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

Piotr Tompalski[1*], Nicholas C. Coops[1], Joanne C. White[2], Michael A. Wulder[2]

[1] Faculty of Forestry, University of British Columbia, 2424 Main Mall, Vancouver, BC, V6T 1Z4, Canada.

[2] Canadian Forest Service (Pacific Forestry Centre), Natural Resources Canada, 506 West Burnside Road, Victoria, BC, V8Z 1M5, Canada

* corresponding author – piotr.tompalski@forestry.ubc.ca

Keywords: remote sensing, forest inventory, LiDAR, ALS, species composition, individual tree volume, error

Tompalski, P., N.C. Coops, J.C. White, M.A. Wulder. (2014). Simulating the impacts of error in species and height upon tree volume derived from airborne laser scanning data. Forest Ecology and Management. Vol. 327, pp. 167-177.

DOI:
http://dx.doi.org/10.1016/j.foreco.2014.05.011

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 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 1.08m (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 13–33%. 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, colour, 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 15–60%.

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 inter-crown patterns to be more easily distinguished (Heinzel and Koch, 2011). These approaches provide an option for obtaining species information from ALS, recognising there are increases in costs associated with additional ground and airborne data and increased processing needs. Moreover, in many cases, these studies are limited to distinguishing between conifer and deciduous species only (Ørka et al., 2009).

The accuracy of ITD based forest inventory depends principally on the detection rate of the trees, when compared to error in DBH and height (Vastaranta et al., 2011). Tree detection accuracy has been reported in various studies to range between 70–90% (Holmgren, 2004; Liang and Matikainen, 2007; Persson et al., 2002), and up to 96% when point clouds are combined with multi-spectral images (Holmgren et al., 2008). Vastaranta et al. (2011) demonstrated detecting 65% of trees results in an error of total volume of 27% and reported that the error in DBH prediction has an effect in volume accuracy of single tree between 5–10%, with minor effect of tree height inaccuracies.

Individual tree volume estimation can be derived from height and DBH allometric relationships which can also incorporate crown diameter (Hall et al., 1989; Kalliovirta and Tokola, 2005; Popescu, 2007) or statistical techniques such as Random Forests (Yu et al., 2011) or k-Most Similar Neighbor (k-MSN) (Vauhkonen et al., 2010). However, it is known that these single tree biomass or volume models are highly species dependent and often only locally applicable resulting in regional and national models also being developed for forest inventories (Jenkins et al., 2003; Zianis et al., 2005).

Our objective in this research is to investigate the impact of incorrect species information and height measurement errors on individual tree volume estimates. To do so we implement a simulation approach using summary data from a large number of forest inventory plots within British Columbia, Canada, covering a wide range of species composition, age, and site classes. Using our approach we undertake four sets of analysis. We first assess the impact of not having a species-specific stem volume model on volume prediction by applying generic and cover-type allometric equations. We then assess the impact of species substitution on the single tree volume estimates based on most likely species compositions; and then demonstrate the impact of height error on single tree volume prediction by species. Lastly, we examine the impact of traditional inventory height errors on single tree volume estimates compared to ALS-derived estimates. We conclude with some recommendations on the use of ALS for single tree volume prediction in mixed species stands.

2. Methods

2.1 Study area

In order to ensure the analysis was undertaken on a representative set of stand conditions that cover a range of species compositions, age, and site index, we aggregated province-wide plot data into three key bioclimatic zones. Across British Columbia, the Biogeoclimatic Ecosystem Classification (BEC) system is a well-established and useful ecosystem-based classification based upon gradients in climate, soil fertility, and availability of water (Meidinger and Pojar, 1991). We selected three BEC zones across British Columbia (BC) representing a range of forest conditions (Figure 1): the Boreal White and Black Spruce (BWBS), the Coastal Western

Hemlock (CWH), and the Interior Cedar Hemlock (ICH). The BWBS zone is located in the northeast of BC, occurring in lowlands or valleys ranging in elevation from 230–1300 m. The climate in this zone can be characterized by short growing seasons and very cold winters, with an annual mean temperature not exceeding 2ºC and annual precipitation averages between 330–570 mm. The forests are mainly composed of white and black spruce, lodgepole pine, trembling aspen, balsam poplar, tamarack, subalpine fir and paper birch. The CWH, located along the entire British Columbia coast, typically occurs at low and middle elevations (up to ~1000 m), and also covers the majority of Vancouver Island and Haida Gwaii. This highly productive zone is the wettest in BC, with an annual precipitation of 2228 mm and a mean annual temperature of 8ºC. Western hemlock is the most common species with stands also comprising Douglas-fir, western redcedar, amabilis fir, Sitka spruce, among others. The ICH zone occurs in two major locations in British Columbia, one at the south-east occupying lower slopes of the Columbia Mountains and the second, east of the Coast Mountains, with a similar elevation range as CWH. The zone is characterized by a continental climate with cool wet winters and dry summers with mean annual temperature between 2–8.7º C and precipitation ranging from 500–1200 mm. This zone has the highest degree of tree diversity of all the BEC zones in the province (Table 1).

Stand exemplars were developed from forest inventory measurements for permanent sample plot data provided by the BC Ministry of Forests, Lands, and Natural Resource Operations (2007). The sample represents natural stands regenerating from harvest or natural disturbance. Plot measurements were taken periodically between 1950 and 2002. The median area of the plots was 538 m^2 targeting a census of 90 trees. The terms "age class 50" and "age class 100" refer to subsamples with a stand age within the 45–55 and 95–105 year intervals, respectively. The third age class consisted of all plots with a stand age that exceeded 200 years. Diameter at breast height was measured for all trees within each plot. Heights were measured for a subsample of trees within each plot and relationships between height and diameter were used to model heights for the remaining trees in the plot. All available inventory plots within each of the three BEC zones were aggregated and the average age, diameter at breast height (DBH), height, species composition, and stocking density were summarized (Table 2). To simplify the analyses, species composition within each BEC zone was limited to those species which occupied more than 5% of the BEC zone, by tree count.

2.2. Inventory measurement accuracies

We undertook a literature review to summarize typical accuracies associated with species composition and height estimation from field measurements, aerial photography and ALS (Table 3). Given the need to confirm the quality of measurements from a new technology and the digital nature of the approach, accuracy statistics are more commonly reported for ALS than conventional estimates derived from air photo interpretation. Accuracy statistics for forest inventory data are often not reported, with the specified target accuracy indicated, rather than quantitative analysis from a systematic assessment. Based on this review, we assessed typical accuracies for species composition from aerial photography as ranging between 30 and 60%. We assessed accuracies for photogrammetric estimates of tree height at a 20% RMSE, and accuracies for ALS-based estimates of individual tree height at 3.46% ± 2.04%.

2.3 Simulation methodologies

To investigate the impact of species composition and height measurement errors on individual tree volume estimates, we conducted a series of simulations to characterize the differences between reference tree volume estimates, and tree volume estimates modified using various error scenarios. To enable the simulations, for each of the BEC zones using the inventory plot characteristics summarized in Table 2, we defined eight stand exemplars (three age classes by three BEC zones, minus the oldest BWBS zone due to lack of plots within that stratum). Each stand exemplar was populated with the species composition from that BEC zone/age stratum and the mean and variance matching the actual inventory plot summaries. Tree DBH was assigned using a truncated normal distribution in order to ensure DBH predictions were greater than the measured minimum of 4 cm. Height was estimated for each tree based on previous published species specific DBH-height models (Hanus et al., 1999; Huang and Titus, 1992; Huang, 1999). If DBH-height models were not available for BC we utilised equations for the nearest jurisdiction (province or US state). To estimate volume of each tree we applied the biomass allometric equations by Ung et al. (2008) which were produced for each province in Canada (updated from Lambert et al. (2005)). These national allometric equations include equations for the 14 most common tree species in Canada and can be utilized to calculate foliage, branch, stem bark, stem wood, or total tree biomass using either DBH or a combination of DBH and height measurements. The equation coefficients were determined by Ung et al. (2008) using 9209 sample tree measurements (573 of those trees were located in BC). Moreover, for cases where the species is not known, Ung et al. (2008) provide a generalized equation for all species, as well as separate equations for hardwood and softwood species. All of the equations have two different forms; one using only DBH, and one using a combination of DBH and height:

- for DBH only: $y = \beta_1 D^{\beta_2} + e$ (same coefficients as below);
- for DBH and height: $y = \beta_1 D^{\beta_2} H^{\beta_3} + e$

where y – biomass [kg]; D – tree DBH [cm]; H – tree height [m]; $\beta_1 \ldots \beta_n$ – equation coefficients; e – error [kg].

