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Review

Generalizing predictive models of forest inventory attributes using an area-based approach with airborne LiDAR data

Marc Bouvier [a,*], Sylvie Durrieu [a], Richard A. Fournier [b], Jean-Pierre Renaud [c]

[a] UMR TETIS Irstea-Cirad-AgroParisTech/ENGREF, Maison de la Télédétection en Languedoc-Roussillon, 500, rue J.F. Breton BP 5095, 34196 Montpellier Cedex 05, France
[b] Centre d'Applications et de Recherches en Télédétection (CARTEL), Département de géomatique appliquée, Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada
[c] Office National des Forêts, 11 rue Ile de Corse, 54000 Nancy, France

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ABSTRACT

This study proposed modifying the conceptual approach that is commonly used to model development of stand attribute estimates using airborne LiDAR data. New models were developed using an area-based approach to predict wood volume, stem volume, aboveground biomass, and basal-area across a wide range of canopy structures, sites and LiDAR characteristics. This new modeling approach does not adopt standard approaches of stepwise regression using a series of height metrics derived from airborne LiDAR. Rather, it used four metrics describing complementary 3D structural aspects of the stand canopy. The first three metrics were related to mean canopy height, height heterogeneity, and horizontal canopy distribution. A fourth metric was calculated as the coefficient of variation of the leaf area density profile. This fourth metric provided information on understory vegetation. The models that were developed with the four structural metrics provided higher estimation accuracy on stand attributes than models using height metrics alone, while also avoiding data over-fitting. Overall, the models provided prediction error levels ranging from 12.4% to 24.2%, depending upon forest type and stand attribute. The more homogeneous coniferous stand provided the highest estimation accuracy. Estimation errors were significantly reduced in mixed forest when separate models were developed for individual stand types (coniferous, mixed and deciduous stands) instead of a general model for all stand types. Model robustness was also evaluated in leaf-off and leaf-on conditions where both conditions provided similar estimation errors.

Contents

* Corresponding author. Tel.: +33 4 67 54 87 19; fax: +33 4 67 54 87 00.
E-mail address: marc.bouvier@teledetection.fr (M. Bouvier).

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1. Introduction

Total aboveground woody volume (hereafter referred to as wood volume) and the stem merchantable volume of a tree (hereafter referred to as stem volume) are key forest inventory attributes that are required by forest managers. Reliable mapping of both volumes facilitates the implementation of sustainable management strategies and practices. These practices enable logging be optimized while contributing to forest ecosystem preservation and climate change mitigation (Picard, Saint-André, & Henry, 2012). Biomass of forest stands, including both aboveground and belowground components, is another attribute that is required to improve our knowledge of the carbon cycle. Wood volume, stem volume and aboveground biomass (AGB) are interdependent, and there are strong correlations among these three attributes (Brown & Lugo, 1984; Fang, Liu, & Xu, 1996). Most forest inventory programs estimate wood and stem volumes from field measurements of stem diameter from sampled trees. Tree heights are also measured, but generally only from a subset of individuals, as height measurements are more difficult and costly to collect than those for stem diameter (Avery & Burkhart, 2001; Kangas & Maltamo, 2006). Forest inventories generally use random or systematic sampling schemes (Scott & Gove, 2002). In both approaches, a limited number of plots are inventoried because this work is both costly and time-consuming. Furthermore, field measurements can only be performed in areas that are accessible to field crews. Remote sensing has the potential to provide quick and accurate measurements of stand attributes over large areas at a much lower cost than with traditional inventory practices. Using remote sensing data, coupled with a small number of field measurements, can thus be an effective solution for overcoming the aforementioned drawbacks of field measurements, while providing accurate and timely information on several key forest attributes.

Optical and radar remote sensing have been widely used to map forest structural attributes and biophysical parameters (Franklin, 2001; Le Toan, Beaudoin, Riom, & Guyon, 1992; Leboeuf, Fournier, Luther, Beaudoin, & Guindon, 2012). Assessment of wood volume and ABG remains challenging, especially for forests with high AGB levels (Cohen & Spies, 1992; Leboeuf et al., 2012). In a recent study, Zolkos, Goetz, and Dubayah (2013) analyzed a large set of published studies on AGB assessment from remote sensing data. The authors have brought to light the considerable variability in the accuracy of AGB predictions according to both forest environment and remote sensing data used.

