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Research article

Spatial pattern analysis of pre- and post-hurricane forest canopy structure in North Carolina, USA

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Abstract

Existing spatial patterns of a forest are in part a product of its disturbance history. Using laser altimetry and field measures of canopy top height to represent pre- and post-hurricane canopy topography, respectively, we measured changes in spatial patterns of stand structure of a United States southern mixed coniferous-deciduous forest. Autocorrelative and fractal properties were measured in this opportunistic study to quantify changes in canopy architecture along twelve, 190-250 m transects that were subjected to moderate to high levels of wind disturbance. Prior to the hurricane, canopy heights were autocorrelated at scales < 40 m with an average fractal dimension of 1.71. After the disturbance, autocorrelation disappeared; the average fractal dimension rose to 1.94. This shift towards spatial randomness illustrates part of the cyclical nature of ecosystem development. It shows how a catastrophic collapse of biomass accumulation corresponds to a decrease in ecosystem organization across a landscape.

Introduction

Forests of the southeastern United States are subject to large infrequent disturbances (LIDs) from hurricanes (Conner 1998) leaving imprints on the landscape or legacies that may persist for decades to centuries (Turner and Dale 1998). Wind gradients, topographic features, site conditions, and stand compositions produce varying disturbance intensities and susceptibilities at different spatial scales yielding complex landscape patterns (Putz et al. 1983; Foster et al. 1998). At local or plot scales, canopy alteration has been assessed by quantifying defoliation or light levels, branch loss, percent of downed, uprooted, bending, snapped, or dead trees (Everham 1995; Bellingham et al. 1996; Everham and Brokaw 1996). These measures often are expressed as timber volume or biomass lost. Rarely are the spatial patterns of these canopy measures considered within a disturbed area (Fernández and Fetcher 1991). At landscape to regional scales, impact effects can be scored and mapped from aerial photography (e.g., Gardner et al. 1992) and satellite imagery (e.g., Kovacs et al. 2001) and has been simulated using hurricane wind and topographic exposure models (Boose et al. 1994). In this study, we focus at the stand scale (< 1 km) assessing hurricane effects on canopy topography, the spatial distribution of canopy top elevations. Canopy topography embodies the history and site conditions of the forest stand. It represents the spatial aggregation of: leaf-level physiology; population/community-level demography; abiotic influences such as soil and climatic characteristics; and endogenous (e.g., gap dynamics) and exogenous (e.g., fire, pest, windthrow) disturbances. Canopy topography, in part, determines light penetration (Terborgh 1985), microclimate

(Parker 1995), boundary layer (Pielke and Avissar 1990) and habitat (Hinsley et al. 2002) properties.

Methods

Study area and hurricane fran

The Duke Forest is located adjacent to Durham, North Carolina, USA near the eastern edge of the North Carolina piedmont plateau. It consists of ≈ 3300 ha of coniferous, coniferous-deciduous mixed, upland deciduous, and bottomland deciduous communities with ongoing research activities since the 1930s. On September 6, 1996, seven days after achieving hurricane status (wind speed > 119 km/hr), Hurricane Fran made landfall near Cape Fear, North Carolina. Category 4 wind speeds (using the Saffir-Simpson scale for hurricane classification) exceeding 185 km/hr extended over much of the North Carolina coastline. While centered over central North Carolina, Fran weakened to tropical storm status (wind speed < 119 km/hr) and subsequently weakened further to tropical depression status (wind speed < 56 km/hr) while moving through Virginia (Mayfield 1996). The eye of Hurricane Fran crossed the Duke Forest with large areas of the forest sustaining substantial canopy alteration. Roadside inventories of the major forest divisions accounted for over 1400 trees downed across 56 km of roads. The majority of tree tipovers anecdotally were caused by the influence of preceding rains loosening the soil in concert with the high winds, whereas the majority of trunk snapping was caused directly by winds. Changes in canopy properties occurred throughout the forest (as shown in Figuur 1). Disturbance was most severe in old hardwood forests. Coniferous-deciduous mixed stands faired better, and young loblolly pine (*Pinus taeda*) plantations were barely affected (W.M. Weiher and A.L. Bedell, pers. comm.).