After calculating biomass, tree volume was calculated by multiplying tree biomass with tree density (Gonzalez, 1990). All results reported in this paper are for tree volume. For each of the eight stand exemplars, we generated six different reference volume estimates. We recognise that these reference volume estimates are themselves not 100% accurate and will be subject to errors in allometry and tree density estimation; however, for the purpose of this study, the reference estimates, which were generated according to standard practices, provide a baseline for comparison against which other scenarios can be assessed.

The six reference volume estimates are as follows:

1. Volume calculated using a generic (all species) equation (denoted as generic; DBH as predictor);
2. Volume calculated using a generic (all species) equation (denoted as generic; DBH and height as predictors);
3. Volume calculated using a cover-type (softwood , hardwood) equation (denoted as cover type; DBH as predictor);
4. Volume calculated using a cover-type (softwood , hardwood) equation (denoted as cover type; DBH and height as predictors);

5. Volume calculated using a species-specific equation (denoted as reference volume; DBH as predictor).
6. Volume calculated using a species-specific equation (denoted as reference volume; DBH and height as predictors).

All analyses are performed at the individual tree level and then summarized for each of the stand exemplars. To assess differences between the volume estimates, individual tree volumes were compared and subtracted as per Equation 1:

$$\Delta y = \frac{y - y_{ref}}{y_{ref}} * 100\% \qquad \text{(Eq. 1)}$$

where: Δy – relative difference between two volume values [%]; y_{ref} – reference volume based on either DBH or DBH and height; y – calculated volume based on either DBH or DBH and height.

Following 100 repetitions, the mean and standard deviation of differences between the reference and simulated volumes were summarized for each stand exemplar. The data was log-transformed to ensure symmetry in the distribution around the median and the Wilcoxon signed-rank test was then applied to test the null hypothesis that the median difference between the reference and the simulated individual tree volumes, within each stands exemplar, was zero.

Four separate analyses were undertaken and are explained below:

1. Error in species composition:

To assess the impact of incorrect species identification on individual tree volume prediction, we randomly assigned species to individual trees for either 5%, 10%, 20%, 30%, 40%, and

50% of the total tree number in the stand exemplar. To ensure this species error was realistic, we limited species substitutions to a list of species found within the BEC zone (Table 2). Differences between reference (without modified species) and simulated individual tree volumes (with modified species) were assessed using the Wilcoxon signed-rank test, as described above.

2. Error in volume between species (next most likely species):

Within each of the three BEC zones, we assessed the impact of applying volume equations designed for all other species found within the zone. Individual tree volume (that is, the reference volume) was calculated for a range of DBH values (4 to 70 cm) using DBH only and DBH and height (Ung et al. 2008) species-specific equations. This reference volume was then compared to the individual tree volume values calculated with species substitution. Relative differences between the volumes were calculated for each species combination and evaluated using the Wilcoxon signed-rank test.

3. Impact of height error on volume by species:

To assess the impact of measurement error on height and the subsequent estimation of volume, a third set of simulations were performed. Reference individual tree volume values were calculated for 1000 trees by generating individual tree DBH and height with DBH-height curve. The reference height values were then altered to incorporate increasingly larger random errors (0.25 – 5.0 m at 0.25 m increment, random normal distribution with mean = 0). To calculate volume values resulting from that error, DBH values were modified proportionally according to the error introduced for the tree heights. Finally, individual tree volume values were compared to the reference volumes.

4. Impact of API-based inventory error on volume compared to ALS derived estimate.

To assess how these errors impact the overall error budget, we undertook a final set of simulations where we modelled differences in individual tree volume incorporating the range of errors typical for both conventional and ALS-based inventory. For this final simulation, ALS estimates of individual tree volume were made using randomly assigned species that occurred within the BEC zone, on the assumption that ALS was unable to provide a reliable species estimate. Additionally, error in individual tree height was introduced, set to a mean =-3.46% and SD = 2.04% (after Andersen et al. 2006; Table 3). Individual tree volume based on conventional inventory approaches (photogrammetry) was prepared in a slightly different manner and had three different variants: (i) error in species equal to 50%, resulting in 50% of trees having randomly assigned species occurring within the BEC zone and no height error; (ii) no error in species, however an error in height of RMSE = 20% (after Holopainen & Talvitie 2004)) and (iii) error in species equal to 50% and error in height. All 4 sets of simulations were compared to the reference individual tree volumes, differences calculated and Wilcoxon statistical test performed (with logarithmic transformation of the variables).

All simulations were performed in R software (R Core Team, 2013). Unless otherwise indicated, simulations were performed using 100 repetitions for each of the eight stand exemplars.

3. Results

3.1 Error in species composition

Table 4 summarizes the effect of different types of allometric equations on individual tree-based volume estimates for each stand exemplar. We used species-specific allometric equations as a reference and compared the results to those obtained using generic or cover-type equations. The effect of errors in species composition is also calculated based on DBH-only or DBH-height equations. For the BWBS stand exemplars at 50 years (BWBS50), the cover-type and generic allometric equations resulted in a 7.8% and 12.9% increase in average volume relative to the reference volume estimate. By comparison, if 50% of the trees within the simulated stand exemplar were randomly assigned to another species and their volume recalculated, the mean difference in individual tree-based volume was on average only 4.2% greater than the reference, and less than one third of the generic case. This trend occurs across all BEC zones and all age classes, with the generic and cover-type equations always resulting in greater differences when compared to the reference volume than when an error in species is introduced. For almost all stand exemplars, the results of Wilcoxon tests indicate that the median difference between the reference and modified individual tree-based volumes is not zero ($\alpha=0.05$). The largest error in volume introduced by randomly assigning species was 29.7% for BWBS100 using 50% species error and the combined DBH-height equation. The largest generic error was 64% for ICH100 (DBH only). There were no clear trends in the differences between the two groups of equations (DBH only, DBH and height), although differences exceeding 50% from the reference estimate were more frequent for DBH modelled volume. The other marked trend is that while the generic and cover-type equations commonly result in an overestimation of volume, the introduction of species error frequently results in an underestimation of volume.

3.2 Error in volume between species

Simulation results for differences in individual tree volume for pure, single species, stand exemplars associated with varying species composition show that volume can vary markedly (Figure 2 for a subset of BEC zones and species). Consider the example where the lodgepole pine (PL) equation is substituted for the Douglas-fir (FD) equation, resulting in average overestimation of individual tree volume by more than 50% (for DBH-only equations). Substituting western hemlock (HW) with Douglas-fir (FD) results in underestimation of about 20% for both the DBH-only and DBH-height equations. In some cases, such as between amabilis fir (BA) and western redcedar (CW), the difference is lower, not exceeding 5% (for DBH-height equation type). Also of note is that the same species substitution does not produce the same response in the DBH-only and DBH-height equations: in some cases the differences in individual tree volume are similar between both equation types (e.g., FD and HW) and in some cases they are quite different (e.g., PL and HW).

A summary of these species substitution results is shown in Figure 3 for both DBH-only and DBH-height equation types. The Wilcoxon test indicated that in almost all species combinations, the median difference between the reference volume estimate and the simulated volume estimate was not zero (α=0.05). In 20 cases (8 in DBH-only and 12 in DBH-height equations) species substitutions resulted in both the mean and standard deviation of the volume differences being less than 5%, and in 70 cases (38 and 32 for DBH-only and DBH-height equations, respectively) the mean individual tree-based volume difference values did not exceed 10%. This provides an indication of those species combinations will result in lower volume error and which species are highly problematic when confused. Figure 3 indicates that for DBH-only, subalpine fir (BL) is found to be the most universal species (least error prone), although species such as balsam poplar (AC), trembling aspen (AT), Engelmann spruce (SE), or white spruce (SW) also result in low errors. For DBH-height equations, strong agreement between Douglas-fir (FD) and western redcedar (CW) is observed, but also white spruce (SW), western larch (LW) and amabilis fir (BA) do not exceed 10% error when substituted with other species. The figure also shows that for DBH-height equation types, the substitution between conifer and deciduous species in most cases leads to differences in volume that are greater than 50%.

