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Regional-scale application of lidar: Variation in forest canopy structure across the southeastern US

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ABSTRACT

Canopy structure is a fundamental property of forest ecosystems that influences microclimate, runoff, decomposition, nutrient cycling, forest disturbance, carbon storage, and biodiversity. Unlike ecosystem properties such as vegetation production, canopy structure mapping is limited by measurement constraints and is primarily measured for small areas. Consequently, few large scale studies of carbon budgets, nutrient cycling, and biodiversity use quantitative data on canopy structure. Progress in broad scale mapping of canopy structure has recently been made by merging field, airborne lidar, and satellite data. As a step towards regional mapping of canopy structure with lidar and satellite data, we examine patterns of lidar-derived canopy structure across five ecoregions from Maryland to Mississippi and evaluate relationships with climate, topography, and soils. We used NASA's Laser Vegetation Imaging Sensor (LVIS) to quantify canopy height, canopy cover, diversity of cover, and upper and lower canopy ratio metric along a 4000-km transect. Controlling for stand age, we found that canopy structure varied among undisturbed, closed-canopy stands across the study area. Compared with the Southeast Plains Ecoregion, the Blue Ridge and Central Appalachians ecoregions were greater in canopy height (25%), canopy cover (18%), and cover in the upper third of the canopy (212%). Values in the Piedmont were similar to those in the Southeast Plains. Locations highest in canopy structure were intermediate in temperature, growing season precipitation, topographic complexity and were located on sandy soils. The strength of biophysical models differed among ecoregions, explaining 13% of the variation in canopy height in the Southeastern Plain to 60% in the Ridge and Valley Ecoregion. Canopy structure also differed among disturbance classes. Undisturbed forests were 30% higher in canopy height, 15% higher in canopy cover, and 18% higher in cover of the upper third of the canopy than disturbed forests. Managed pine plantations were intermediate in canopy structure between disturbed and undisturbed forests. This study demonstrates that airborne lidar data can be used to distinguish differences in canopy structure among undisturbed forests in varying biophysical settings and between undisturbed and disturbed forests across sub-continental transects. The results suggest that airborne lidar data in conjunction with data on biophysical gradients can be used as a basis for extrapolating canopy structure at fine spatial scales across regional extents. This would allow for fine-scale characterization of forest structure continuously across large regions. Such methods should allow breakthroughs in the use of canopy structure in ecosystem management and global change studies.

1. Introduction

Canopy structure is a fundamental property of forest ecosystems that strongly influences their characteristics. Canopy structure is typically defined in terms of canopy height, total canopy cover, the distribution of canopy cover among forest height strata, and horizontal variation among these factors (Franklin and Van Pelt, 2004). These elements of canopy structure can influence microclimate (Didham and Lawton, 1999; Parker, 1995), runoff (Brodersen et al., 2000), decomposition and nutrient cycling (Hobbie, 1992), forest disturbance (Frolking et al., 2009), carbon storage (Asner et al., 2010), and biodiversity (MacArthur and MacArthur, 1961; Goetz et al., 2010; Whitehurst et al., 2013).

Because of the importance of canopy structure to ecosystem properties, foresters and ecologists have long invested in methods

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of measuring forest structure. Until recently, these methods were laborious field measurements that were restricted to relatively small plots (<0.10 ha) (Whitehurst et al., 2013). The use of aerial and satellite based remote sensing in the past decade has dramatically improved our ability to quantify forest structure (Hyde et al., 2006; Bergen et al., 2009; Lefsky et al., 2005). For example, the light detecting and ranging sensor (lidar) uses return rates of laser pulses to quantify the 3-D structure of forest canopies including canopy height, biomass, canopy cover, and canopy layering in vertical height classes (Dubayah and Drake, 2000; Lefsky et al., 2002; Vierling et al., 2008; Goetz et al., 2007; Swatantran et al., 2012; Whitehurst et al., 2013). Due to the cost of acquiring airborne lidar data, most studies to date have been done within relatively small areas such as specific forest stands or small watersheds (e.g., Hofton et al., 2002; Goetz et al., 2007; Dubayah et al., 2010; Goetz et al., 2010; Swatantran et al., 2012; Whitehurst et al., 2013). Satellite based methods have been used to quantify forest height globally (Lefsky, 2010; Simard et al., 2011), but low accuracies and wide spacing of samples limit the use of these data at regional scales.

In contrast to canopy structure, other ecosystem properties such as climate, vegetation production, and land cover are mapped continentally to globally at annual or finer intervals (Running et al., 2004) and are widely used in studies of carbon budgets, nutrient cycling, ecosystem productivity, and biodiversity. Such studies would benefit from consideration of canopy structure if data were available at appropriate spatial scales. Progress in mapping canopy structure at regional scales has recently been made (Asner et al., 2010, 2011). Data from field sampling, stratified lidar sampling, and Landsat-based mapping of land cover were used to estimate carbon stocks over a 4.3 million ha area in the Amazon and the one-million hectare Island of Hawaii. In these applications, the authors found that canopy structure varied with geologic substrate, landform, vegetation type, land cover and disturbance type.