Data acquisition

In October 1994 before the majority of leaf abscission had occurred for this mixed evergreen-deciduous forest, the Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) sensor, developed by NASA Goddard Space Flight Center (Blair et al. 1994), was flown simultaneously with the Shuttle Imaging Radar (SIR-C) over the Duke Forest (see description in Harrell et al. 1997) to collect transects of laser pulse returns. The SLICER system used laser scanning to provide geolocated measurements of the vertical structure of vegetation and ground elevation beneath canopy layers (Weishampel et al. 1996; Lefsky et al. 1999; Means et al. 1999).

Laser altimetry or lidars are used as a way to remotely obtain vertical measurements and other characteristics of vegetation such as crown closure (see Lefsky et al. 2002). Pulses of near-infrared laser radiation are transmitted and based on precisely recording their round trip travel time, from the source to the target, distances, i.e., heights of reflecting surfaces, are measured. From these measures a variety of ecological or biophysical parameters can be derived such as growth form identification; aerodynamic roughness; timber yields; biomass, LAI, and basal area estimates; and canopy and ground topography (e.g., Maclean and Krabill 1986; Nelson et al. 1988; Nelson et al. 1997; Menenti and Ritchie 1994; Lefksy et al. 1999; Means et al. 1999; Weishampel et al. 2000). The measurement of interest in this study was canopy top height.

The SLICER sensor produced a waveform with a 0.11 m vertical resolution that represented the vertical distribution of intercepted surfaces or the reflectance of photons in a circular laser footprint from the forest structure. By subtracting the start of the waveform (the canopy top) from essentially the end of the waveform (the ground elevation), canopy heights were calculated. Pre-hurricane canopy heights were extracted using software algorithms for ground detection developed by Lefsky et al. (1999) provided by the Laser Altimeter Processing Facility at NASA Goddard Space Flight Center. The aircraft speed and the transmitter pulse repetition rate determined the spacing of the footprints across the three footprint tracks produced by this version of SLICER. By combining laser ranging data, aircraft GPS position, and laser pointing data, SLICER's footprints were geolocated (following methods similar to those described by Hofton et al. 2000) to within a horizontal accuracy of 10 m. Each footprint was approximately 10 m in diameter nominally spaced 10 m along and across three tracks as shown in Figure 1.

Field measurements. During July 1997, post-hurricane data were collected. Twelve segments of the SLICER flight lines were revisited. Five pairs of these are parallel transects from the same flight line. In these cases, each transect pair represents the outside footprints separated by an intervening line of footprints; thus, there was ≈ 20 m between footprint

