. 1992. Access to the upper forest canopy with a large tower crane. BioScience 42: 664–670.

Pielke, R.A., Sr., R. Avissar, M. Raupach, A.J. Dolman, X. Zeng and S. Denning. 1998. Interactions between atmosphere and terrestrial ecosystems: Influence on weather and climate. Global Change Biol. 4: 461–475.

Sanford, R.L. Jr., P. Paaby, J.C. Luvall and E. Phillips. 1994. Climate, geomorphology, and aquatic systems. Pp. 19–33 *in* L.A. McDade, K.S. Bawa, H.A. Hespenheide and G.S. Hartshorn, eds. La Selva: Ecology and Natural History of a Neotropical Rain Forest. University of Chicago Press, Chicago.

Solé, R.V. and S.C. Manrubia. 1995. Are rainforests self-organized in a critical state? J. Theor. Biol. 173: 31–40.

Satō, K. and Y. Iwasa. 1993. Modeling of wave regeneration in subalpine *Abies* forests: Population dynamics with spatial structure. Ecology 74: 1538–1550.

Strahler, A.N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Bull. Geol. Soc. Amer. 63: 1117–1142.

Weishampel, J.F., J.B. Blair, R.G. Knox, R. Dubayah and D.B. Clark. 2000. Volumetric lidar return patterns from a primary tropical rainforest canopy. Int. J. Remote Sensing 21: 409–415.

Weishampel, J.F., K.J. Ranson and D. Harding. 1996. Remote sensing of forest canopies. Selbyana 7: 6–14.

Weishampel, J.F. and D.L. Urban. 1996. Linking a spatially explicit gap model with a 3-dimensional solar routine to simulate latitudinal effects. Ecol. Modeling 86: 101–111.

Zeide, B. 1991. Fractal geometry in forestry applications. Forest Ecol. Managem. 46: 179–188.