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Modeling aboveground tree woody biomass using national-scale allometric methods and airborne lidar

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ABSTRACT

Estimating tree aboveground biomass (AGB) and carbon (C) stocks using remote sensing is a critical component for understanding the global C cycle and mitigating climate change. However, the importance of allometry for remote sensing of AGB has not been recognized until recently. The overarching goals of this study are to understand the differences and relationships among three national-scale allometric methods (CRM, Jenkins, and the regional models) of the Forest Inventory and Analysis (FIA) program in the U.S. and to examine the impacts of using alternative allometry on the fitting statistics of remote sensing-based woody AGB models. Airborne lidar data from three study sites in the Pacific Northwest, USA were used to predict woody AGB estimated from the different allometric methods. It was found that the CRM and Jenkins estimates of woody AGB are related via the CRM adjustment factor. In terms of lidar-biomass modeling, CRM had the smallest model errors, while the Jenkins method had the largest ones and the regional method was between. The best model fitting from CRM is attributed to its inclusion of tree height in calculating merchantable stem volume and the strong dependence of non-merchantable stem biomass on merchantable stem biomass. This study also argues that it is important to characterize the allometric model errors for gaining a complete understanding of the remotely-sensed AGB prediction errors.

1. Introduction

Accurate spatially-explicit estimates of forest aboveground biomass (AGB) and carbon (C) stocks provide critical information for understanding and mitigating climate change (Houghton et al., 2009; Le Toan et al., 2011; Achard et al., 2014). Numerous studies have been done to map AGB using optical, radar, and lidar remote sensing data (see, e.g. Lu, 2006; Koch, 2010; Gleason and Im, 2011; Chen, 2013; Lu et al., 2014 for reviews). Along with the sheer number of studies are the often divergent AGB and C estimates from different remotely-sensed models over the same geographical area (Mitchard et al., 2014). The differences among remotely-sensed AGB estimates can be attributed to a multitude of factors including sensor and remote sensing data type, forest conditions of field plots, field plot size, statistical models, and accuracy assessment methods (Zolkos et al., 2013).

One crucial but insufficiently investigated factor that can lead to substantial AGB biomass prediction variations is the allometric model used to estimate tree biomass (Clark and Kellner, 2012). The tree biomass for calibrating a remote sensing AGB model has rarely directly *measured*; instead, it is *estimated* using allometric models with other easily measurable tree- and site-level attributes, such as DBH (diameter at breast height), tree height and wood density, as predictors (Chen et al., 2015). To estimate AGB over large spatial scales, different allometric models have been proposed over the tropics (Brown, 1997; Chave et al., 2014) and in the United States (Heath et al., 2008; Woodall et al., 2011).

In the United States, the Forest Inventory and Analysis (FIA) program of the Department of Agriculture Forest Service (USDA-FS) has developed several kinds of allometric methods to estimate AGB at the national scale. For years, FIA has used allometric models at the species- or species groups levels to estimate tree AGB within each of the FIA regional (Pacific Northwest, Interior West, Northern, and Southern) units, which hereinafter is called the regional method. Each FIA regional unit often uses different model forms (e.g., power or exponential models) and biomass predictors (e.g., some use tree height and site index while others do not) to fit AGB allometric models. The model differences sometimes reflect not necessarily the true allometry variations caused

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by local climate, soil, and evolution history but to a large extent the personal choice of each region's model builder based on his/her knowledge and preference. This results in artifacts of biomass variations across different regions.

To alleviate this issue, Jenkins et al. (2003) did a meta-analysis of more than 2500 species-level allometric models in the literature and developed allometric models for 10 broad species groups using only one model form (i.e., power) and the same biomass predictor (i.e., DBH), hereinafter called the Jenkins method. However, since the number of species groups is small (only 10), each group is taxonomically much broader than the individual species or species groups of the regional method. So, although the Jenkins method estimates AGB consistently, it is very likely that, on a national average, it has AGB prediction errors larger than the regional method.

The Component Ratio Method (CRM) (Heath et al., 2008; Woodall et al., 2011) was proposed in recent years as an attempt to combine the strengths of both the regional and Jenkins methods. In other words, CRM is designed to integrate the national consistency from the Jenkins method and the high precision of AGB prediction from the regional method. Since 2012, the USDA-FS has used CRM instead of the Jenkins method, the conventional "gold standard" for estimating biomass, in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.

The shift from the conventional Jenkins and regional methods to CRM has significant implications because the national biomass estimates derived from them provide critical information for the U.S. to make policies in response to global warming and climate change, especially in the intergovernmental negotiations. The choice of allometric methods affects not only the biomass estimates derived from the U.S. national forest inventory (i.e., FIA) plots (e.g., Woodbury et al., 2007; Domke et al., 2012) but also the remotely sensed biomass maps when the estimated AGB is used to calibrate remote sensing data.

