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Multi-temporal terrestrial laser scanning for modeling tree biomass change

Shruthi Srinivasan *, Sorin C. Popescu, Marian Eriksson, Ryan D. Sheridan, Nian-Wei Ku

Spatial Science Laboratory, Department of Ecosystem Science and Management, Texas A&M University, 1500 Research Parkway, Suite B-217, College Station, TX 77843, USA

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ABSTRACT

Above ground biomass (AGB) is a crucial ecological variable and has to be accurately estimated to understand potential changes of the climate system and to reduce uncertainties in the estimates of forest carbon budget. The overall goal of this research is to estimate tree level AGB change using multi-temporal terrestrial laser scanning (TLS) datasets for trees in East Texas. Specific objectives are to (1) develop models using TLS parameters to estimate tree level AGB; and (2) investigate different conceptual approaches for estimating AGB change. Since majority of the AGB estimation models are developed only using diameter at breast height (DBH), we investigated the potential of TLS by extracting various geometric and statistical parameters for tree level AGB estimation. National and regional level AGB estimation models were developed for loblolly pines. To estimate the change in AGB, three different approaches were followed. The best AGB estimation model for loblolly pines had DBH, height variance, and interquartile distance as independent variables. The best AGB estimation model for hardwoods included volume and crown width as independent variables. For AGB change of loblolly pines, direct modeling of AGB change with TLS data available for 2009 and 2012 provided the best results. An extensive literature review reveals that this is the first study to model the change in AGB using different innovative and conceptual approaches with multi-temporal TLS data. The results of our study indicate the capability of TLS to model the change in tree level AGB, with potential for reducing the amount of field work when using multi-temporal terrestrial TLS datasets. We believe that the results of this study will benefit forest management and planners for prudent decision making, and other remote sensing studies from airborne and spaceborne platforms, for map upscaling, data fusion, or calibration purposes.

1. Introduction

Accurate measures of forest structural parameters and the monitoring of their changes through time are essential to forest inventory and growth models, managing wildfires, modeling of carbon cycle, and forest management systems (Næsset et al., 2004). Most extant methods, which include indirect and direct measurement techniques, are limited in their capability to acquire accurate, spatially explicit measurements of forest three-dimensional structural parameters. The accuracy of these measurements can be improved using lidar (light detection and ranging) (Kussner and Mosandl, 2000; Henning and Radtke, 2006).

Lidar, which is an active sensor, emits a series of laser pulses, and measures the distance to targets based on the speed of light and travel time of the laser pulses to and from a system (Lefsky et al., 2002a). Unlike passive optical remote sensing, lidar remote sensing provides detailed information on both horizontal and vertical distribution of vegetation in forests (Lim et al., 2003). Applications of lidar remote sensing such as measurement of the structure and function of vegetation canopies and estimation of tree height, crown width, basal area, stem volume, and aboveground biomass (AGB) are elaborated in various studies (Lefsky et al., 2002b; Chen et al., 2007; Popescu and Zhao, 2008; Falkowski et al., 2009). Nondestructive measurements of AGB can be done using airborne lidar with a higher accuracy compared to AGB measurements obtained through other remote sensing techniques (Lefsky et al., 2002a; Bortolot and Wynne, 2005; Popescu, 2007; Hudak et al., 2012). Nevertheless, tree height estimates with small footprint discrete return airborne lidar tend to slightly underestimate manual measurements done in the field, as the laser pulses are not always reflected from tree tops. Airborne lidar may not capture the complete vertical distribution of the canopy (Lim et al., 2003). Terrestrial laser scanning (TLS) fills the gap between tree scale manual measurements and large scale airborne lidar measurements by providing a wealth of precise information on various

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* Corresponding author. Tel.: +1 858 774 6270.
E-mail address: shruthi1389@gmail.com (S. Srinivasan).

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forest structural parameters (Dassot et al., 2011) and a digital record of the three dimensional structure of forests at a given time. Hence, to obtain accurate understory information and detailed canopy vertical structure depiction, TLS can produce better results when compared to airborne lidar and field measurements (Loudermilk et al., 2009).

The use of terrestrial or ground-based laser scanners for forest management planning and mapping vegetation properties has grown dramatically in the last decade (Moskal et al., 2009; Moskal and Zheng, 2012; Kankare et al., 2013). Terrestrial laser scanners have a high potential to acquire three-dimensional data of standing trees accurately and rapidly through non-destructive methods, which has resulted in the multiple use of this technology in studying forest environments (Lovell et al., 2003; Dassot et al., 2011). Several studies have shown that TLS is a promising technology in providing objective measures of tree height, diameter at breast height (DBH), stem density, canopy cover, and AGB (Bienert et al., 2006; Hopkinson et al., 2008; Kankare et al., 2013). Evans et al. (2006) addressed the use of lidar for forest assessments and proposed two significant domains in which lidar could be a major contributor: tree growth and yield modeling at individual tree level for pine plantations using multi-temporal lidar data, and implementation of retrieved individual tree measurements from lidar data in immersive visualization environments for the assessment of forest stands.