Knowledge of biophysical and land use effects on canopy structure is critical to designing lidar and field data collection so as to sample the major sources of variation in canopy structure. As a step towards regional mapping of canopy structure with lidar and satellite data in the southeastern US, we examine patterns of lidar-derived canopy structure across five ecoregions stretching from Maryland to Mississippi and evaluate relationships with climate, topography, and soils, biophysical factors that influence forest growth and the development of canopy structure. In his classic monograph on vegetation of the Great Smoky Mountains, Whittaker (1956) examined the influence of environmental gradients on vegetation structure and composition. He concluded that forest stature, growth rates, and species composition varied across the environmental gradients of these mountains, reaching peak levels in particular "favorable" biophysical settings. Forests in the favorable lower elevation cove forests were as much as 50% taller than forests on ridge tops at higher elevations.

Some 50 years after this publication, Whittaker's gradient approach to vegetation distribution is considered foundational to ecology (Begon et al., 2006). Canopy structure is thought to be a product of primary productivity as governed by limiting biophysical factors and disturbance (Spies and Turner, 1999) (Fig. 1). Biophysical factors such as climate, topography, and soils influence resources and conditions within a forest through the mediating effects of canopy structure. These resources and conditions influence plant population growth rates and the capacity of the ecosystem to support species richness (S_K) (Brown et al., 2001). Actual species richness is a product of the size of the regional species pool and how those resources and conditions are allocated among species. Population growth rates and species richness influence primary productivity (Tilman, 2000) and the rate of development of canopy structure (Larson et al., 2008). While primary productivity builds canopy structure, disturbance can destroy plant tissue, kill plants, and thus reduce canopy structure (Pickett and White, 1985). Thus, canopy height and structural complexity are functions of time since disturbance and rates of primary productivity as governed by biophysical conditions.

This model of canopy structure is the basis of the concept of site index in forestry. Site index is used as a measure of site productivity and is defined by maximum tree height at a given time since disturbance (typically 50 years) (Skovsgaard and Vanclay, 2008). Trees are expected to be taller at a given age in sites with favorable climate, soils, and other limiting factors. Consistent with this assumption, Weiskittel et al. (2011) found that site index in western US forests was strongly related to climate and to gross primary productivity. In addition to tree height, the basis of site index, Larson et al. (2008) found that the complex structures of old growth forests developed more quickly in locations of high site index (see also Boucher et al., 2006). Additional evidence that canopy structure varies with biophysical factors comes from Homeier et al. (2010) who found that tree height and basal area were inversely related to elevation across a 700-m elevational gradient in the Ecuadorian Montane Rain Forest and that basal area was correlated with soil nutrients. Moreover, across a subcontinental transect from the maritime climate and favorable soils of the western Oregon and Washington to the continental climate of the Northern Rocky Mountains, a measure of forest structural complexity decreased by about half (Verschuyl et al., 2008).

Despite Whittaker's pioneering work nearly half a century ago, patterns of canopy structure across the forests of the southeastern US and controlling biophysical factors remain poorly known. Consequently, we sampled with an airborne lidar instrument a 4000-km transect from Washington DC to Jackson, MS (Fig. 2). The data were used to quantify canopy height, canopy cover, and canopy layering across five ecoregions. These data offer a unique opportunity to improve understanding of variation in 3-d canopy structure across the biophysical gradients of the SE US. Lidar transects were recently flown over the boreal forest of Canada (Bolton et al., 2013), a region of much harsher climate and lower primary productivity than the southeastern US. We compare our results with those of that study and discuss how the effects of biophysical factors on canopy structure may vary across continental gradients.

The objectives of this study were as follows.

(1) Quantify variation in forest canopy structure within and among ecoregions for forest stands showing no sign of recent disturbance.
(2) Determine the biophysical factors (climate, topography, soils, forest productivity) that best account for this variation.
(3) Evaluate differences in canopy structure among undisturbed, disturbed, and plantation forests.

2. Materials and methods

2.1. Overview

Objectives 1 and 2 focused on local and regional variation of canopy structure of forests across the southeastern US and the influence of biophysical factors on this variation in canopy structure. Data on canopy structure were collected using an airborne lidar system. From among the samples collected along the route, a subset was selected for this analysis that met the criteria of closed-canopy forest with no visual evidence of recent disturbance. Canopy structure of these samples was quantified as the number of canopy height classes represented and the proportional abundance of canopy cover within these height classes. Predictor data were obtained pertaining to climate, soils, topography, and forest productivity. Means and variation in canopy structure of stands of