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geospatial technologies

Augmenting Site Index Estimation with Airborne Laser Scanning Data

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Site index (SI), defined as stand dominant height at a given reference age, is a commonly used measure of forest productivity. SI is typically estimated by applying species-specific models to a sample of dominant trees in the stand (age–height curves). Once assessed, SI allows managers to project stand height at given age. Airborne laser scanning (ALS) is a technology that acquires three-dimensional point clouds and enables accurate estimates of various single tree and stand-level attributes, including height. In this research, we investigate differences between stand heights derived from SI curves and stand heights measured with ALS data in a coastal forest dominated by western hemlock (*Tsuga heterophyla*) in western Canada. Our results show significant differences between compared stand heights: The mean difference between the ALS-derived stand height and the SI-derived was 3.5 m, with the largest differences observed for stands dominated by western redcedar (*Thuja plicata*). The main drivers influencing height differences were stand complexity and canopy cover, whereas the number of species in the stand or site characteristics, including elevation, slope, and aspect had less of an impact on SI estimation. The impact of the difference in SI estimation was demonstrated by estimating overall stand volume at a projected stand age of 80 years. The average relative difference between volumes calculated with original and ALS-corrected SI was 51.5%. Implications of this research affirm that SI methods currently used in this area are best suited to even-aged, pure stands. ALS data can be used to augment SI estimation, especially in complex, heterogeneous forest stands, as it is able to accurately characterize stand heights. When incorporated into forest inventories ALS-derived stand heights can have a marked impact on height and volume information of forest stands.

Keywords: site index, ALS, remote sensing, stand height, volume, LiDAR

Information of forest volume is of importance from a number of organizational and temporal perspectives. Knowledge of where and how much timber is present can inform harvesting activities; whereas, projections of future volume aids in long-term planning by industry as well as allocations by jurisdictional authorities. On both private and public lands, harvesting activities are typically prescribed by some form of sustainable forest management guidelines. An important element of sustainability is harvesting at a rate that can be accommodated through planning and subsequent regeneration. An annual allowable cut can be defined based on considerations of forest area and productivity. The annual allowable cut is greater in locations with higher productivity and allows the forests to return more rapidly following harvest. The capacity to correctly project growth over time is important to inform on current stocks, as well as to support accurate predictions of future volume (e.g., timber supply). Over publically held forests, such as in Canada, governments allocate tenure to industry and require implementation of sustainable forest management practices as well as payment (also known as stumpage) for the volume of timber removed. The underestimation of volume over time can impact timber supply analyses and associated infrastructure investments (e.g., milling capacity). Conversely, overprediction of volume could result in excessive harvesting and overbuilding of milling capacity. As such, accurate predictions of volume are of value to both industry and governments. Further, the use of volume as predictor of biomass for estimation of carbon stocks and sequestration over time highlights additional needs for accurate and consistent estimates.

Historically, predictions of forest growth and yield have been made using knowledge of site conditions for a given species to allow for estimates of volume. Forest site productivity is defined as "the potential of a particular forest stand to produce aboveground wood volume, referring to the production unit formed by the site and the stand of trees in concert" (Skovsgaard and Vanclay 2008). Site index (SI) is a common measure of site productivity and growth and is an important attribute for forest management, informing inventory, silviculture, timber supply analysis, and carbon budget modeling,

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among others. SI is typically defined as the capacity of land to produce wood volume (maximum or mean annual increment) and is generally assessed indirectly, based on a measure of height growth achieved at a given age (Sturtevant and Seagle 2004). Although definitions of SI vary, they all typically use tree height as an indicator of the amount of biomass produced (Green et al. 1989, West 2004), and as a result, stand dominant height is a readily accepted indicator of forest productivity due to its ease of measurement and robustness (Skovsgaard and Vanclay 2008). Green et al. (1989) identified four factors that determine the value of SI as a measure of site productivity: (i) SI is species specific, and therefore the stand should be dominated by the species for which productivity is being assessed; (ii) the stand should be even aged with a closed canopy; (iii) the individual site trees that are measured within the stand must be free of damage; and (iv) stand age should be between a given age range (i.e., appropriate for the SI method being used). The growth of site trees also should not include periods of suppression. Estimates of SI in complex, uneven-aged, multilayered stands are unlikely to be as accurate as estimates from even-aged, single-strata stands (Huang and Titus 1993). In such cases, the choice of site trees used to determine SI is critical and significantly affects the result (Mailly et al. 2004). SI is a continuous variable, but for management purposes, SI is often categorized into site classes, with increments of 5 or 10 m, or into even broader site classes such as good, medium, poor, and low (Corns 1992, Stearns-Smith 2001, Skovsgaard and Vanclay 2008). The simplification of SI into these aforementioned categories enables linkages to yield tables that are stratified in a similar manner and used for applications such as timber supply analyses and carbon budget modeling.