LiDAR has emerged as one of the very promising technologies for forest applications and its potential for forest attribute estimation at several scales is widely acknowledged (Leeuwen & Nieuwenhuis, 2010; Næsset, 2004; Nelson, Krabill, & Tonelli, 1988). These active systems provide precise distance measurements that are based on elapsed time between the emission of a laser pulse and the measurement of the return signal. The spatial position of all the recorded returns upon the Earth's surface is calculated from both the position and orientation of the LiDAR system. These are measured using a differential global positioning system (DGPS) and an accurate inertial unit. The resulting point cloud is processed to assess diverse LiDAR metrics. LiDAR systems have either a small footprint (0.1–0.3 m) or a large footprint (8–70 m) (Lim, Treitz, Wulder, St-Onge, & Flood, 2003). Both of these systems have been used to estimate forest inventory attributes (Lefsky, Cohen, et al., 1999; Lefsky et al., 2002; Means et al., 2000; Næsset, 2002). Airborne Laser Scanner (ALS) is a LiDAR system combined with a scanning system. ALS is thus able to record data over a swath, the width of which depends upon both the scanning angle and flight altitude. These systems can be used to provide wall-to-wall coverage of areas of interest (Wulder et al., 2012). Two approaches can be applied using small-footprint discrete return ALS: (1) a tree-based approach (Li, Guo, Jakubowski, & Kelly, 2012; Maltamo, Eerikäinen, Pitkänen, Hyyppä, & Vehmas, 2004; Popescu, Wynne, & Nelson, 2003; Véga et al., 2014); or (2) an area-based approach (ABA) (Means et al., 2000; Næsset, 1997, 2002; Nelson et al., 1988). Current ALS that offer high sampling rates can be used to estimate single-tree attributes in a tree-based approach. However, individual tree segmentation algorithms frequently can be difficult to implement because they generate omission and inclusion errors when individualizing trees (Falkowski et al., 2006; Goerndt, Monleon, & Temesgen, 2010; Véga & Durrieu, 2011). Overlapping tree crowns can add confusion when identifying individual trees (Gleason & Im, 2011). Therefore, detection performance regarding individual trees is reduced in complex stands. ABAs are commonly used to generate maps of forest attributes in diverse forest biomes, temperate forests (Hall, Burke, Box, Kaufmann, & Stoker, 2005; Zhao & Popescu, 2009), boreal forests (Lim, Treitz, Baldwin, Morrison, & Green, 2003; Næsset & Gobakken, 2008), tropical forests (Asner, 2009; Kronseder, Ballhorn, Böhm, & Siegert, 2012), and savannah woodlands (Lucas et al., 2006). In such approaches, stand attribute estimations are computed from the statistical relationships between plot-level LiDAR metrics that are commonly extracted from point cloud data and stand attributes, which are derived from field plots. In general, numerous candidate metrics are derived from point height distributions at the plot-level, e.g., maximum and mean height values, percentiles of the distributions, and canopy densities (Næsset, 2002). Metrics that provide the greatest explanation are then selected, with only a few remaining in the final model (Hall et al., 2005; Lim & Treitz, 2004; Lim, Treitz, Wulder, et al., 2003; Patenaude et al., 2004). ABAs have been used to develop models for specific forested areas and for specific species or a specific group of species, which has led to a huge number of different models using diverse LiDAR metrics.

Currently, ABAs that are used to predict stand attributes have two major drawbacks, despite their proven usefulness for forest inventory and mapping (Næsset, 2002). The first drawback stems from the fact that candidate metrics generated from LiDAR data are known to be strongly inter-correlated (Chen, 2013). Furthermore, too many candidate metrics are generated, which complicates metric selection and the development of robust models (Hall et al., 2005; Khan, Van Aelst, & Zamar, 2007; Magnussen, Næsset, Gobakken, & Frazer, 2012). The second drawback is that metrics used to describe stand structure are generally derived from the vertical distribution of LiDAR returns. Indeed, these metrics do not sufficiently take into account several other canopy characteristics, including horizontal canopy heterogeneity. To overcome these drawbacks, new metrics have been identified to enhance the description of tree spatial distributions and, consequently, stand attribute predictions. For instance, canopy volume and canopy cover metrics have proved to be useful for AGB and volume estimation, in addition to height metrics (Chen, Gong, Baldocchi, & Tian, 2007; Hall et al., 2005; Kim et al., 2009; Næsset & Gobakken, 2008). These metrics take into account horizontal vegetation structures within model predictions. Other metrics have been estimated from the vegetation density profile. Profiles were integrated to estimate the distribution and total amount of foliage. These metrics have proved to be valuable for stand and tree attribute estimation (Allouis, Durrieu, Véga, & Couteron, 2013; Lefsky, Harding, Cohen, Parker, & Shugart, 1999). In such approaches, new metrics are generally identified, which are deemed to be unbiased and consistently meaningful (Magnussen & Boudewyn, 1998). The use of meaningful metrics that describe the 3D structural aspects of the stand canopy could help overcome the current limitations of ABA.

Model generalization is a key question that must be addressed to predict stand structural attributes (Chen, 2010). Few studies have assessed the potential of some LiDAR metrics for the prediction of diverse stand attributes or across diverse forest area types. Lefsky, Harding, et al. (1999) found that the quadratic mean canopy height (QMCH) improved estimates of AGB and basal area (BA). Lim, Treitz, Baldwin, et al. (2003) used mean laser height that was computed from filtered LiDAR returns, based upon the intensity return values, to estimate wood volume, AGB and BA. Magnussen et al. (2012) proposed a conceptual model for predicting tree-size-related forest attributes