3.3 Impact of height error on volume by species

In Figure 4 we show the differences in volume between reference individual tree volumes and volumes generated with an increasing height error calculated for 1000 trees of each species. As it can be seen, the mean relative differences in volume are always positive, for all species. For height errors that are typical for airborne ALS acquisitions (i.e., 3.46% ± 2.04%), the relative differences between the reference individual tree volumes and the simulated individual tree volumes do not exceed, on average, 2%. White spruce appears to be most sensitive to height errors, with a difference in volume of 22.6% when computed using a height error of 5 m. In contrast, volume calculations of amabilis fir are the least impacted by this height error.

3.4 Impact of API-based inventory error on individual tree volume compared to ALS derived estimates

The final set of simulations compared differences between reference individual tree volumes and simulated individual tree volumes for stand exemplars with both simulated species and height errors (Figure 5). Each BEC zone and age class is represented by a panel; each with four simulation results. Similar patterns can be observed across all exemplars. First, the mean differences in individual tree volumes are nearly always positive (i.e., volume is overestimated) for all API-based inventory simulated errors, whereas for the ALS simulated error, individual tree volume is typically negative (i.e., volume is underestimated) in the ALS simulated stand exemplars. The spread of the difference values is much larger for conventional errors (API) than for the ALS and this trend is consistent across all BEC zone and age class combinations. It is observed that in some cases while the mean differences of the API simulated individual tree-based volume is small; the variation observed is much greater. However, the results of the Wilcoxon test (Table 5) show that only in one case (CWH50) were the reference and simulated individual tree-based volumes not significantly different. The modification of height and full randomization of species resulted in statistically different volume distributions for almost all ALS simulated stand exemplars.

4. Discussion

In this research, we undertook a variety of simulations to better understand and characterize the impact of species and height errors on the accuracy of individual tree volume estimates. To do so we generated a number of simulations designed to establish what the difference in individual tree volume was when a generic or cover-type equation was used, or when there was a given error in species, compared to reference estimates. Additionally, tree heights were modified with a random error with the subsequent influence in volume observed. Finally, a comparison of stand exemplars representing (i) typical API-based forest inventory accuracy and (ii) typical ALS accuracy was performed.

The results indicate that there are often large differences in individual tree volumes calculated using different types of volume equations. Individual tree volume calculated without species information (i.e., when generic or cover-type equations are used) leads to an overestimation in all of the BEC zones we analyzed, and in some cases this volume overestimation exceeded 50%. The overestimation varied in magnitude by age class and BEC zone. Conversely, the relative differences between reference tree volumes and modified tree volumes with different proportions of substituted species were much lower. Even in cases where 50% of the trees in the simulated stand exemplar were assigned the incorrect species, errors were not as great as when individual tree volumes were calculated using the generic equations. This clearly indicates that it is better to "take an educated guess" with regards to dominant species in the stand than to rely on the use of a generic equation.

It can be observed that in some cases, species substitution leads to minimal errors in individual tree volume estimates, likely resulting from similarities between different tree species in terms of their size, shape, growth dynamics, or site conditions. Defining cohorts of tree species that yield similar volume estimates for a given DBH and height, allows proxy species to be identified that can be used when detailed species information is unavailable.

The height based simulations (Figure 4) always produced an overestimation of individual tree volume even when random height errors introduced will be less than 0 (recall that error distribution ranged from 0.25–5.0 m; around 0.0 m mean). This overestimation is an effect of non-linear equation used for calculating the individual tree volume. The relative difference between the reference volume and volume calculated for a taller tree is not equal to a relative difference between the same reference and a shorter tree. For example, the volume calculated for a 30 cm thick western hemlock is 0.8023 m^3. If the tree's height is increased by 3 m or reduced by 3 m to simulate error in height measurement, the resulting volumes will be 1.09 m^3 and 0.56 m^3 respectively. The relative differences in volume (Eq. 1) are not equal: 0.29 m^3 and -0.23 m^3 respectively (36.4% and -23.5%), resulting in mean values of the differences calculated on 1000 trees always being positive. The impact of this finding is that if there are overestimates in height from ALS data, volume errors will be greater, than if the equivalent height error was underestimated. For typical ALS height errors of less than 1 m and negative bias, the impact on stand volume is likely to be unimportant. We acknowledge that as technology improves for conventional forest inventory approaches, accuracy also increases. Improvements in digital photogrammetry (such as Semi Global Matching, SGM) can be directly transferred into lower height errors (White et al., 2013b) when implementing a conventional forest inventory; and in some cases may result in errors that are very similar to ALS-based approaches. As image quality improves, species identification becomes easier, although there is a global lack of trained interpreters (Morgan et al., 2010). Simulation of height errors typical for both API-based inventories and ALS, demonstrated that smaller error of ALS derived height measurements result in smaller differences in volume estimates than API based inventories, even if the species is assigned at random (given an *a priori* knowledge about species composition based on the BEC zone). Our analysis represents a variety of productivity, species, and site conditions typical to British Columbia which showed very similar simulation results. Therefore our general findings are thought to be valid for a wide range forest species compositions and sites in North America, or even worldwide. Similar models that allow for the calculation of tree volume and biomass exist for Canada and also exist for many other regions such as the USA (Jenkins et al., 2003), Europe (Zianis et al., 2005) and Australia (Keith et al., 2000). Outside of southern Ontario, British Columbia represents some of the most complex forest environments in Canada offering species diversity that is not commonly found nationally. Across much of the Canadian boreal, species diversity is limited (e.g., dominated by jack pine and black spruce, with regionally important species such as trembling aspen or balsam poplar). For much of Canada, knowledge of dominant cover type and expectations of species assemblages can serve to guide regionally appropriate species determination for equation selection.

For ALS-based forest inventory performed with ITD approach, the outcomes of our study indicate species-specific equations should be used rather than generic equations because they result in lower errors in modelled volumes even with large errors in species composition. However, species occurring within one ecozone tend to have similar allometric equations contributing to lower errors in volume estimates, and initial knowledge about the possible species composition is thus required for our conclusion to hold. Taking into account the results of Vastaranta et al. (2011), we conclude that among all of factors considered to influence volume prediction accuracy, the tree detection rate remains the most important, followed by error in DBH measurement, error in height measurement, and error in species composition. It should be noted that the use of generic allometric equations increases the overall error in volume estimates more than typical measurement errors that are commonly associated with individual model inputs.

It is important to recognise that species information is not only relevant for individual tree volume calculations, but also may be critically important for biomass estimation, biodiversity characterization, tracking spread of pests and disease, wood quality assessment, and economic considerations in support of mill operations and harvest planning. Hence, if ALS estimates of individual tree volume are more accurate than conventional inventory estimates, even with incorrect species identification, knowledge of species is still important for other forestry purposes. Not surprisingly then, reliable species identification from ALS using point clouds is an active area of research and has shown some promising results. In typical cases however, these studies are based on extremely dense (Li et al., 2013) or multi-temporal ALS datasets (Brandtberg, 2007; Kim et al., 2011, 2009). Notable results have also been obtained with full waveform datasets (Heinzel and Koch, 2011) or when ALS data is integrated with other spatial datasets, providing spectral information, like satellite or airborne imagery (Holmgren et al., 2008), or hyperspectral data (Dalponte et al., 2014; Jones et al., 2012). Recent studies by Suratno et al. (2009) are also a good example of using relatively low density data for classifying conifer species. Overall classification accuracy for species identification varies from ~60 to ~80%. If after applying all these additional data collection and processing steps, species remains incorrect in 20% to 40% of cases (as indicated in studies conducted to date), the costs and effort required may not be justified. The quality of species estimates will depend on factors such as the number and possibly how distinctive (spectrally, morphologically) species are in a given location. The simulations presented in this research may allow some users to decide upon allocation of appropriate species-specific allometric equations via local knowledge and expectation rather than via estimation using alternate data sources.