A demonstrated technology for the accurate estimation of stand height is airborne laser scanning (ALS), which allows for the collection of highly accurate, three-dimensional point clouds using light detection and ranging (LiDAR) measurements acquired from an aircraft (Baltsavias 1999). Additional equipment installed on the aircraft (global navigation satellite systems receiver and inertial measurement unit), allows the precise recording of the coordinates of the laser beam reflections from objects on the ground. Single laser beams can penetrate through canopy cover, and multiple reflections can be recorded. These reflections, commonly referred as laser echoes, can have several additional attributes assigned, including echo number, intensity, flightline, or scan angle (Baltsavias 1999, Wehr and Lohr 1999, Lefsky et al. 2002). ALS has proven to be an excellent data source to characterize forest stands, providing capability to generate accurate terrain models, estimates of tree and stand height, basal area, or stem volume (Dubayah and Drake 2000, Popescu 2002, Lim et al. 2003, Næsset et al. 2004). It has progressed to an operational technology that provides reliable estimates of crucial forest characteristics, and it has become a common tool used in forest inventories (Wulder et al. 2013). Most of the ALS-based methods that allow for the estimation of stand biomass, volume, or basal area are based on various height metrics, including height percentiles, proportions, and descriptive statistics like maximum, mean, or standard deviation (SD) of point height values (Gobakken and Næsset 2005, Hollaus et al. 2007). As LiDAR pulses can penetrate through the forest canopy, it is also possible to assess vertical forest structure (Coops et al. 2007, Falkowski et al. 2009) or detect understory vegetation (Wing et al. 2012). The accurate tree and stand height estimates provided by ALS data (Means et al. 2000, Andersen et al. 2006) are the foundation of these methods. These accuracies are reported to be high, with root mean square error (RMSE) values for conifer stands below 0.63 m (Persson et al. 2002), although, as mentioned by Gatziolis et al. (2010), the error in tree height estimation can be markedly larger on steep terrain and can exceed 5% of the true tree height.

Although SI is an important attribute in forest inventories, there has not been extensive research into the use of ALS data for estimating SI, especially in Canada. Gatziolis (2007) compared plot-level SI across 21 Douglas-fir-dominated, even-aged, 15-m radius plots in Oregon, USA, with reference height measurements collected with a total station. The dominant age of the stands ranged from 27 to 74 years, and significant correlations (R^2=0.88) were found between the reference and ALS-based SI estimates. Packalén et al. (2011) used ALS data to estimate SI on homogeneous, single-species eucalyptus plantations in Brazil, with RMSE of 2.7%. Chen and Zhu (2012) derived the dominant stand height by applying watershed segmentation on ALS-derived canopy height models and used SI equations to estimate site quality. Véga and St-Onge (2009) applied stereo matching on a number of aerial photographs collected since 1945 and applied ALS-derived ground elevations to generate a time series of canopy height models in jack pine (*Pinus banksiana*)-dominated forest stands. SI was subsequently estimated by fitting age–height curves to reconstructed stand height records. Ham et al. (2013) compared SI estimated from a field inventory, a soil database, and ALS data and reported significant differences in SI when both ALS and field inventory and ALS and soil databases were compared, with higher SI values derived with ALS. Wulder et al. (2010) investigated the implications of SI estimates on carbon stocks in Douglas-fir = dominated stands located on Vancouver Island, Canada. They reported significant differences between the original and ALS-derived SI values, with 42% of stands having a greater SI class when compared to reference data (i.e., SI from the forest inventory) and significant differences between biomass estimates generated using reference and ALS-derived SI values.

