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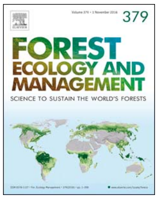

# Comparison of lidar- and allometry-derived canopy height models in an eastern deciduous forest

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## ABSTRACT

Tree crown geometry and height, especially when coupled with remotely sensed data, can aid in the characterization of tree and forest structure. In this study, we develop mixed-effects model allometric equations for tree height, crown radius, and crown depth using data collected on 374 trees across 14 species within the extent of the joint Center for Tropical Forest Science (CTFS) and Smithsonian Institute's Forest Global Earth Observatory (ForestGEO) MegaPlot on Prospect Hill at Harvard Forest, Massachusetts. We applied allometry to a census of the 35-ha plot on Prospect Hill to evaluate tree height and crown radius estimates using a lidar canopy height model. We found significant relationships using stem diameter-at-breast-height (*DBH*) and species to estimate tree height ($\rho r^2 = 0.70$, RMSE = 2.96 m), crown depth ($\rho r^2 = 0.35$, RMSE = 3.24 m) and crown radius ($\rho r^2 = 0.43$, RMSE = 1.22 m). Using Fast Fourier Transforms (FFTs), we compared the power spectra of a lidar canopy height model to five synthetic canopy height models derived from allometric estimates of height and crown radius. The FFTs showed good agreement between lidar and synthetic canopy height models (CHMs) at spatial wavelengths longer than 64 m, or about the distance across 3–4 dominant tree crowns, and poorer agreement at shorter spatial wavelengths, which we attribute to the simple crown shape applied to modeled crowns and a lack of crown overlap in the synthetic CHMs compared to the lidar CHM. At the tree level, some species exhibited tight links between lidar-measured height and estimated tree height (e.g., *Quercus rubra*, *Quercus velutina*, *Pinus strobus*), suggesting height allometry provided reasonable estimates of tree height for some species despite a negative bias in the synthetic canopy height models relative to the lidar canopy height model.

## 1. Introduction

The structural status of forests is driven by processes of carbon uptake, disturbance regimes, and their historical trajectories (Frolking et al., 2009, Espirito-Santo et al., 2014), and is influenced by complex interrelationships of architectural components of trees. Understanding relationships among different characteristics of tree and forest structure (e.g., stem diameter, canopy height, crown geometry, species assemblages, aboveground biomass) is critical to assessing and extrapolating field measurements to inaccessible sites using remote sensing data (e.g., Spies, 1998; Xie et al., 2008; Frolking et al., 2009; Saatchi et al., 2011; Homolova et al., 2013, Meyer et al., 2013; Mauya et al., 2015; Palace et al., 2015). To best utilize the advances in remote sensing technologies for forest demography and biomass research, it is necessary that site-specific field-data driven allometric models are developed and tested (Hunter et al., 2013). In particular, estimation of stand biomass using remote sensing tools, e.g. light detection and ranging (lidar), could greatly benefit from tree-level allometry, such as height and crown geometry (Dalponte and Coomes, 2016), as well as automated tree crown detection tools (Palace et al., 2008; Duncanson et al., 2015; Ferraz et al., 2016). If such characteristics of trees can be statistically linked to bole biomass predictors, such as stem diameter at breast height (*DBH*), stand biomass estimation can theoretically be scale-invariant using commonly used allometric equations to estimate biomass at the tree-level (Zhao et al., 2009).

Many studies have used remote sensing data, specifically lidar, to characterize and monitor forest structure. Approaches to characterizing biomass across large areas at large spatial scales (ranging from hectares

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to square kilometers) using relationships developed between field data and lidar metrics are common (Dubayah et al., 2010; Ni-Meister et al., 2010; Saatchi et al., 2011; Yao et al., 2011; Asner et al., 2012; Palace et al., 2015; Manuri et al., 2017). Typically, biomass allometry for estimation using lidar data use a range of modeling approaches to relate field-estimated biomass (i.e. calculated by *DBH* allometry) to lidar-derived metrics like mean canopy height at the plot level, lidar maximum height, energy or return percentiles, and more complex metrics like entropy (Lefsky et al., 1999; Dubayah et al., 2010; Saatchi et al., 2011; Treuhaft et al., 2014; Sullivan et al., 2014; Palace et al., 2015; Palace et al., 2016). Recent applications have used lidar for mapping logging roads and skid trails in order to estimate the carbon impact of logging operations (e.g. Anderson et al., 2014; Ellis et al., 2016). These approaches to biomass estimation and carbon impacts of logging, however, have mostly been successful at scales ranging from hectares to kilometers, and estimates are generally mapped across landscapes and regions, as opposed to the individual tree-level, which theoretically could be aggregated for plot and regional estimates of biomass (van Leeuwen and Nieuwenhuis, 2010).

