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Simulating the impacts of error in species and height upon tree volume derived from airborne laser scanning data

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ABSTRACT

A key requirement of sustainable forest management is accurate, timely, and comprehensive information on forest resources, which is provided through forest inventories. In Canada, forest inventories are conventionally undertaken through the delineation and interpretation of forest stands using aerial photography, supported by data from permanent and temporary sample plots. In recent years, Airborne Laser Scanning (ALS) data have been shown to provide accurate estimates of a range of forest structural attributes. As a result, ALS has emerged as an increasingly common data source for enhanced forest inventory programs. Capture of species compositional information with ALS, based upon the nature of the data, is less reliable than structural variables, with species information typically derived from spectral or textural interpretation of aerial photography or very high spatial resolution digital imagery. Utilizing national allometric equations for the major species found in British Columbia, Canada, and a series of individual tree-level simulations, we analyzed (i) how incorrect species identification can influence individual tree volume prediction; (ii) which of the possible species substitutions result in higher volume errors; (iii) how the error in height that is typical for photogrammetry-based and ALS-based forest inventories impacts individual tree volume estimates; and (iv) the impact of combined errors in both species composition and height on overall individual tree volume estimates. Our results indicate that species information is important for volume calculations, and that the use of generic (i.e. all species) or cover-type allometric equations can lead to large errors in volume estimates. We also found that, even with a 50% error in species composition (whereby incorrect species-specific equations are substituted), volume estimates derived from species-specific allometric equations were more accurate than estimates derived from generic or cover-type equations. Our findings indicate that errors in species composition have less impact on individual tree volume estimates than errors in height measurement. The implications of these results are that, with very accurate estimates of height provided by ALS and knowledge of what dominant species is expected in a stand, accurate estimates of volume can be generated in the absence of more detailed species composition information.

1. Introduction

In Canada, the acquisition of information to support the sustainable management of forest resources is challenging given the large forest area and limited accessibility (Wulder et al., 2007). In the actively managed forests of southern Canada, forest companies and the provincial governments undertake forest inventory programs to obtain information on the current state of the forest with respect to its species composition, volume, age, health, and growth as well as other non-forest timber values such as habitat quality or soil and water characteristics. Historically, forest inventories were primarily designed to capture variations in forest structure and composition to serve timber harvesting objectives. Over the past two decades there has been a significant shift with forest inventories starting to serve multiple resource management objectives (Tomppo et al., 2010).

Aerial photographic interpretation (API) is used to delineate homogeneous units of forest resources (based on species composition, height, and stocking) followed by attribution utilizing digital photogrammetric tools (Morgan et al., 2010). Ground inventory plots are then installed to accurately capture a variety of tree and stand characteristics including species, diameter, stocking, cover, and height on a subset of trees. From these measurements allometric equations are used to predict volume and in some cases

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biomass (Gillis et al., 2005). Although recent changes from analogue to digital aerial photogrammetry has resulted in increases in measurement accuracy and processing time, the basic principle of parallax to produce height measures remains the same.

The accuracy of interpreted variables from aerial photography is found to vary by the attribute of interest. As a baseline, field measurements of tree height can offer accuracies as great as 1–2% (Andersen et al., 2006; Wing et al., 2004). The accuracy is lower with measurements performed using stereophotogrammetry, which relies on the scale and resolution of the photographs, the precision of the photogrammetric instruments, and the skill of the interpreter. The resolution and associated pixel size are directly related to scale of the photograph and flying height. For example, assuming a flying height of 2000 m above the ground and an image overlap of 60%, the theoretical maximum accuracy of height measurements, defined as the minimal recognized parallax difference, is 1.08 m (Avery, 1977). In addition, the overall accuracy of the height measurement is based on accurate coordinates of the top of the tree and the base of the stem. As the ground is often not visible through the canopy, the closest ground elevation is considered as the stem base which can translate into significantly higher measurement error in height than the theoretical minimum (St-Onge and Jumelet, 2004).

Stem volume of a single tree, derived from aerial photography is typically determined using models based on species, tree height and, in some cases, crown area (Spencer and Hall, 1988), and errors in any of these measurements directly impact model estimation. Eid and Næsset (1998) determined the accuracy of volume models derived from aerial photographic techniques and found volume was underestimated by 4–38%, with the average standard deviations of the differences ranging between 13%and 33%. The authors combined their results with other studies and noted that the bias in volume estimation can be extreme, ranging from −50% to 60%. A similar study reported accuracy of stem volume predictions of 46%, although in this case the applied methods were based on image extracted features, not the height measurements themselves (Hyyppä and Hyyppä, 2001).