5. Conclusion

Accurate characterizations of forest structure and composition are required to support sustainable forest management. The use of ALS as a forest measurement tool results in increased stand inventory accuracy. However, the lack of multispectral information from ALS point clouds (among other considerations), limits the capacity to obtain accurate determination of tree species. In this research we simulated various forest plots using inventory data from British Columbia, Canada. Using generic, cover-type, and species-specific allometric equations, we verified the relative importance of accurate measurements of height and information on species composition for estimating individual tree volume.

Our simulations indicate that the selection of allometric equations is critical for reliable volume estimates. Accurate tree species identification increased the accuracy of volume calculations over the use of generic or cover-type (i.e., deciduous/conifer) equations which resulted in higher volume estimation errors. Moreover, even with a 50% error in species composition, volume estimates were more accurate than when no species information was used at all (i.e., when generic equations are used). Overall, accuracy of height measurements was more important for accurately estimating individual tree volumes than species composition.

6. Acknowledgements:

We acknowledge the Inventory Branch of the British Columbia Ministry of Forests, Lands and Natural Resource Operations for compilation of forest inventory data and Dr Robbie Hember for compiling regional level characteristics. We thank Dr Wiebe Nijland for editorial assistance. The Canadian Wood Fiber Centre, of the Canadian Forest Service of Natural Resources Canada, provided funding to support this research with additional support from an NSERC Discovery grant to N. Coops.

7. References

Andersen, H.E., Reutebuch, S.E., McGaughey, R.J., 2006. A rigorous assessment of tree height measurements obtained using airborne lidar and conventional field methods. Can. J. Remote Sens. 32, 355–366.

Avery, T.E., 1977. Interpretation of Aerial Photographs, Third. ed. Minneapolis, Minnesota.

Baltsavias, E.P., 1999a. Airborne laser scanning: basic relations and formulas. ISPRS J. Photogramm. Remote Sens. 54, 199–214.

Baltsavias, E.P., 1999b. A comparison between photogrammetry and laser scanning. ISPRS J. Photogramm. Remote Sens. 54, 83–94.

BC Ministry of Forests, Lands, and Natural Resource Operations, 2007. Permanent Sample Plots, Ministry of Forests, Lands and Natural Resource Operations. [WWW Document]. URL http://www.for.gov.bc.ca/hts/vri/psps/psp.html

Boan, J.J., Mclaren, B.E., Malcolm, J.R., 2013. Predicting Non-Inventoried Forest Elements using Forest Inventory Data: The Case of Winter Forage for Woodland Caribou. Ecoscience 20, 101–111. doi:10.2980/20-2-3567

Brandtberg, T., 2007. Classifying individual tree species under leaf-off and leaf-on conditions using airborne lidar. ISPRS J. Photogramm. Remote Sens. 61, 325–340.

Brandtberg, T., Warner, T.A., Landenberger, R.E., McGraw, J.B., 2003. Detection and analysis of individual leaf-off tree crowns in small footprint, high sampling density lidar data from the eastern deciduous forest in North America. Remote Sens. Environ. 85, 290–303. doi:10.1016/S0034-4257(03)00008-7

Ciesla, W.M., 1990. Tree species identification on aerial photos: expectations and realities, in: Protecting Natural Resources with Remote Sensing: The Third Forest Service Remote Sensing Applications Conference Held at the University of Arizona and the Doubletree Inn, Tucson, Arizona, April 9-13, 1990. pp. 308–319.

Congalton, R.G., Mead, R.A., 1983. A Quantitative Method to Test for Consistency and Correctness in Photointerpretation *. Photogramm. Eng. Remote Sens. 49, 69–74.

Dalponte, M., Ørka, H.O., Ene, L.T., Gobakken, T., Næsset, E., 2014. Tree crown delineation and tree species classification in boreal forests using hyperspectral and ALS data. Remote Sens. Environ. 140, 306–317. doi:10.1016/j.rse.2013.09.006

Deegan, G., Befort, W.A., 1990. Photointerpretation accuracy across two decades of forest inventory, in: Stateof-the-Art Methodology of Forest Inventory: A Symposium Proceedings. Citeseer, pp. 318–323.

Eid, T., Næsset, E., 1998. Determination of stand volume in practical forest inventories based on field measurements and photo-interpretation: The Norwegian experience. Scand. J. For. Res. 13, 246–254. doi:10.1080/02827589809382982

Falkowski, M.J., Smith, A.M.., Hudak, A.T., Gessler, P.E., Vierling, L. a, Crookston, N.L., 2006. Automated estimation of individual conifer tree height and crown diameter via two-dimensional spatial wavelet analysis of lidar data. Can. J. Remote Sens. 32, 153–161. doi:10.5589/m06-005

Gillis, M.D., Omule, A.Y., Brierley, T., 2005. Monitoring Canada’s forests: the National Forest Inventory. For. Chron. 81, 214–221.

Gonzalez, J.S., 1990. Wood density of Canadian tree species. Inf. Rep. NOR-X-315. For. Canada, Northwest Reg. North. For. Cent.

Hall, R.J., Morton, R.T., Nesby, R.N., 1989. A Comparison of Existing Models for DBH Estimation from Large-scale Photos. For. Chron. 65, 114–120.

Hanus, M.L., Marshall, D.D., Hann, D.W., 1999. Height-diameter equations for six species in the coastal regions of the Pacific Northwest.

Heinzel, J., Koch, B., 2011. Exploring full-waveform LiDAR parameters for tree species classification. Int. J. Appl. Earth Obs. Geoinf. 13, 152–160.

Hilker, T., Wulder, M.A., Coops, N.C., 2008. Update of forest inventory data with lidar and high spatial resolution satellite imagery. Can. J. Remote Sens. 34, 5–12.

Höfle, B., Pfeifer, N., 2007. Correction of laser scanning intensity data: Data and model-driven approaches. ISPRS J. Photogramm. Remote Sens. 62, 415–433. doi:10.1016/j.isprsjprs.2007.05.008

Hollaus, M., Wagner, W., Maier, B., Schadauer, K., 2007. Airborne Laser Scanning of Forest Stem Volume in a Mountainous Environment. Sensors 7, 1559–1577. doi:10.3390/s7081559

Holmgren, J., 2004. Prediction of tree height, basal area and stem volume in forest stands using airborne laser scanning. Scand. J. For. Res. 19, 543–553. doi:10.1016/S0034-4257(03)00140-8

Holmgren, J., Persson, Å., Söderman, U., 2008. Species identification of individual trees by combining high resolution LiDAR data with multi-spectral images. Int. J. Remote Sens. 29, 1537–1552. doi:10.1080/01431160701736471

Holopainen, M., Talvitie, M., 2004. Forest Inventory By Means Of Tree-Wise 3D-Measurements Of Laser Scanning Data And Digital Aerial Photographs. Int. Arch. Photogramm. Remote Sens. XXXVI, 167–172.

Huang, S., 1999. Ecoregion-Based Individual Tree Height-Diameter Models for Lodgepole Pine in Alberta. West. J. Appl. For. 14, 186 – 193.

Huang, S., Titus, S.J., 1992. Comparison of nonlinear height-diameter functions for major Alberta tree species [WWW Document]. Can. J. For. Res. Vol 22. URL http://www.math.ualberta.ca/~wiens/home page/pubs/treemodels.pdf

Hyyppä, H.J., Hyyppä, J.M., 2001. Effects of Stand Size on the Accuracy of Remote Sensing-Based Forest Inventory. IEEE Trans. Geosci. Remote Sens. 39, 2613–2621.

Hyyppä, J., Hyyppä, H., Leckies, F., Gougeon, F., Yu, X., Maltamo, M., 2008. Review of methods of small-footprint airborne laser scanning for extracting forest inventory data in boreal forests. Int. J. Remote Sens. 29, 1339–1366.

Hyyppä, J., Inkinen, M., 1999. Detecting and estimating attributes for single trees using laser scanner. Photogramm. J. Finl. 16.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2003. National-Scale Biomass Estimators for United States Tree Species. For. Sci. 49.

