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Improving Lidar-based aboveground biomass estimation of temperate hardwood forests with varying site productivity

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ABSTRACT

Accurate quantification of forest aboveground biomass (AGB) is the foundation to the responses of diverse forest ecosystems to the changing climate. Lidar-based statistical models have been used to accurately estimate AGB in large spatial extents, especially in boreal and temperate softwood forest ecosystems. However, the few available models for temperate hardwood and hardwood-dominated mixed forests are low in accuracy due both to the deliquescent growth form of hardwood trees and the strong site-to-site variations in height-diameter relationship. In this study, we established multiplicative nonlinear regression models that incorporated both lidar-derived metrics and soil-based site productivity classes (high and low productivity sites) to estimate aboveground biomass in temperate hardwood forests. The final optimized model had high accuracy ($R^2 = 0.81$; RMSE = 45.5 Mg ha^{-1}) with reliable performance in ABG estimation by integrating relative height metrics at 75 and 70 percentiles (RH75 and RH70), canopy coverage and site productivity class. An optimized model that included an index of site productivity explained 14% more variance than the best-fit model without the term. Moreover, the relationship between AGB and lidar-based metrics was nonlinear on low productivity sites and nearly linear on high productivity sites, further indicating the importance of including direct or indirect measures of site productivity in lidar-based biomass models, particularly for those applied to temperate hardwood forests. Our new lidar-based model provides a potential framework to integrate lidar-based structural information and soil-based site productivity to improve AGB estimation in temperate hardwood forests.

1. Introduction

Lidar (Light detection and ranging) is considered as a promising technology to quantify and monitor aboveground biomass (AGB) in forest ecosystems, providing essential information to understand their dynamics in response to a set of grand challenges such as climate change, invasive species, and land use change (Lim et al., 2003; Wulder et al., 2012). Previous studies have utilized lidar-based forest structure metrics with statistical modeling to successfully estimate AGB in boreal forests (Huang et al., 2013; Montesano et al., 2014; Næsset et al., 2011; Popescu, 2007), temperate softwood/softwood-dominated mixed forests (Hudak et al., 2012; Pflugmacher et al., 2012; Zhao et al., 2009) and tropical/subtropical hardwood forests (Asner et al., 2010; Cao et al., 2016; Ferraz et al., 2016; Kronseder et al., 2012). However, few studies have presented desirable AGB estimations in temperate hardwood and hardwood-dominated mixed forests.

Existing lidar-based models are often challenged by either relatively low accuracy (i.e., low R^2 values) or unreliable model performance (i.e., high RMSE value) in estimating AGB in temperate hardwood and mixed forests (see Table A1 in Appendix). For example, Anderson et al. (2006) applied single linear regression using a relative height metric (RH50) to estimate AGB in temperate mixed forests in New Hampshire, USA with a R^2 of 0.41. Lim and Treitz (2004) employed the power function and RH metrics to predict AGB distribution in temperate mixed forests in Ontario, Canada, which has a relatively high accuracy ($R^2 = 0.90$) but with low reliability (RMSE = 50.2 Mg ha^{-1}). Duncanson et al. (2015) included individual-tree metrics in multiple linear models to estimate AGB estimation in three temperate forests across USA but required high density returns (50 pts. m^{-2} in this study). Though the availability of high return density lidar campaigns is increasing worldwide to address ecological and environmental questions, these data are still associated with intensive computation and limited spatial coverage (Duncanson et al., 2014; Popescu et al., 2003).

The challenges for accurate modeling of AGB in temperate

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hardwood forests are multifold. First, lidar-based AGB estimations typically rely on height metrics as primary model predictors/variables (Zolkos et al., 2013). The deliquescent growth form of hardwood trees challenges height-based metrics due to the similarity of the vertical height profiles with varied tree volume/density (Banskota et al., 2011; Boudreau et al., 2008). Second, the varied site productivity disperses height-diameter relationships in different forest sites (Skovsgaard and Vanclay, 2008) and across different species, which make it difficult to derive height-based lidar metrics to estimate diameter-based field-observed AGB (Jenkins et al., 2003). Site productivity has traditionally been derived from the height growth of overstory trees, as tree height growth have been viewed to better integrate the effects of climate, soil, terrain and other edaphic conditions (Skovsgaard and Vanclay, 2013) than diameter growth. Therefore, site productivity, either direction or through inclusion of tree height as a covariate modifying the power relationship between AGB and diameter, has been included in many allometric equation based AGB studies (e.g. site productivity is related to the power parameter b in the form $A = aD^b$, where A and D stand for AGB and diameter respectively, a and b are model parameters) (Basuki et al., 2009; Chave et al., 2014; Ketterings et al., 2001). However, differences in the height-diameter relationship with site are barely considered in most lidar-based AGB estimations. Therefore, it is necessary to establish a reliable lidar-based model regarding both the canopy structure and site productivity to reduce the uncertainties in AGB estimations.

