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Estimating forest structure in a tropical forest using field measurements, a synthetic model and discrete return lidar data

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ABSTRACT

Tropical forests are huge reservoirs of terrestrial carbon and are experiencing rapid degradation and deforestation. Understanding forest structure proves vital in accurately estimating both forest biomass and also the natural disturbances and remote sensing is an essential method for quantification of forest properties and structure in the tropics. Our objective is to examine canopy vegetation profiles formulated from discrete return LIght Detection And Ranging (lidar) data and examine their usefulness in estimating forest structural parameters measured during a field campaign. We developed a modeling procedure that utilized hypothetical stand characteristics to examine lidar profiles. In essence, this is a simple method to further enhance shape characteristics from the lidar profile. In this paper we report the results comparing field data collected at La Selva, Costa Rica (10° 26′ N, 83° 59′ W) and forest structure and parameters calculated from vegetation height profiles and forest structural modeling. We developed multiple regression models for each measured forest biometric property using forward stepwise variable selection that used Bayesian information criteria (BIC) as selection criteria. Among measures of forest structure, ranging from tree lateral density, diameter at breast height, and crown geometry, we found strong relationships with lidar canopy vegetation profile parameters. Metrics developed from lidar that were indicators of height of canopy were not significant in estimating plot biomass (p-value $= 0.31$, $r^2 = 0.17$), but parameters from our synthetic forest model were found to be significant for estimating many of the forest structural properties, such as mean trunk diameter (p-value $= 0.004$, $r^2 = 0.51$) and tree density (p-value $= 0.002$, $r^2 = 0.43$). We were also able to develop a significant model relating lidar profiles to basal area (p-value $= 0.003$, $r^2 = 0.43$). Use of the full lidar profile provided additional avenues for the prediction of field based forest measure parameters. Our synthetic canopy model provides a novel method for examining lidar metrics by developing a look-up table of profiles that determine profile shape, depth, and height. We suggest that the use of metrics indicating canopy height derived from lidar are limited in understanding biomass in a forest with little variation across the landscape and that there are many parameters that may be gleaned by lidar data that inform on forest biometric properties.

1. Introduction

Tropical forests are huge reservoirs of terrestrial carbon and are experiencing rapid degradation and deforestation. REDD+ is a UN based initiative to retain forests and subsequent carbon through payment to maintain existing forested regions (http://www.un-redd.org). Understanding forest structure proves vital in accurately estimating both forest biomass and also the natural disturbances and regrowth important in REDD+ planning (Asner, 2011; Asner et al., 2013; Berenguer et al., 2014). Remote sensing proves an essential tool for quantifying forest properties and structure due to the vastness and remoteness of many forests in the tropics (Frolking et al., 2009).

Forests are complex ecosystems with diverse species assemblages, crown structures, size class distributions, and historical disturbances (Asner et al., 2002; Broadbent, Asner, Peña-Claros, Palace, & Soriano, 2008; Clark et al., 2001; Keller, Asner, Silva, Palace, 2004; McMichael et al., 2013, 2014; Palace et al., 2008). Tropical forests have been argued to be the most structurally diverse forests (Richards 1952; Whitmore, 1982). Forest structural components include canopy geometry and tree architecture, size distributions of trees, and species diversity (Hurtt et al., 2003; Spies, 1998). These structural properties of forests are closely linked with ecosystem functioning (Clark et al., 2001; Frolking et al., 2009; Spies, 1998). The dynamic processes of growth and disturbance are reflected in the structural components of forests,

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such as tree trunk diameter size distributions and canopy profiles, defined as the vertical distribution of foliage (Rice et al., 2004; Shugart, Hopkins, Burgess, & Mortlock, 1980; Tansley, 1935; Unger, Homeier, & Leuschner, 2013). The structural complexity of forests makes monitoring, understanding, and forecasting carbon dynamics difficult (Frolking et al., 2009). In tropical forests, gap formation or the death of individual trees is considered the prime disturbance mechanism (Denslow, 1987; Espírito-Santo et al., 2014; Vitousek & Denslow, 1986).