Jones, T.G., Coops, N.C., Sharma, T., 2012. Assessing the utility of LiDAR to differentiate among vegetation structural classes. Remote Sens. Lett. 3, 231–238. doi:10.1080/01431161.2011.559289

Kaartinen, H., Hyyppä, J., Yu, X., Vastaranta, M., Hyyppä, H., Kukko, A., Holopainen, M., Heipke, C., Hirschmugl, M., Morsdorf, F., Næsset, E., Pitkänen, J., Popescu, S., Solberg, S., Wolf, B.M., Wu, J.-C., 2012. An International Comparison of Individual Tree Detection and Extraction Using Airborne Laser Scanning. Remote Sens. 4, 950–974. doi:10.3390/rs4040950

Kaasalainen, S., Hyyppä, H., Kukko, A., Litkey, P., Ahokas, E., Hyyppä, J., Lehner, H., Jaakkola, A., Suomalainen, J., Akujärvi, A., Kaasalainen, M., Pyysalo, U., 2009. Radiometric Calibration of LIDAR Intensity With Commercially Available Reference Targets. IEEE Trans. Geosci. Remote Sens. 47, 588–598.

Kalliovirta, J., Tokola, T., 2005. Functions for Estimating Stem Diameter and Tree Age Using Tree Height , Crown Width and Existing Stand Database Information. Silva Fenn. 39, 227–248.

Kankare, V., Räty, M., Yu, X., Holopainen, M., Vastaranta, M., Kantola, T., Hyyppä, J., Hyyppä, H., Alho, P., Viitala, R., 2013. Single tree biomass modelling using airborne laser scanning. ISPRS J. Photogramm. Remote Sens. 85, 66–73. doi:10.1016/j.isprsjprs.2013.08.008

Keith, H., Barrett, D., Keenan, R., 2000. Review of Allometric Relationships for Estimating Woody Biomass for New South Wales, the Australian Capital Territory, Victoria, Tasmania and South Australia.

Kim, S., Hinckley, T., Briggs, D., 2011. Classifying individual tree genera using stepwise cluster analysis based on height and intensity metrics derived from airborne laser scanner data. Remote Sens. Environ. 115, 3329–3342.

Kim, S., McGaughey, R.J., Andersen, H.-E., Schreuder, G., 2009. Tree species differentiation using intensity data derived from leaf-on and leaf-off airborne laser scanner data. Remote Sens. Environ. 113, 1575–1586.

Lambert, M., Ung, C., Raulier, F., 2005. Canadian national tree aboveground biomass equations. Can. J. For. Res. 35, 1996–2018.

Leckie, D.G., Gillis, M.D., 1995. FOREST INVENTORY IN CANADA WITH EMPHASIS ON MAP PRODUCTION. For. Chron. 71, 74–88.

Leckie, D.G., Gillis, M.D.D., 1995. Forest inventory in Canada with emphasis on map production. For. Chron. 71, 74–88.

Leeuwen, M. Van, Nieuwenhuis, M., 2010. Retrieval of forest structural parameters using LiDAR remote sensing. Eur. J. For. Res. 129, 749–770. doi:10.1007/s10342-010-0381-4

Lefsky, M.A., Cohen, W.B., Harding, D.J., 2002a. Lidar remote sensing of above-ground biomass in three biomes. Glob. Ecol. 393–399.

Lefsky, M.A., Cohen, W.B., Parker, G.G., Harding, D.J., 2002b. Lidar remote sensing for ecosystem studies. Bioscience 52, 19–30.

Li, J., Hu, B., Noland, T.L., 2013. Classification of tree species based on structural features derived from high density LiDAR data. Agric. For. Meteorol. 171, 104–114.

Liang, X., Matikainen, L., 2007. DECIDUOUS-CONIFEROUS TREE CLASSIFICATION USING DIFFERENCE BETWEEN FIRST AND LAST PULSE LASER SIGNATURES. IAPRS XXXVI, 253–257.

Means, J.E., Acker, S.A., Fitt, B.J., Renslow, M., Emerson, L., Hendrix, C.J., 2000. Predicting forest stand characteristics with airborne scanning Lidar. Photogramm. Eng. Remote Sens. 66, 1367–1371.

Meidinger, D. V, Pojar, J., 1991. Ecosystems of British Columbia, B.C. Victoria, BC.

Morgan, J., Gergel, S., Coops, N.C., 2010. Aerial photography: a rapidly evolving tool for ecological management. Bioscience 60, 47–59.

Næsset, E., 2002. Determination of Mean Tree Height of Forest Stands by Digital Photogrammetry. Scand. J. For. Res. 17, 446–459. doi:10.1080/028275802320435469

Næsset, E., Økland, T., 2002. Estimating tree height and tree crown properties using airborne scanning laser in a boreal nature reserve. Remote Sens. Environ. 79, 105–115.

Ørka, H.O., Næsset, E., Bollandsås, O.M., 2009. Classifying species of individual trees by intensity and structure features derived from airborne laser scanner data. Remote Sens. Environ. 113, 1163–1174.

Persson, A., Holmgren, J., Söderman, U., 2002. Detecting and measuring individual trees using an airborne laser scanner. Photogramm. Eng. Remote Sensing 68, 925–932.

Popescu, S.C., 2007. Estimating biomass of individual pine trees using airborne lidar. Biomass and Bioenergy 31, 646–655. doi:10.1016/j.biombioe.2007.06.022

R Core Team, 2013. R: A language and environment for statistical computing. R Found. Stat. Comput. Vienna, Austria.

Reutebuch, S.E., Andersen, H.E., Mcgaughey, R.J., 2005. Light detection and ranging (LIDAR): an emerging tool for multiple resource inventory. J. For. 103, 286–292.

Spencer, R.D., Hall, R.J., 1988. Canadian Large-Scale Aerial Photographic Systems. Photogramm. Eng. Remote Sens. 54, 475–482.

St-Onge, B., Jumelet, J., 2004. Measuring individual tree height using a combination of stereophotogrammetry and lidar. Can. J. For. Res. 34, 2122–2130.

St-Onge, B., Jumelet, J., Cobello, M., Véga, C., 2004. Measuring individual tree height using a combination of stereophotogrammetry and lidar. Can. J. For. Res. 34, 2122–2130.

Suratno, A., Seielstad, C., Queen, L., 2009. Tree species identification in mixed coniferous forest using airborne laser scanning. ISPRS J. Photogramm. Remote Sens. 64, 683–693.

Thompson, I.D., Maher, S.C., Rouillard, D.P., Fryxell, J.M., Baker, J.A., 2007. Accuracy of forest inventory mapping: Some implications for boreal forest management. For. Ecol. Manage. 252, 208–221.

Tomppo, E., Gschwanter, T., Lawrence, M., Mcroberts, R.E., 2010. National Forest Inventories. Pathways for Common Reporting. Springer.

Ung, C.-H., Bernier, P., Guo, X.-J., 2008. Canadian national biomass equations: new parameter estimates that include British Columbia data. Can. J. For. Res. 38, 1123–1132. doi:10.1139/X07-224

Vastaranta, M., Holopainen, M., Yu, X., Hyyppä, J., Mäkinen, A., Rasinmäki, J., Melkas, T., Kaartinen, H., Hyyppä, H., 2011. Effects of Individual Tree Detection Error Sources on Forest Management Planning Calculations. Remote Sens. 3, 1614–1626.

Vastaranta, M., Melkas, T., Holopainen, M., H., K., Hyyppä, J., Hyyppä, H., 2009. Laser-Based Field Measurements in Tree-Level Forest Data Acquisition. Photogramm. J. Finl. 21, 51–61.

Vauhkonen, J., Korpela, I., Maltamo, M., Tokola, T., 2010. Imputation of single-tree attributes using airborne laser scanning-based height, intensity, and alpha shape metrics. Remote Sens. Environ. 114, 1263–1276.

Wehr, A., Lohr, U., 1999. Airborne laser scanning-an introduction and overview. ISPRS J. Photogramm. Remote Sens. 54, 68–82.

West, P.W., 2004. Tree and Forest Measurement. Springer.