For tree- and plot-level field based biomass estimates, allometric equations have been developed predominantly using *DBH*, though some have been established with height modifiers (e.g. Chave et al., 2005). The allometric uncertainty associated with *DBH*-only models typically impacts the first significant digit of ensuing estimates, especially when models are applied outside the population within which they were developed (Kershaw et al., 2016), and as it represents a form of bias it does not vanish with increasing sample size. Hunter et al. (2013) demonstrated, however, that plot-level field biomass estimates that also incorporate height are subject to 5–6% error due to imprecise tree height measurements in dense forests. To that end, site-specific height allometry or accurate height measurements using lidar to retrieve tree-level heights could serve to reduce measurement error and improve biomass estimation uncertainty. Furthermore, *DBH*-height allometric equations have been developed for individual sites and globally (e.g. Feldspauch et al., 2011), which when used out-of-population or (in the case of regional or global equations) at specific sites can result in even greater uncertainty in biomass estimates (Hunter et al., 2013). For a thorough treatment of *DBH*, height, and tree volume or biomass allometry, see Kershaw et al. (2016, ch. 6).

It is possible that remote sensing estimates of biomass could stand to be improved further by including crown size variables in models. Indeed, Goodman et al. (2014) showed significant improvement in aboveground biomass estimates when accounting for tree crown radius. Other studies have also shown that tree crown variability is useful for estimating biomass. Jucker et al. (2017) developed a global database of stem diameter, height, and crown diameter, and go on to show that crown diameter and tree height can be used to estimate both stem diameter and aboveground biomass of individual trees. Ferraz et al. (2016) applied crown detection techniques to estimate tree and crown shape characteristics, then developed biomass equations which they assessed at multiple scales. Approaches to remote biomass estimation using crown geometry characteristics will prove most useful when combined with rapid and accurate tree crown delineation (Swetnam and Falk, 2014; Ferraz et al., 2016), but even given success, there are challenges to linking crown geometry and biomass at the tree-level caused by crown plasticity.

Because vertical and horizontal accuracies of commercial airborne lidar systems are generally around ± 15 cm and ± 50 cm, it is a valuable tool that can be used for assessing field-based allometric models. At tropical forest sites and some low complexity temperate sites, crown geometry has been assessed and compared from both field-based and remote sensing measurements (e.g. Asner et al., 2002; Broadbent et al., 2008; Palace et al., 2008). Although it would be useful for directly assessing tree-level height and crown geometry allometry, efforts to compare lidar remote sensing measurements to field-based estimates are relatively uncommon in mixed deciduous temperate forests. Here, we examine the potential to assess height and crown allometry using lidar data at Harvard Forest, a temperate forest site in Petersham, Massachusetts. The motivation for this study was to demonstrate the development of mixed effects allometric models for tree height and crown geometry, which we apply to census data of a 35-ha plot to develop a simple canopy height model (CHM). Using multiple error correction approaches for the allometry, we estimate the power spectra of their 2-dimensional Fast Fourier Transforms which we use to compare CHMs at the site level and at finer spatial scales. To assess allometric equations for tree height, we compared the synthetic allometric canopy height models to the lidar canopy height model at the species-level. Lastly, we leverage our comparison between lidar and allometric CHMs to evaluate allometric relationships in the context of plant functional traits, crown plasticity and structural variation, and tree form models.

## 2. Methods

### 2.1. Field census

Between June 2010 and March 2014, a census of a 35-ha plot on the Prospect Hill Tract in Harvard Forest, Massachusetts was conducted in a joint effort by the Center for Tropical Forest Science (CTFS) and the Smithsonian Institute's Forest Global Earth Observatory (ForetGEO) as part of the MegaPlot network (Anderson-Teixeira et al., 2015). Within the extent of the plot (Fig. 1), all woody stems ≥1 cm stem *DBH* were identified by species and tagged, and stem diameter was measured using a diameter tape. The census was completed by numerous field technicians, with quality control and quality assurance completed according to CTFS ForestGEO protocol and methodology (http://www.ctfs.si.edu/). In total, approximately 116,000 woody stems were recorded during the census with 51 unique species identified (Orwig et al., 2015).

### 2.2. Field-based measurements of canopy geometry

In September and October 2013, variable radius plot sampling (Bitterlich, 1984) was completed within the extent of the ForestGEO plot. Thirty-nine randomly selected plots were located approximately using a handheld Garmin GPSmap 76CSx handheld GPS unit (error ± approx. 5 m). Actual plot centers were recalculated post hoc by calculating the centroid of the $\mathrm{UTM}_{x,y}$ locations of tagged trees in the Prospect Hill Tract plot space relative to the x,y locations of the same trees in the local coordinates of the variable radius plot. At each plot, a 4.59 $\mathrm{m}^2$/ha basal area factor prism was used to sample trees 5 cm and greater *DBH*; the sample trees thus represent a size-weighted sample of the full population of the trees over 5 cm *DBH* on the tract (Kershaw et al., 2016, ch. 9). At each sampled tree, we recorded species and tag number (except where they had fallen off or not been measured for census yet), as well as measured the distance and bearing from plot center, *DBH*, tree height, crown base height, and crown radius toward and away from plot center. This pair of crown radii can be used to estimate crown area without bias, irrespective of crown shape (Gregoire and Valentine, 1995). Crown radii and tree height measurements were made using a laser range finder with a viewfinder and integrated tilt sensor (DISTO D5, Leica Geosystems). Crown radii were measured by using the viewfinder to determine when the observer was under the dripline of the tree crown toward and away from plot center, and by measuring the distance to the stem using a laser range finder which was subsequently adjusted for the distance between stem face and stem center.

### 2.3. Allometry and canopy height models

#### 2.3.1. Mixed effects modeling

Allometric equations were developed in R (version 3.0.1) using a