AGB is defined as all the living biomass above the soil that includes stem, stump, branches, bark, seeds, and foliage; it is associated with important components such as tree health, forest regeneration, and energy conversion (Jenkins et al., 2003). It is a crucial ecological variable, which has to be accurately estimated to reduce the uncertainties in the estimates of forest carbon budget and understand potential changes of the climate system. Further, half of the dry biomass is considered to account for carbon, which is of great scientific interest to understand the carbon cycle (Houghton et al., 2009; Lin et al., 2010; Zolkos et al., 2013). Næsset et al. (2011) developed non-linear biomass models using airborne lidar derived height metrics and canopy density. The authors performed a stepwise forward selection procedure to select the best set of independent variables to estimate biomass. They observed that the estimated biomass was not statistically different from field measured biomass for lidar based models.

Yao et al. (2011) used a ground-based, scanning near-infrared full waveform lidar and retrieved tree diameters and stem count density to determine aboveground standing biomass. They obtained a coefficient of determination of 0.85 between the lidar derived and field measured biomass. Lefsky et al. (2002b) developed a single equation to estimate AGB from lidar derived canopy structure in three distinct study sites that explained 84% of the variance. Zolkos et al. (2013) combined and contrasted results from different studies on the estimation of AGB from lidar remote sensing and found that AGB estimated from remote sensing models were closely related to field measured AGB if the residual standard error was less than or equal to 20 Mg ha^{-1}. They also discussed that significantly better results for the estimation of AGB were obtained using airborne lidar data compared to radar or optical data. However, very little research has been done in estimating AGB at individual tree level with TLS data, which could be used in the detailed evaluation of silvicultural techniques (Kankare et al., 2013).

Lidar is also a promising technology to study growth and derive forest parameters (Hudak et al., 2009). Few studies have investigated forest succession using lidar to predict long-term carbon sequestration (Falkowski et al., 2009; Hudak et al., 2012). Successful modeling of change in airborne lidar estimated biomass has been done using three different approaches: (1) computing the change in biomass by subtracting the estimated biomass between two different years; (2) modeling of biomass change by a system of models; and (3) direct modeling of biomass change (Bollandsås et al., 2013). Hopkinson et al. (2008) assessed the plot level mean tree height growth for homogenous red pine conifer plantations over a five period using repeat airborne lidar datasets. They found that lidar estimated growth rates slightly underestimated the field measured growth rates. Falkowski et al. (2009) mapped forest succession using lidar metrics with an overall accuracy higher than 90%. Hudak et al. (2012) quantified AGB due to forest growth using repeat airborne lidar surveys. They developed predictive tree AGB models using random forest algorithm and monitored biomass change using repeat discrete return airborne lidar and field surveys. They reported mean canopy height as the most significant predictor for tree biomass. Though their results suggested that biomass change and carbon dynamics in conifer forests were monitored efficiently with discrete return multi-temporal airborne lidar datasets, a few challenges concerning repeated measures using airborne lidar exist, such as differences in lidar acquisition pulse density. Yu et al. (2006) were able to measure four years of height growth of 82 Scots pines (*Pinus sylvestris*) with multi-temporal laser surveys, and they developed a tree-to-tree matching algorithm. The three change detection techniques used in their study were: (1) differencing between canopy height models; (2) comparison between canopy profile, and (3) analysis of difference between height histograms. An *R*-squared value of 0.68 was obtained when field measured individual tree height growth was validated against laser derived individual tree height growth. However, multi-temporal airborne laser scans poses some difficulties such as changes in flight conditions and flight path. Though very limited research has been done on AGB change estimation using lidar, several authors have discussed the potential of this technology to study forest growth (Yu et al., 2006; Næsset et al., 2013). Situations where airborne laser data cannot be used for change detection studies are described by the previously mentioned authors, and they suggest the use of TLS for future growth analysis.

The use of TLS for spatially explicit assessment of plot level forest canopy structure was examined by Henning and Radtke (2006) in leaf-off and leaf-on conditions. The authors quantified differences in characterizations obtained under the two conditions. The comparison results of leaf-on and leaf-off provided a RMSE of 0.169 m in DBH and mean position error of 0.29 m. Their results support the applications of TLS for multi-temporal observation. However, registration of TLS data across time was not studied by the authors, but when performed could prove advantageous for multi-temporal change detection. Kaasalainen et al. (2010), Kankare et al. (2013) analyzed the potential of TLS to measure standing tree biomass in a laboratory environment. One main drawback of local scale AGB estimates produced using field measurements or low resolution satellite imagery are the estimate uncertainties. However, TLS data allows for non-destructive and detailed modeling of individual trees. For example, Kankare et al. (2013) developed single tree based AGB models from multiple scan TLS data and reported improved accuracies for branch biomass. They input 83 TLS based variables and performed lasso regression and stepwise regression to estimate biomass. Kaasalainen et al. (2010) concluded that TLS is a promising technology for studying biomass change, and they obtained high *R*-squared values of 0.95–0.99 when TLS estimated standing tree biomass were validated with field measured biomass.

The majority of existing studies only investigate biomass estimation in static conditions, i.e., determining various forest parameters and estimating AGB at a single point in time. Thus, by utilizing multi-temporal lidar data, there is potential in increasing the scope of lidar remote sensing for carbon modeling, wildfire risk assessment, and other applications (Hudak et al., 2009). Biomass is dynamic and hence has to be monitored continuously to provide information on sinks and sources of carbon. It is also essential to