White, J.C., Wulder, M.A., Varhola, A., Vastaranta, M., Coops, N.C., Cook, B.D., Pitt, D., Woods, M., 2013a. A best practices guide for generating forest inventory attributes from airborne laser scanning data using an area-based approach. Inf. Rep. FI-X-10. Nat. Resour. Canada, Can. For. Serv. Can. Wood Fibre Centre, Pacific For. Centre, Victo- ria, BC. 50 p. Available online http// cfs.nrcan.gc.ca/publications?id=34887.

White, J.C., Wulder, M.A., Vastaranta, M., Coops, N.C., Pitt, D., Woods, M., 2013b. The Utility of Image-Based Point Clouds for Forest Inventory: A Comparison with Airborne Laser Scanning. Forests 4, 518–536. doi:10.3390/f4030518

Wing, M.G., Solmie, D., Kellogg, L., 2004. Comparing Digital Range Finders for Forestry Applications. Jounral For. 102, 16–20.

Wulder, M.A., Bater, C.C.W., Coops, N.C., Hilker, T., White, J.C., 2008. The role of LiDAR in sustainable forest management. For. Chron. 84, 807–826.

Wulder, M.A., Campbell, C., White, J.C., Flannigan, M., Campbell, I.D., 2007. National circumstances in the international circumboreal community. For. Chron. 83, 539–556.

Wulder, M.A., Coops, N.C., Hudak, A.T., Morsdorf, F., Nelson, R., Newnham, G., Vastaranta, M., 2013. Status and prospects for LiDAR remote sensing of forested ecosystems. Can. J. Remote Sens. 39, 1–5.

Yu, X., Hyyppä, J., Vastaranta, M., Holopainen, M., Viitala, R., 2011. Predicting individual tree attributes from airborne laser point clouds based on the random forests technique. ISPRS J. Photogramm. Remote Sens. 66, 28–37. doi:10.1016/j.isprsjprs.2010.08.003

Zhao, K., Popescu, S.C., Nelson, R.F., 2009. Lidar remote sensing of forest biomass: A scale-invariant estimation approach using airborne lasers. Remote Sens. Environ. 113, 182–196.

Zianis, D., Muukkonen, P., Makipaa, R., Mencuccini, M., 2005. Biomass and Stem Volume Equations for Tree Species in Europe. Silva Fenn.

LIST OF TABLES AND FIGURES

Table 1. List of abundant (**) and common (*) tree species occurring in three chosen BEC zones according to Meidinger and Pojar, 1991.

Scientific name	Common name	Species symbol	species occurence in BEC zone		
			BWBS	CWH	ICH
Abies amabilis	amabilis fir	BA		**	
A. grandis	grand fir	BG			*
A. lasiocarpa	subalpine fir	BL	*		*
Chamaecyparis nootkatensis	yellow-cedar	YC		*	
Larix laricina	tamarack	LT	*		
L. occidentalis	western larch	LW			*
Picea engelmannii	Engelmann spruce	SE			*
P. glauca	white spruce	SW	**		
P. mariana	black spruce	SB	**		
P. sitchensis	Sitka spruce	SS		**	
Pinus contorta	lodgepole pine	PL	**	*	*
Pseudotsuga menziesii	Douglas-fir	FD		**	*
Taxus brevifolia	western yew	TW		*	*
Thuja plicata	western redcedar	CW		**	**
Tsuga heterophylla	western hemlock	HW		**	**
Alnus rubra	red alder	DR		**	
Betula neoalaskana	Alaska paper birch	EXP	*		
B. papyrifera	paper birch	EP	*		*
Populus balsamifera ssp. Balsamifera	balsam poplar	ACB	*		
Populus balsamifera ssp. Trichocarpa	black cottonwood	ACT		*	*
P. tremuloides	trembling aspen	AT	**		*

Table 2. Species occurrences for different age classes and biogeoclimatic zone.

age class 50						100						200					
Biogeoclimatic zone: BWBS																	
species	%	DBH		height		species	%	DBH		height							
		mean	sd	mean	sd			mean	sd	mean	sd						
PL	0.60	11.2	3.1	12.8	2.4	SS	0.78	19.7	7.6	20.2	5.4						
AT	0.36	11.0	3.7	13.3	3.1	SW	0.16	19.2	5.4	18.2	2.5						
AC	0.04	12.8	4.8	14.5	6.1	SE	0.06	27.4	8.9	25.2	6.7						
Mean and SD of tree number: 3341± 2487						Mean and SD of tree number: 1628 ± 787											
Biogeoclimatic zone: CWH																	
species	%	DBH		height		species	%	DBH		height		species	%	DBH		height	
		mean	sd	mean	sd			mean	sd	mean	sd			mean	sd	mean	sd
HW	0.49	16.2	9.2	17.2	7.7	HW	0.46	22.5	13.8	21.3	10.9	HW	0.51	41.1	24.6	27.2	11.5
FD	0.28	16.3	10.2	16.4	7.4	FD	0.27	29.5	16.3	24.8	10.0	BA	0.22	40.7	24.1	27.1	12.2
CW	0.11	12.0	8.5	10.6	5.4	CW	0.18	18.7	16.0	14.2	8.5	CW	0.21	69.8	50.3	29.0	12.0
SS	0.06	24.5	14.4	21.0	7.6	SS	0.06	44.1	24.1	29.9	10.5	FD	0.06	87.4	26.8	46.6	11.1
BA	0.06	13.7	8.5	12.9	6.9	BA	0.04	24.3	15.6	19.9	11.3						
Mean and SD of tree number: 2076 ± 1365						Mean and SD of tree number: 1212 ± 972						Mean and SD of tree number: 360 ± 117					
Biogeoclimatic zone: ICH																	
species	%	DBH		height		species	%	DBH		height		species	%	DBH		height	
		mean	sd	mean	sd			mean	sd	mean	sd			mean	sd	mean	sd
PL	0.54	13.6	4.4	16.3	3.4	FD	0.30	21.5	11.0	20.4	7.5	CW	0.44	24.7	31.0	12.2	7.7
FD	0.16	14.3	6.1	14.1	4.3	CW	0.29	13.1	7.5	10.9	5.6	BL	0.26	11.9	5.9	10.8	5.0
LW	0.15	13.3	5.4	15.8	4.4	HW	0.18	13.9	6.8	13.7	6.3	HW	0.21	29.0	20.5	18.4	11.9
AT	0.10	12.2	3.6	13.6	2.8	PL	0.16	18.2	6.0	20.6	4.5	LW	0.09	11.5	2.0	13.5	1.5
HW	0.05	11.0	5.1	11.6	4.2	LW	0.07	20.8	8.5	23.2	6.1						
Mean and SD of tree number: 2098 ± 2366						Mean and SD of tree number: 2038 ± 1802						Mean and SD of tree number: 3249 ± 3761					

Table 3. Review of measurement accuracies for DBH, height, and species composition from ground surveys, photogrammetry, and ALS data. Values used in simulations are shown in bold.

general description, stand characteristics, remarks	Error value	Location	reference
Field measurements			
DBH (caliper)	±0.001 m		(West, 2004)
Tree height	±0.5 m		(West, 2004)
Tree height (clinometer)	Bias: -0.59 m (-5.2%) SE: 0.99 m (10.1%)	Finland	(Vastaranta et al., 2009)
Tree height (hypsometer)	1-2%	US	(Wing et al., 2004)
Species composition, photogrammetry			
Error in tree species composition, accuracy of forest resource inventory (FRI)	**30-60%**	Ontario, Canada	(Thompson et al., 2007)
Error in tree species composition, analog photogrammetry	15-20% (based on expert opinion)	Canada	(D.G. Leckie and Gillis, 1995)
Cover type, analog photogrammetry	30-41%	Minnesota, USA	(Deegan and Befort, 1990)
Height, photogrammetry			
Norway spruce stands, error in mean stand height with digital photogrammetry	-5.42 m (mean error value)	Norway	(Næsset, 2002)
White cedar stands, with ALS-derived DTM	Mean = 0.59 m SD = 1.01 m	Montreal, Canada	(St-Onge et al., 2004)
Various stands	**RMSE = 20%**	Finland	(Holopainen and Talvitie, 2004)
Height, ALS			
Tree height accuracy, conifer stands	Mean difference 0.18 m; SD= 3.15 m, R^2 = 0.91	Norway	(Næsset and Økland, 2002)
Tree height accuracy, stands dominated with Douglas-fir	R^2 = 0.93, RMSE = 3.4	Oregon, USA	(Means et al., 2000)
Norway spruce, scots pine and birch stands	RMSE = 0.63, R=0.99	Sweden	(Persson et al., 2002)
Deciduous tree stands, leaf-off conditions	R^2 = 0.69	West Virginia, USA	(Brandtberg et al., 2003)
Douglas fir stands	**Mean = -0.73 m; SD = 0.43 m (-3.46% ± 2.04%)**	Washington, USA	(Andersen et al., 2006)

Table 4. Mean and standard deviation for differences (%) between reference volume (calculated with species-specific equations) and volume calculated with cover-type equations (i.e., conifer/deciduous), a generic equation, and with a given amount of error in species composition. The asterisk indicates the *p*-value < 0.05 for Wilcoxon signed rank test.