In the past, the Jenkins and regional methods have been used in remote sensing studies to map biomass from local to national scales (e.g., Blackard et al., 2008; Kellndorfer et al., 2012; Zhao et al., 2012). However, few have investigated the use of CRM for remotely sensed biomass studies. Moreover, a critical analysis of CRM, especially its relationships to the Jenkins and the regional methods from which it is derived, is lacking in the literature. To my best knowledge, no research has explored the impacts of using CRM in lieu of Jenkins and regional methods on remotely-sensed AGB modeling. Thus, the main objective of this study is to use data from three study sites in the Pacific Northwest region for (1) investigating the relationships among CRM, Jenkins, and regional allometric methods and (2) exploring the impacts of the alternative allometry on the lidar-biomass model performance.

2. Study area and data

2.1. Study area

The study area encompasses a total of three sites: two in California and one in Oregon (Fig. 1). The two California sites are located on the eastern slope of the Sierra Nevada mountain range: one is the USDA-FS Sagehen Creek Experimental Forest and the other is the USDA-FS Lake Tahoe Basin Management Unit (LTBMU). The third site is the Panther Creek Watershed located in the Yamhill River Basin in western Oregon. Hereinafter, the three sites are called Sagehen, Tahoe, and Panther, respectively.

The three sites are all conifer forests, but their species compositions are different. The Sagehen site covers approximately 3925 ha, where the major species include white fir (*Abies concolor* Lindl. ex Hildebr.), red fir (*Abies magnifica* A. Murray), lodgepole pine (*Pinus contorta* Douglas ex Loudon), Jeffrey pine (*Pinus jeffreyi* Balf.), sugar pine (*Pinus lambertiana* Douglas), western white pine (*Pinus monticola* Douglas ex D. Don), and mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) (Chen et al., 2012). The Tahoe site covers about 93,598 ha, and the major vegetation is Jeffrey pine, white fir, California red fir (*Abies magnifica* A. Murray bis), lodgepole pine, incense cedar (*Calocedrus decurrens* (Torr.) Florin), quaking aspen (*Populus tremuloides* Michx.), western white pine, sugar pine, western juniper (*Juniperus occidentalis* Hook.), and mountain hemlock. The Panther site is about 2580 ha where the species is dominated by Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), with significant amounts of red alder (*Alnus rubra* Bong.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western red cedar (*Thuja plicata* ex D. Don), grand fir (*Abies grandis* (Douglas ex D. Don) Lindl.), bigleaf maple (*Acer macrophyllum* Pursh) and several other species (Flewelling and McFadden, 2011) .

2.2. Forest field data

For Sagehen, field data from 80 circular plots of 12.6 m radius (0.05 ha) were used. These plots, as a part of the systematic grid of field plots measured in 2004–2006, were used to sample the forest types of the study area with 125-m spacing. The plots were located with Trimble® GeoXH™ handheld GPS with Zephyr Geodetic antenna with an average horizontal accuracy of 0.1 m. At each plot, all trees greater than 5 cm in diameter at breast height (DBH, breast height = 1.37 m) were measured with a nested sampling design. Canopy trees ($\geqslant$19.5 cm DBH) were tagged and measured in the whole plot; understory trees ($\geqslant$5 cm DBH to <19.5 cm DBH) were measured in a randomly selected third of the plot. Tree measurements include species, DBH, tree height, and vigor. A total of six vigor classes were defined that include information about whether a tree is dead or alive (Chen et al., 2012).

At Tahoe, over 1000 trees were mapped in 2012 for 56 circular plots of 17.6 m radius (0.1 ha) using a Nikon DTM-322 total station. These plots were initially established through two LTBMU projects: (1) the Multi-Species Inventory and Monitoring (MSIM) project that collected field plots on National Forest System (NFS) lands throughout the basin from 2002–2005; (2) the Lake Tahoe Urban Biodiversity (LTUB) project that established plots across multiple land ownerships at lower elevations (<7500 ft) in the basin from 2003 to 2005. Plot locations were selected using a combination of systematic/grid sampling and stratified random sampling (White and Manley, 2012). At each plot, all trees greater than 2 cm in DBH were measured. Tree measurements include species, DBH, tree height, height to live crown, and tree status (live, dead, unhealthy, or sick) (Saah et al., 2013).

The field data at Panther are from 78 circular plots of 16 m radius (0.08 ha or 0.2 acre) and were collected in the fall and winter of 2009 and spring of 2010. The field data include information about species, DBH, tree height, height to live crown, and tree status (live, cut, or dead). At each plot, all trees with DBH >0.5 cm are measured. Out of the 78 plots, 42 were established through a stratified random sample using canopy cover, canopy height, forest stand maps, hardwood percentage, crown depth indices derived from airborne lidar data collected in 2007 and NAIP (National Agriculture Imagery Program) imagery in 2005. The rest 36 plots were installed in conjunction with a soil survey, which was not dependent upon the forest conditions. Plot centers were established to an error of <0.25 m using a combination of GPS and cadastral survey (Flewelling and McFadden, 2011) (Table 1).

2.3. Airborne lidar data

The lidar data at Sagehen were collected from September 14 to 17, 2005 using an Optech ALTM 2050 system on an airplane flying