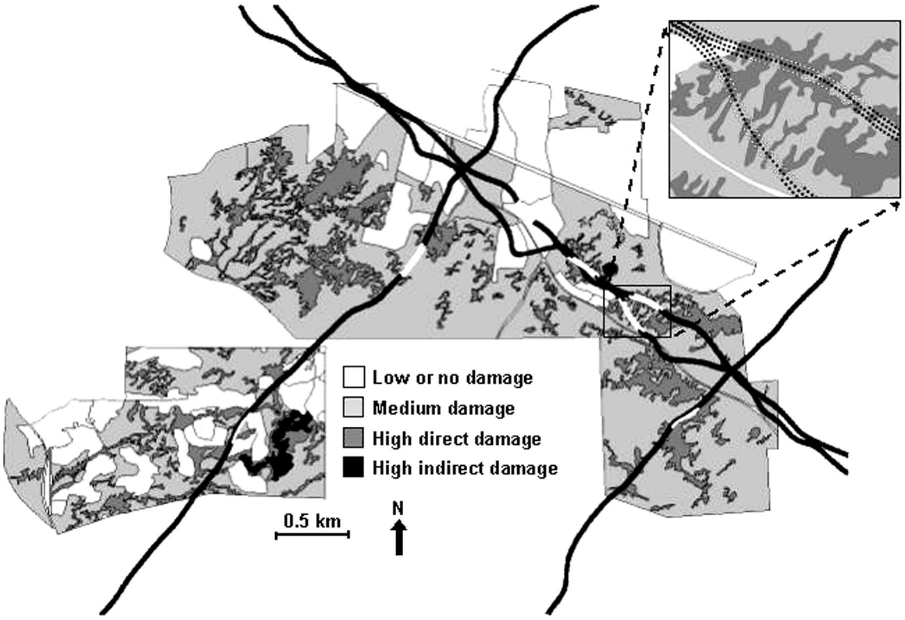

Figure 1. SLICER flight lines over the Durham Division of the Duke Forest. The white segments are the location of the twelve study transects. Each line consists of three parallel lines of laser footprints designated by continuous black circles. Degrees of canopy alteration were assessed with aerial photography and field surveys by the Duke Forest staff. The panel shows locations of individual footprints for sections of two flight lines. Heights from the two outer transects (the white circles) of each flight line segment were analyzed.

centers (Figuur 1). Transect lengths ranged from 190 to 250 m, i.e., 19 to 25 footprints. These transects were from uneven aged stands where there was little human disturbance since the 1970's and no major disturbance events since the hurricanes of 1955 and 1954 (Connie, Diane, and Ione). Prior to 1950 some stands were thinned and liberated. Four transects were in loblolly pine – oak (*Quercus spp.*) communities, six transects were in Shortleaf pine (*Pinus echinata*) – oak communities, and two transects were in white (*Quercus alba*), black (*Quercus velutina*), and southern red oak (*Quercus falcata*) communities.

Based on a post-hurricane field and aerial survey, ten transects were in moderate (30-60% of the trees had fallen) to highly ($>$ 60%) impacted areas and the remaining two transects were in less ($<$ 30%) impacted areas. These flight line segments were selected to prevent crossing vegetation community and forest management history boundaries. The center of each footprint in each transect was located using a real-time differential Global Positioning System (Timble Pro-XR). Following a manner similar to Clark et al. (1996), we used optical and laser range finders and clinometer techniques to estimate the height of the highest object (i.e., leaf or branch) within a footprint (i.e., the 10 m diameter cylindrical volume projected above the geolocated footprint center point on the ground). Repeated measures showed this technique to have within meter precision.

Because ground detection accuracy with SLICER is highly dependent on ground topography and understory density, height measures were compared to field measurements for loblolly pine plantation sites taken in conjunction with the SIR-C flight at the same time SLICER was flown (Harrell et al. 1997). Trees in the plantations ranged in age from 0 to 80 years and in height from 1 to 38 m. Figure 2 shows the relationship between field and sensor measures. Using the ground detection algorithms, SLICER on average overestimated the field-measured heights of small trees ($<$ 10 m) by 3–5 m and underestimated field-measured height of taller trees ($>$ 20 m) by 1–2 m. Overestimation of the small trees corresponds to the inability to accurately discern the ground whereas underestimation of tall trees can be related to insufficient photon reflection in the upper portions of the loblolly canopy. Because the pre-hurricane stands in this study generally possessed a closed upper canopy, the overestimation of the smaller trees by the lidar is not considered to be a major source of error. Regardless, to compensate for these discrepancies, pre-hurricane SLICER heights were calibrated to the field