		Differences [%]; volume calculated using DBH only								Differences [%]; volume calculated using DBH and height							
Stand exemplar (BEC zone + age class)		Cover-type equation	Generic equation	Error in species						Cover-type equation	Generic equation	Error in species					
				5%	10%	20%	30%	40%	50%			5%	10%	20%	30%	40%	50%
BWBS50	mean	7.8*	12.9*	0.4*	0.8*	1.7*	2.5*	3.4*	4.2*	11.7*	9.3*	-0.7*	-1.4*	-2.7*	-4.1*	-5.5*	-6.8*
	sd	10.2	6.8	2.1	2.9	3.9	4.6	5.0	5.2	20.7	14.6	3.6	4.9	6.7	7.9	8.7	9.3
BWBS100	mean	6.7*	21.9*	0.4*	0.8*	1.6*	2.5*	3.3*	4.1*	45.8*	50.2*	2.9*	5.9*	11.9*	17.8*	23.7*	29.7*
	sd	6.2	8.0	2.2	3.0	4.1	4.8	5.3	5.6	22.6	21.5	13.1	18.1	24.2	27.7	29.8	30.6
CWH50	mean	41.5*	64.0*	-0.2*	-0.3*	-0.7*	-1.0*	-1.3*	-1.6*	24.4*	28.3*	0.2	0.5	1.2*	1.7*	2.2*	2.9*
	sd	26.5	33.5	3.9	5.5	7.8	9.6	11.0	12.3	13.1	12.9	4.4	6.2	8.9	10.8	12.3	13.8
CWH100	mean	25.9*	43.2*	-0.5*	-1.1*	-2.2*	-3.2*	-4.3*	-4.5*	16.1*	21.2*	-0.1	-0.3	-0.5	-0.8*	-1.0*	-1.0*
	sd	25.5	32.1	3.9	5.6	7.7	9.2	10.5	12.1	11.8	11.5	3.9	5.7	8.1	9.9	11.5	12.6
CWH200	mean	-1.5	8.5*	-1.3*	-2.6*	-5.3*	-8.0*	-10.7*	-13.4*	10.7*	17.7*	-0.6*	-1.2*	-2.4*	-3.6*	-4.7*	-5.9*
	sd	19.7	22.9	6.0	8.3	11.3	13.0	14.0	14.5	17.4	17.1	4.0	5.6	7.9	9.4	10.6	11.6
ICH50	mean	17.6*	33.8*	-1.2*	-2.4*	-4.9*	-7.3*	-9.7*	-12.2*	12.8*	15.0*	-1.2*	-2.5*	-5.0*	-7.5*	-10.1*	-12.6*
	sd	27.1	33.4	6.7	9.3	12.8	15.0	16.6	17.8	19.8	19.0	5.6	7.7	10.4	11.9	12.8	13.1
ICH100	mean	42.0*	64.0*	1.2*	2.3*	4.8*	7.1*	10.2*	13.3*	14.6*	19.0*	0.4	0.8	1.8	2.6*	1.2*	-0.1*
	sd	31.1	38.1	8.0	11.1	15.5	18.5	21.5	23.9	15.0	14.6	4.2	5.9	8.3	10.1	12.1	13.7
ICH200	mean	25.4*	44.0*	0.9*	1.8*	3.6*	5.5*	7.3*	6.8*	7.0*	11.7*	-0.4*	-0.8*	-1.6*	-2.3*	-3.1*	-4.6*
	sd	28.7	36.4	6.5	9.0	12.5	15.0	17.0	19.1	13.0	12.9	4.0	5.6	7.9	9.6	11.0	12.5

Table 5. Results of Wilcoxon test (*p*-values) performed on reference and modified simulated plots. Values less than 0.05 shown in bold type.

	BWBS50	BWBS100	CWH50	CWH100	CWH200	ICH50	ICH100	ICH200
API v1	0.301	0.405	0.416	**0.010**	**0.013**	0.246	**0.002**	0.069
API v2	0.130	**0.005**	0.184	**0.000**	**0.006**	**0.000**	**0.000**	**0.000**
API v3	0.491	0.062	0.470	**0.000**	**0.010**	**0.000**	**0.000**	**0.000**
ALS	**0.000**	**0.000**	0.140	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**

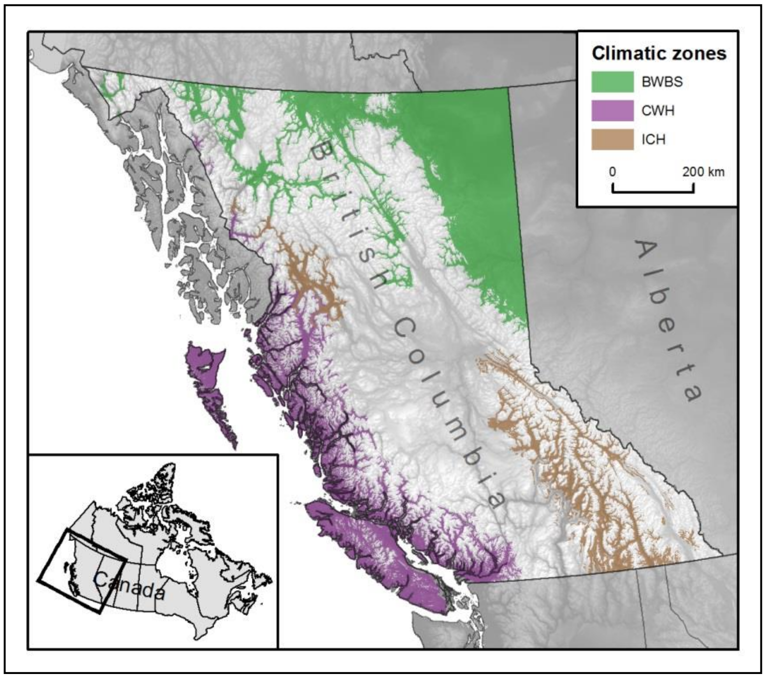

Figure 1. Study area is located in British Columbia, Canada. The location and extent of the three biogeoclimatic (BEC) zones are indicated: Boreal White and Black Spruce (BWBS); Coastal Western Hemlock (CWH); and Interior Cedar-Hemlock (ICH).

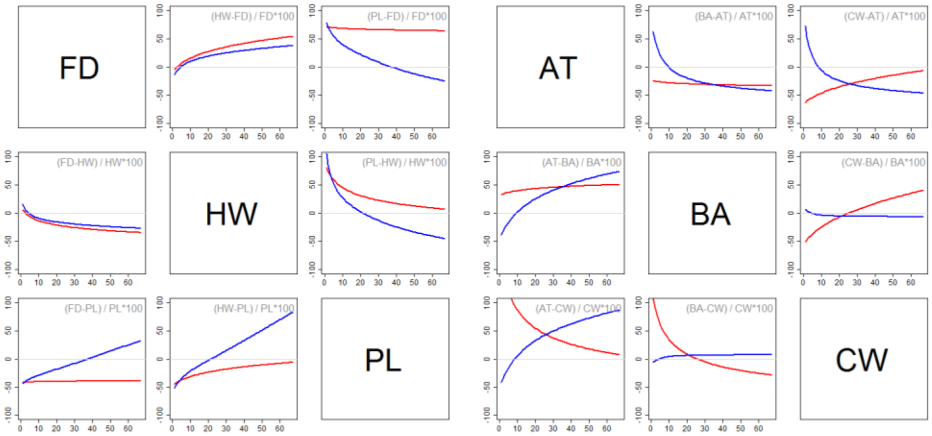

Figure 2. Some examples of the difference (%) between individual tree volumes calculated with equations for different species and a sequence of DBH values (x-axis). Colours indicate equation type: red indicates the use of an equation based on DBH only; blue indicates the use of an equation based on DBH and height.