Our objective in this research is to investigate the robustness of existing forest inventory SI estimates and determine if ALS data can be used to provide improved SI estimates. To do so, we first compare ALS-derived stand heights with stand heights predicted using forest inventory SI and stand age. Second, we examine if there are certain stand characteristics that consistently result in either an over- or underestimation of stand height in the reference data (relative to the ALS-derived stand height). Third, we generate a revised SI value using the ALS data in concert with the forest inventory information and assess the impact of the revised SIs on future stand merchantable volume projections. Finally, we conclude with some recommendations on the potential role of ALS data in assessing site productivity and discuss how ALS data can be used to improve existing SI estimates for applications such as timber supply analysis and carbon budget modeling.

Methods

Study Area

The study area was situated on the Pacific Northwest coast of North America on northern Vancouver Island, British Columbia, Canada (Figure 1). Located within the Coastal Western Hemlock biogeoclimatic zone (CWH), the study area is characterized by high annual precipitation (μ = 2,228 mm), mild winters, and cool summers (Meidinger and Pojar 1991). Elevation within study area ranges from sea level to 1,200 m, with an average slope of 20°. This area contains highly productive, temperate rainforest stands dominated by western hemlock (*Tsuga heterophylla*). Other common tree

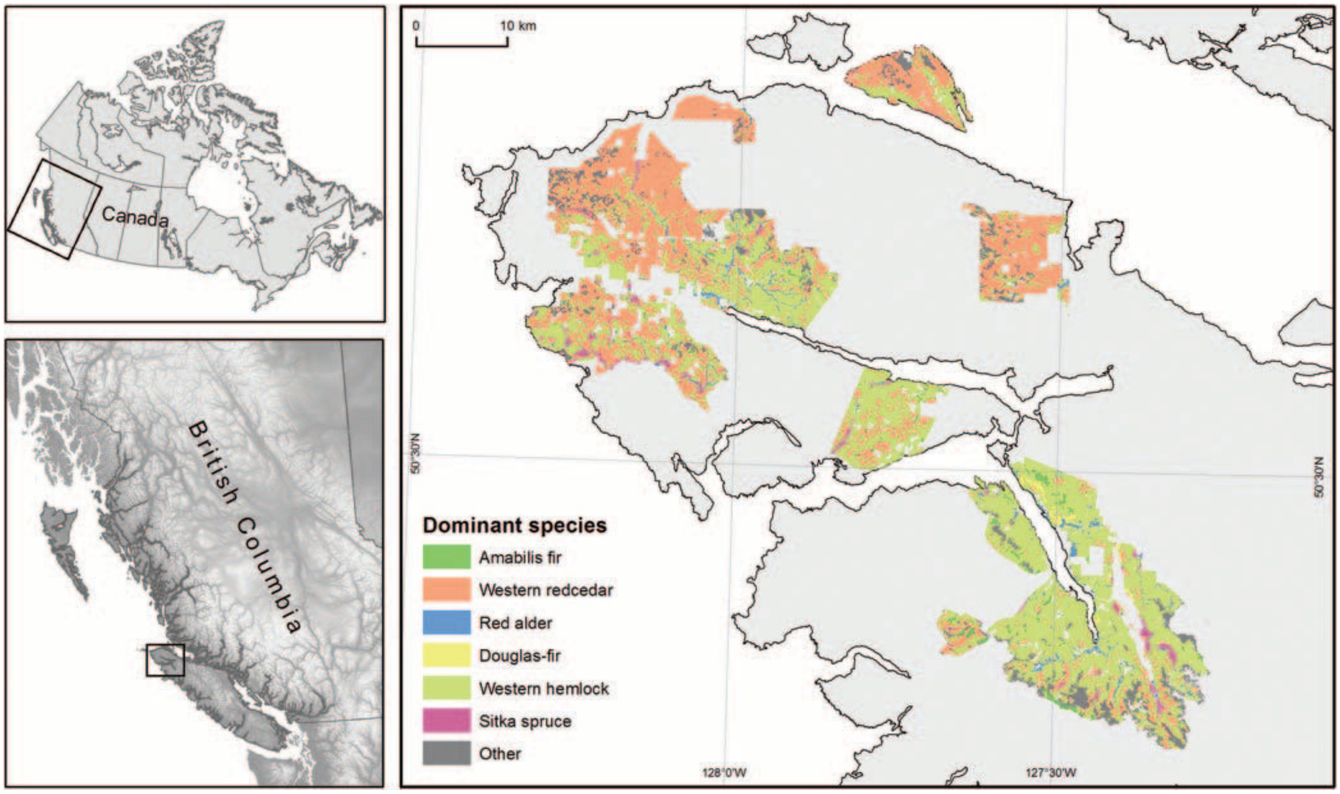

Figure 1. Study area location with dominant species distribution.

Table 1. Forest stand characteristics in the study area.

			All stands				Stands with age 30–140 yr			
			Area		No. stands		Area		No. stands	
Common name	Scientific name	Species code	Ha	%	#	%	Ha	%	#	%
Western hemlock	*Tsuga heterophylla*	Hw	56,715.9	52.8	8,501	54.6	21,804	78.3	2,155	74.3
Western redcedar	*Thuja plicata*	Cw	36,290.1	33.8	4,688	30.2	2,200.3	7.9	192	6.6
Red alder	*Alnus rubra*	Dr	2,432.5	2.3	655	4.2	2,064.8	7.4	363	12.5
Sitka spruce	*Picea sitchensis*	Ss	2,069.6	1.9	298	1.9	911.3	3.3	100	3.4