Knowledge of the three dimensional canopy structure of tropical forests is important for understanding gap formation and dynamics, light penetration, and surface roughness; all potential parameters in ecological models that are demographic, physiological, or physical in nature (Aber, 1979a; Denslow, 1987; Hartshorn, 1980; Marthews, Burslem, Phillips, & Mullins, 2008; Monsi, Uchijima, & Oikawa, 1973; Schemske & Brokaw, 1981; Terborgh, 1985). Specific forest structural properties are more easily measured, such as trunk diameter, and are links to providing insight and understanding of other properties that are more difficult to measure, such as biomass (Chave, Riéra, & Dubois, 2001). In addition forest structure provides insight into ecological processes and forest dynamics. One structural aspect of forests, the vertical profile of canopy vegetation, contains information about foliage distribution, trunk size distribution, light penetration and availability for understory vegetation, and canopy geometry (MacArthur & MacArthur, 1961, Stark et al., 2012; Sullivan, Palace, Ducey, 2014). Equations that estimate canopy profiles have been developed that link the MacArthur and Horn (1969) framework to broader statistical methodology, improving efficiency, flexibility, and the ability to incorporate auxiliary information (Aber, 1979a, 1979b; Maynard et al. 2013; Ni-Mester, Jupp, & Dubayah, 2001). LIght Detection And Ranging (lidar) data has been tested for efficacy within the forests (Chambers et al., 2007; DeFries, 2008, Stark et al., 2012; Sullivan et al., 2014). Lidar remote sensing has potential to measure properties of the forest through and below the top of the canopy, thus providing an additional dimension to structure studies (Hilker et al., 2014; Jensen, Humes, Vierling, & Hudak, 2008; Tang et al., 2012; Vierling, Rowell, Chen, Dykstra, & Vierling, 2002). Past work has demonstrated that lidar-derived canopy vegetation profiles compare well with ground-based profiles (Harding, Lefsky, Parker, & Blair, 2001). Other studies have shown that canopy vegetation profile metrics are useful for predicting biomass and other structural variables (*e.g.* Drake, Dubayah, Knox, Clark, & Blair, 2002; Drake et al., 2002; Garcia, Riano, Chuvieco, & Danson, 2010; Hurtt et al., 2004; Jensen et al., 2008; Lefsky et al., 1999; Lefsky et al., 2005, 2006; Means et al., 1999; Nelson, Short, & Valenti, 2004; Tang et al., 2012).

Discrete return lidar instruments are capable of producing several returns per square meter, and using return counts and summed intensities in discrete return lidar voxels (*i.e.* volumetric pixels) can be aggregated to develop vegetation profiles (Blair & Hofton, 1999). The high density of individual returns has made discrete return lidar data particularly amenable to high spatial resolution digital surface modeling of both ground (*e.g.* Hodgson, Jensen, Schmidt, Schill, & David, 2003; Hodgson et al., 2005) and forest canopies (*e.g.* Popescu & Zhao, 2008). Past work has demonstrated that lidar-derived canopy vegetation profiles compare well with ground-based profiles using full waveform lidar (*e.g.* Harding et al., 2001), and somewhat less-so using discrete return lidar (*e.g.* Lovell, Jupp, Culvenor, & Coops, 2003; Hopkinson et al., 2013; Sullivan et al., 2014).