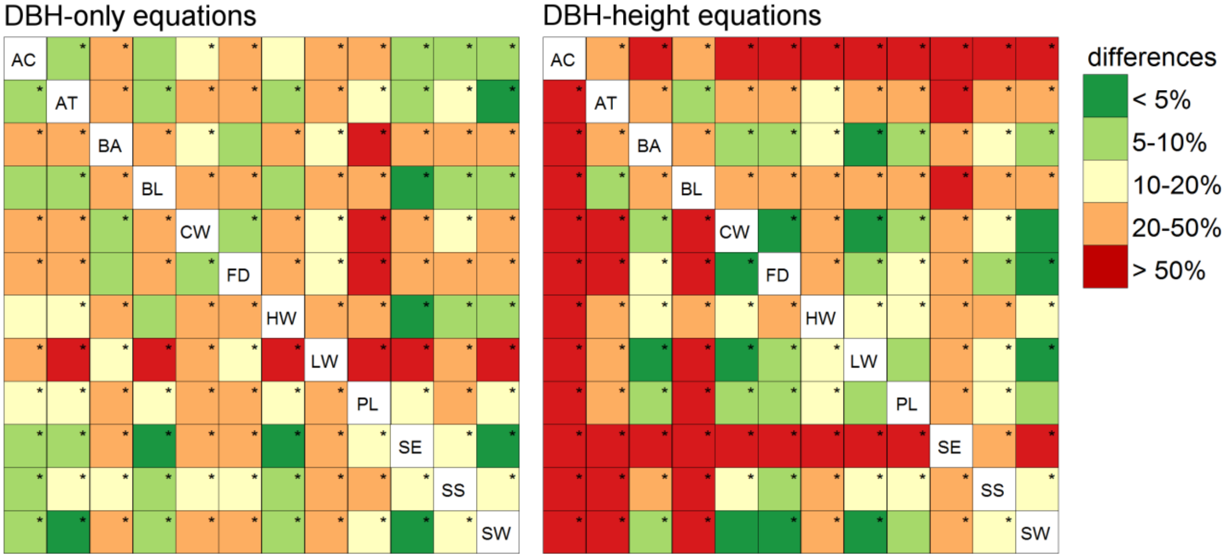

Figure 3. Matrices presenting the error categories resulting from species substitutions. Relative differences between reference and simulated individual tree volumes were categorized into five groups as indicated. The volume of each instance was calculated in this case for a smaller range of DBH values: 20 – 50cm and the vector of differences was used to calculate mean and standard deviation values. The asterisk indicates significant differences in individual tree volumes as determined using the Wilcoxon signed rank test (α = 0.05).

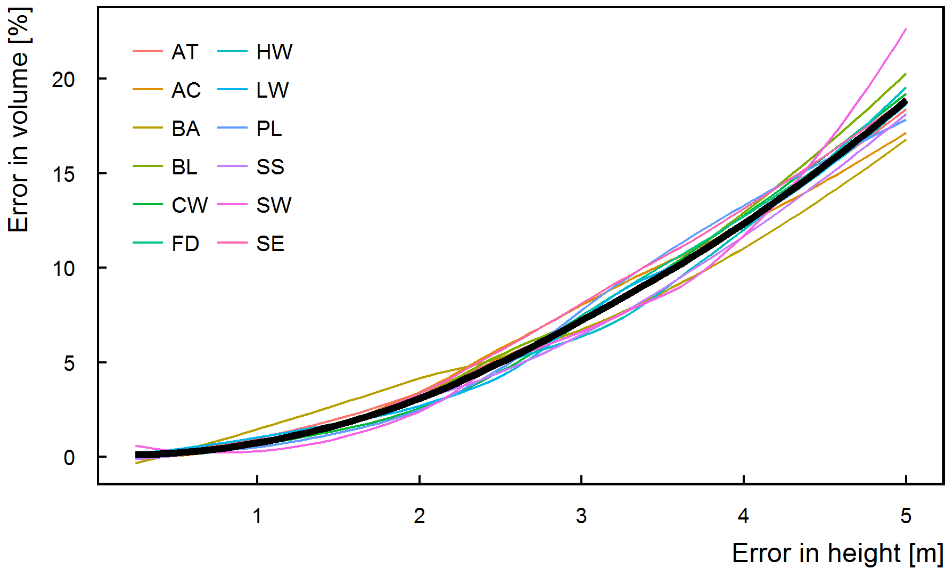

Figure 4. Mean relative differences in volume (%) between a reference individual tree volume and a simulated tree volume with modified height values indicated by the error (standard deviation) in height value. Each line represents an average for 1000 trees of the same species. Black line relates the mean across all species.

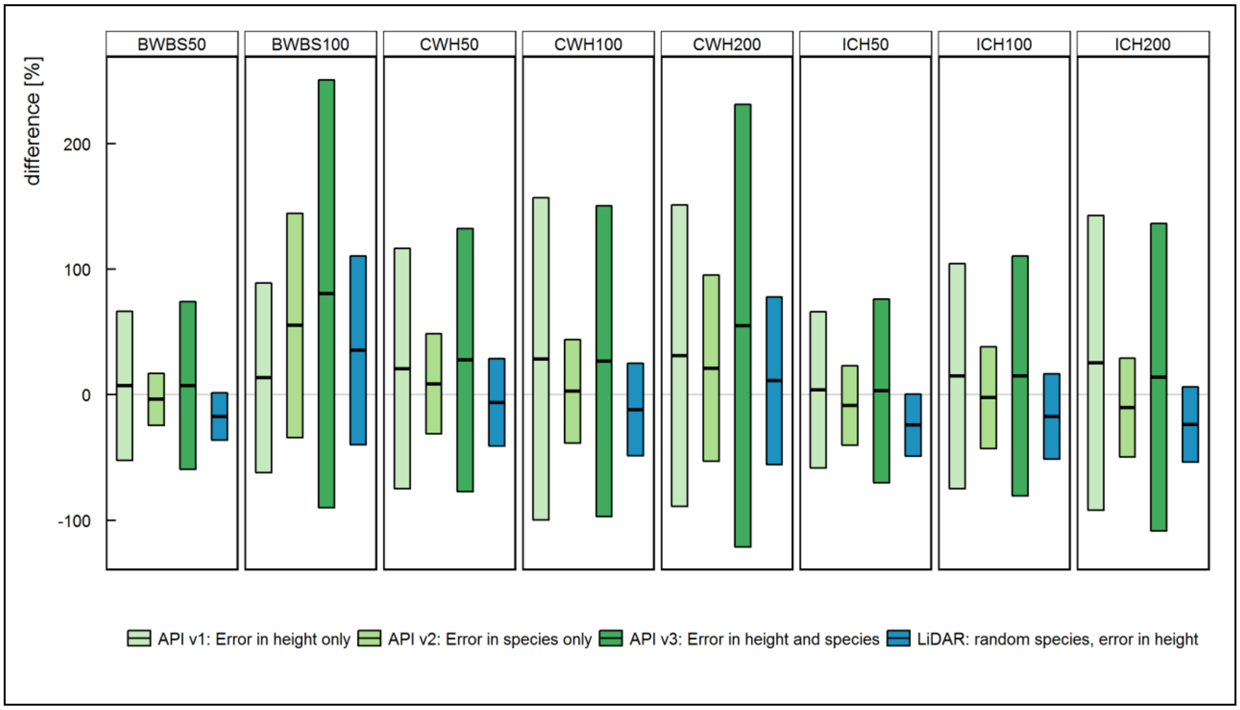

Figure 5. Differences between reference individual tree volumes and simulated individual tree volumes for errors in species attribution, height, or both (mean ± SD), for conventional forest inventory (air photo interpretation or API), and ALS-based measures.