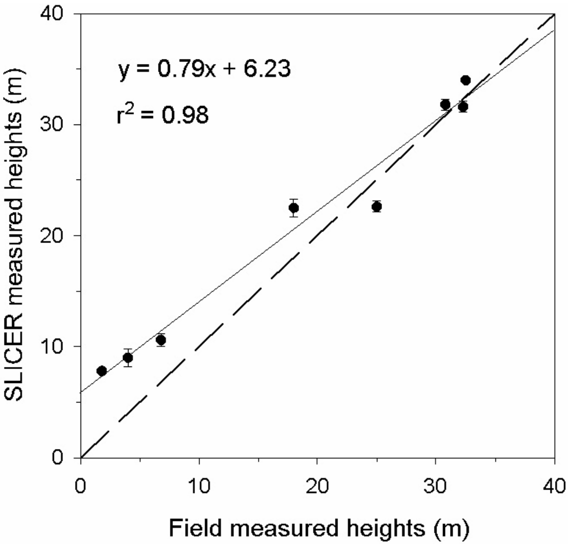

Figure 2. Comparison of field and sensor estimates of canopy height for eight loblolly stands of different ages. The dashed line represents a 1:1 relationship. Extensions above and below markers are ± 1 standard error.

measurements based on the regression relationship shown in Figure 2. However, it should be noted that the canopy architecture of the uneven-aged, mixed forest communities are more structurally complex than the loblolly plantations.

Spatial pattern analysis

To quantify differences in canopy topography due to hurricane disturbance, we used autocorrelative (Legendre and Fortin 1989) and geostatistical/fractal methods (Palmer 1988). These measures provide a quantitative description of the spatial structure and determine if a statistically significant pattern is present or absent. Positive autocorrelation means that variables at a particular distance apart have similar values, whereas negative autocorrelation means the variables at a particular distance apart have dissimilar values. Autocorrelation computes an index of covariance for the variables at different distance classes and assigns them to a class based on a computed weight with a range of -1 to 1. A correlogram, a graph of autocorrelation, displays the variable's spatial reliance on the ordinate versus the variable's distance among localities i.e. lag classes. To quantify autocorrelation, we used Moran's I (Moran 1948).

To calculate the fractal dimension, we used the variogram method (Vedyushkin 1994). Using this method for transect data treated as a spatially continuous, the fractal dimension varies between 1 and 2. A value of 1 indicates no change in the variable in space; a value of 2 indicates complete spatial randomness. Values between 1 and 2 represent a fractional dimension. These somewhat redundant analysis techniques (Palmer 2002) have been used in comparable studies of spatial patterns of canopy height (Clark et al. 1996; Weishampel and Urban 1996; Weishampel et al. 2000) as well as to discern age, density, and biomass patterns in Duke Forest loblolly stands (Shugart et al. 2000). To compare values of pre- and post-hurricane canopy topography, we used a paired t-test with transect-level measures of the average canopy height and the correlogram slope and the fractal dimension based on the spatial distribution of the height measures.

Results

As found with tropical rain forests (Brokaw and Grear 1991), the average canopy height in this temperate forest was reduced due to hurricane winds. Prior to the hurricane, the average canopy height measured by the laser altimeter for all footprints in the twelve transects was 25.8 m. After the hurricane, the average canopy height measured in the field was significantly lower ($P < .001$) at 19.2 m. Canopy heights for the taller loblolly pine dominated communities shifted from 29.6 to 17.8 m. Reduction in canopy heights for the shortleaf pine and oak dominated communities was less as they changed from 22.0 to 19.5 m. The frequency distribution of canopy top heights within the footprints (Figuur 3) depicts this overall hurricane-mediated shift.

The hurricane not only altered the canopy height measures, but also affected the spatial pattern of height distributions, i.e., the canopy topography. High positive autocorrelations at lag distances < 20 m present before the hurricane were absent after the hurricane. The average slope of the correlograms significantly ($P < .01$) changed from -0.008 to -0.002. This signifies that the spatial pattern of canopy height measures changed from a non-random, gradient-like pattern to random. Likewise, the overall fractal dimension significantly ($P < .01$) changed from a mean value of 1.71 to 1.94. This suggests that the vertical/horizontal spatial structure of the forest that was previously organized as a fractal became more random-like due to the disturbance.