Interpretation of species composition from aerial imagery relies on additional features within the image, such as radiometric properties (tone, color), size, shape, texture, pattern, shadow and context. These features are used to delineate homogeneous areas on stereopairs and allow a trained interpreter to combine them and differentiate between tree species (Morgan et al., 2010). Species estimation from aerial photography is also impacted by error (Congalton and Mead, 1983). Accuracy depends not only on the scale, resolution, film and sensor type (black and white, color, near infrared) but also on optical viewing conditions (such as presence of cloud, haze or smoke) and the skill and local knowledge of the interpreter. The studies that have investigated this topic have found that expert opinion, training, and inherent geographic biases play a role in species estimation with accuracy more appropriately specified as a range of error values rather than a single number (Deegan and Befort, 1990; Leckie and Gillis, 1995; Thompson et al., 2007). Moreover, the accuracy is also impacted by the species composition, with errors being lower for conifer than deciduous stands, single- or two species stands versus mixed stands, and older versus younger stands (Boan et al., 2013). Accuracy is also impacted by stress, crown form variations and lighting conditions (Ciesla, 1990). Across all of these studies the range of accuracy of species determination falls between 15% and60%.

Airborne Laser Scanning (ALS) is increasingly becoming a data source for forest inventory and industrial forest management activities worldwide (Wulder et al., 2013). This active remote sensing technology acquires three dimensional points clouds using LiDAR (Light Detection And Ranging) measurements captured from an aircraft. A GPS receiver is utilized to precisely determine the position of the aircraft and is coupled with additional equipment to allow for tracking of the pointing of the aircraft and recording the position on the ground of each received laser pulse. Most ALS systems are capable of recording more than one return from each pulse of laser energy, which is especially valuable in forested environments resulting in a greater number of points under the canopy (Baltsavias, 1999a; Wehr and Lohr, 1999). Typical attributes associated with each of the geolocated points from the ALS point cloud include information about return number, flightline, and scan angle. Additional information on the intensity of the LiDAR backscatter is also recorded, however this value is often not calibrated to any known standard, and is dependent on a number of additional factors such pulse strength and footprint size (Höfle and Pfeifer, 2007; Kaasalainen et al., 2009).

Most notable from the outcomes of using point clouds acquired with airborne laser scanning technology for forest monitoring are the accurate measurements of tree height, stand biomass and volume estimates (Hilker et al., 2008; Hyyppä et al., 2008; Lefsky et al., 2002b; Zhao et al., 2009). Studies have shown that tree height estimation from ALS can exceed both field-based and aerial-derived estimates, providing reliable values for both single tree and plot level measurements with errors typically lower than 1.5 m and R^2 values higher than 0.8 (Van Leeuwen and Nieuwenhuis, 2010). It has also been demonstrated that accurate estimates of stand biomass can be derived from ALS-based metrics using a variety of methods including height percentiles, canopy cover, or voxel based approaches (Hollaus et al., 2007; Lefsky et al., 2002a).

ALS-based forest inventories can be divided into two major groups – area-based and individual tree-based approaches (Reutebuch et al., 2005; Wulder et al., 2008). In the area-based approach, forest inventory variables, derived from sample plots, are modelled as a function of LiDAR point cloud distributions. To do so, the reference data collected on these plots is related to various descriptive statistics of the point cloud that corresponds to the spatial extent of the plot. Models are applied across the entire area of interest in order to create estimates of specific forest attributes (White et al., 2013a).

In the individual tree detection (ITD) approach the canopy height model is used to detect the tree crown polygons and then single tree attributes are estimated with various ALS features derived for each detected polygon (Hyyppä and Inkinen, 1999; Persson et al., 2002; Kaartinen et al., 2012). Although this approach requires dense point clouds (Wulder et al., 2008), it allows to precisely map individual tree attributes, including height, crown diameter, biomass (Falkowski et al., 2006; Popescu, 2007; Kankare et al., 2013).

When compared to conventional photogrammetric approaches ALS point clouds offer a higher capacity for consistency and automation (Baltsavias, 1999b) as well as improved tree height measurement accuracy (Holopainen and Talvitie, 2004). However, the lack of spectral information in the point clouds can be problematic with respect to routine tree species identification. Therefore any classification process to determine tree species that is based on ALS data alone, is more complex than when using spectral data derived from aerial or satellite imagery (Kim et al., 2011; Ørka et al., 2009; Suratno et al., 2009). This issue has been previously addressed through the fusion of ALS point clouds with optical imagery (Holmgren et al., 2008), through the use of very dense point clouds or full waveform LIDAR datasets, which allow intercrown patterns to be more easily distinguished (Heinzel and Koch, 2011). These approaches provide an option for obtaining species information from ALS, recognizing there are increases in costs associated with additional ground and airborne data and increased processing needs. Moreover, in many cases, these studies are