Stem biomass comprises the largest fraction of aboveground biomass in mature forests, and it is related to the product of basal area and height. Much work has been done on temperate forest structure using lidar data, such as LAI, habitat quality and other structural parameters that go beyond just biomass estimation (Clawges, Vierling, Vierling, & Rowell, 2008; Jensen et al., 2008; Morsdorf, Kotz, Meier, Itten, & Allgower, 2006). Many of these advances in temperate forests have not been seen in tropical forests because of the lack of lidar collection in tropical regions, difficulty in conducting field based measurements, differences in field based methodology confounding interpretation, lack of ongoing experimental plots for comparison, unique and unknown historical forest disturbances, and complexity of the structure due to the diversity of tree species (Asner et al., 2013; Chambers et al., 2007; Frolking et al., 2009).

We stress that lidar derived vegetation profiles contain information that provides information on tree stand size distributions in addition to other forest biometric properties (*e.g.* canopy geometry) (Hunter et al., 2013; Stark et al., 2012). In the tropics, studies have largely focused on height metrics from lidar-derived vegetation profiles, whereas other metrics such as lacunarity and entropy show promise to provide information on disturbance history (Weishampel, Drake, Cooper, Blair, & Hofton, 2007), in addition to biomass (Stark et al., 2012; Zhao, Popescu, & Nelson, 2009). In tropical forests, work using lidar has been conducted at La Selva, Costa Rica to estimate forest structural properties. Discrete return lidar instruments have provided improvements on the estimation of LAI and metrics related to canopy geometry and architecture (Tang et al., 2012; Vierling et al., 2002). Tang et al. (2012) estimated field measured LAI using the entire waveform collected by NASA's Laser Vegetation Imaging Sensor (LVIS) (Dubayah et al., 1997). Dubayah et al. (2010) compared field measured biomass with various lidar estimated height metrics derived from LVIS waveforms. Treuhaft et al. (2010) used Fourier analysis of waveform profiles to estimate biomass. These three studies used LVIS waveform lidar data. Using discrete lidar, Kellner, Clark, and Hubbell (2009) examined gap transition at La Selva, Costa Rica using two datasets 8.5 years apart.

In this study we sought to relate field-measured forest characteristics, including biomass, height, diameter, basal area, and an array of canopy geometric parameters, such as maximum height and crown depth, to measures derived from discrete return lidar data. Previous studies have established relationships between lidar metrics, primarily percentile measures or relative height classes, to field data. We developed a suite of metrics from untransformed and transformed relative vegetation profiles (RVPs) calculated from discrete return airborne lidar data. These metrics are not commonly used and we consider them to be analogous to field-based measurements, such as the number of canopy local maxima in a RVP, measures of canopy vegetation distribution diversity and evenness (entropy), and estimates of gap fraction. We developed a modeling procedure that utilized hypothetical stand characteristics to generate synthetic vegetation profiles that could be compared with profiles developed from field and lidar data. Essentially, this method was used in an effort to estimate stand characteristics by comparing lidar RVPs to a series of modeled RVPs with known stand conditions (*e.g.* shape and scale of the diameter distribution). We also included lidar coherence metrics pulled from discrete Fourier transforms of untransformed profiles based on the approach of Treuhaft et al. (2010). We expect that these metrics, used in lieu of and in addition to relative height percentiles used in other studies (*e.g.* Drake et al., 2003; Dubayah et al., 2010), may prove valuable because they account for sub-dominant canopy structure and variability in canopy vegetation profiles.

2. Methods

2.1. Site location

Our study was conducted within the La Selva Biological Station (10° 26′ N, 83° 59′ W), in the Atlantic lowlands of Costa Rica, operated by the Organization for Tropical Studies (McDade & Hartshorn, 1994). Using a set of *a priori* constraints on site selection and GIS data layers (trails existing studies, water bodies, vegetation type) provided by the La Selva (http://www.ots.ac.cr), twenty plots were randomly selected throughout La Selva on which to measure field-based biometric properties and examine with remotely sensed lidar data (Fig. 1). For ease of access, sites were chosen within 100 m and greater than 30 m of established trails. To address potential issues with local topography, sites were selected that were at least 50 m from rivers and water bodies. To avoid disturbing ongoing long term research, plots were selected so