Here, we develop a reliable and robust lidar-based regression model to predict AGB in mixed hardwood forests in the Central Hardwood Forest region in eastern USA. Specifically, we aim to (1) determine robust lidar metrics for AGB estimation; (2) investigate the impacts of site variances on AGB estimation by incorporating site productivity classes (high and low productivity sites) in lidar-based models; and (3) test the accuracy and reliability of the optimized model. Our study provides a valuable framework on which others may optimize the lidar-based AGB estimation models in temperate hardwood forests with regards to site productivity effects.

2. Material and methods

2.1. Study area

The study was located in the Yellowwood State Forest (YSF), in southern Indiana, USA (39.2° N, 86.3° W) (Fig. 1). The YSF falls into the humid continental climate region with warm-wet summers (21 to 27 °C) and cold winters (−4 to 2 °C). The topography of this unglaciated region is complex, abounding with hills and knolls; elevation ranges from 167 to 300 m with mean slope of 39.1%. The study area is dominated by temperate hardwood forests with a small portion of conifer (mostly pine, *Pinus* spp.) plantations. Dominant species include northern red oak (*Quercus rubra*), white oak (*Q. alba*), black oak (*Q. veluntina*), shagbark hickory (*Carya ovata*), tulip-poplar (*Liriodendron tulipifera*), and sugar maple (*Acer saccharum*). Multiple silvicultural treatments in these sites have created a diverse array of forest canopy structures, varying greatly in both horizontal and vertical dimensions.

2.2. Field plot data

Forest inventory data were collected in Compartment 2 of the YSF between January and March in 2010 (Gallion, 2012) (Fig. 1) as part of the Indiana Department of Natural Resources – Division of Forestry continuous forest inventory (CFI) effort. The CFI sampling methodology largely followed the procedures of U.S. Forest Inventory Analysis (FIA) program but with different plot size and sampling intensity. Each FIA plot has four subplot with 7.3 m radius in every 2428 ha (6000 acres), while each CFI plot has one 7.3 m plot radius every16.2 ha (one per every 40 acres) (Shao et al., 2014). All trees with diameter at breast height (DBH) of ≥12.7 cm (5 in.) within CFI plot were measured. Further detailed inventory methods are in Gallion (2012). For this study, we extracted measurements of DBH, tree height, and dominated-species-based site productivity from 59 CFI plots within study area. Field-based AGB observations were first estimated at the tree-level using species-specific Jenkins et al. (2003) DBH allometric equations. The AGB of each tree within inventory plots were then summed for plot-level AGB.

2.3. Lidar data and soil map

Airborne lidar data was acquired from the Indiana Statewide Lidar program (2011–2013 Indiana Statewide Lidar, 2016). The data covering the study area was collected in 2011 during the leaf-off season. An Optech Gemini Lidar system (ALS50) was used to collect multiple returns lidar with 99 kHz of pulse repetition rate, 40° of scan angle and 35.8 Hz of scan frequency. The laser system was flown 2000 m above ground, resulted in a 1731 m swath width with 20–30% overlap and an averaged 1.4 pts m^{-2} point density. Both canopy height model (CHM) and digital elevation model (DEM) were generated at 1-m resolution with all returns using FUSION/LDV software system developed by the

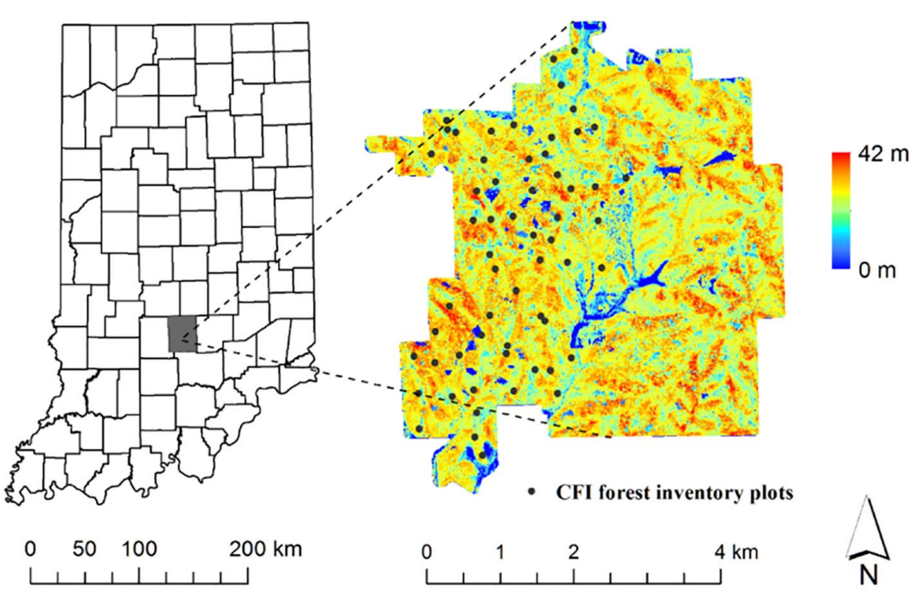

Fig. 1. Canopy height model (CHM) of the study area (on the right), located in the southeast part of Yellowwood State Forest in Indiana, USA (Indiana state map on the right). Black dots stand for the locations of forest inventory plots used in this study.