Discussion

Though stem bending, snapping, and uprooting, defoliation, and timber volume are related to tree size and canopy height and have been used to assess forest damage (Everham 1995; Everham and Brokaw 1996; Platt et al. 2000), most wind disturbance studies do not directly measure height. Most studies arbitrarily score or rank the levels of canopy-level effects. In contrast, laser altimetry provides a direct measure of canopy height. Canopy topography puts height measures into a spatial context. It exhibits variation over a range of scales and can be quantified using spectral (Ford 1976), geostatistical (Weishampel et al. 1992), fractal (Pachepsky et al. 1997), multifractal (Drake and Weishampel 2000), and wavelet (Bradshaw and Spies 1992) techniques among others (see Keitt 2000).

Though canopy topography has been shown to be dynamic from year to year (Parker 1993) without high winds, the changes depicted here were dramatic and correspond to conservation (K, pre-hurricane) and release (Ω, post-hurricane) ecosystem stages detailed by Holling (1995). Prior to Hurricane Fran, the forest possessed high levels of connectedness or organization which are associated with high amounts of stored capital (e.g., biomass, nutrients). Spatially this was represented as a system that is positively autocorrelated at scales <40 m, perhaps reflecting acclimations to local site conditions. In essence, the hurricane increased entropy. Spatially this shake-up was represented by a reduction of organization, i.e., randomness across scales of 0-100 m. Though at coarser landscape-to-regional scales (10-500 km) hurricane-induced patchiness may not be random corresponding to terrain, weather, and stand variables (Foster et al. 1998), here the result of the hurricane at the stand scale in moderately to highly affected areas was a jump to randomness as the forest begins its reorganization (α) process (Holling 1995). Such changes in canopy topography will influence microclimate (within-canopy and understory light fields; Fernández and Fetcher 1991) and spatial patterns of subsequent tree regeneration as well as coarser-scale climatic properties (Pielke et al. 1998). These canopy patterns need to be considered when modeling light conditions (MacFarlane et al. 2003) in a disturbed stand.

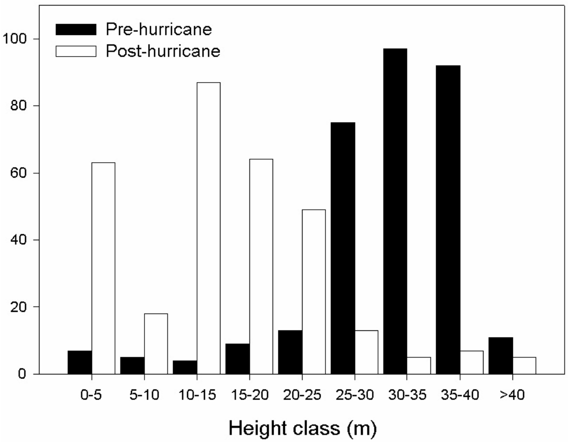

Figure 3. Frequency distribution of pre- and post-hurricane canopy top heights (N=313) from the twelve transects.

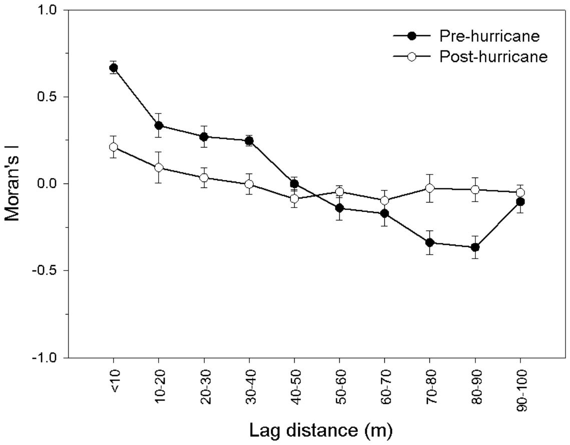

Figure 4. Average correlograms of pre- and post-hurricane canopy topography from the twelve transects. The extensions above and below the markers represent ± 1 standard error.

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