Douglas-fir	*Pseudotsuga menziesii*	Fd	740.0	0.7	100	0.6	410.4	1.5	30	1.0
Amabilis fir	*Abies amabilis*	Ba	1,490.7	1.4	261	1.7	400.7	1.4	44	1.5
Yellow cedar	*Chamaecyparis nootkatensis*	Yc	5,500.5	5.1	744	4.8	31.4	0.1	2	0.1
Mountain hemlock	*Tsuga mertensiana*	Hm	1,776.3	1.7	219	1.4	19.2	0.1	6	0.2
Lodgepole pine	*Pinus contorta*	Pl	389.9	0.4	85	0.6	16.8	0.1	8	0.3
Balsam poplar	*Populus balasamifera* spp. trichocarpa	Ac	2.9	0.003	3	0.02	N/A	N/A	N/A	N/A
Total			107,408	100	15,554	100	27,859	100	2900	100

Note that for subsequent analyses, we only included those stands that were 30–140 yr in age (no stands for Ac). Also, we grouped species that represented less than 1% of the total area (Yc, Hm, Pl) and reported them as "other". N/A, not applicable.

species in the study area included western redcedar (*Thuja plicata*), Douglas-fir (*Pseudotsuga menziesii*), red alder (*Alnus rubra*), amabilis fir (*Abies amabilis*), yellow cedar (*Chamaecyparis nootkatensis*), mountain hemlock (*Tsuga mertensiana*), and Sitka spruce (*Picea sitchensis*). The average age of stands was 144 years ($\sigma = 127$ years).

Forest Inventory Data

A strategic-level forest inventory, compiled according to standard provincial forest inventory procedures (i.e., air photo interpreters delineated homogenous forest stands and interpreted attributes such as age, height, and species composition) was used as the reference data (Ministry of Forest Lands and Natural Resource Operations 2014a). Attributes, such as dbh, volume, species, age, and SI were modeled and validated with field plot measurements (Gillis and Leckie 1993). The stand attributes were projected forward to the year 2012 to provide single time reference for all stands (Sandvoss et al. 2005). The forest inventory in the study area contained 15,554 stands and represented a total area of 107,408 ha with 10 unique tree species (Table 1). The mean stand height for the subset of stands between 30 and 140 years in age was 20.51 m with SD of 9.48 m, whereas the mean basal area per hectare was 48.9 m^2 with SD of 25.7 m^2.

ALS Point Clouds

ALS point clouds were acquired in 2012 using an Optech ALTM3100EA scanning system (Table 2) and were clipped to

Table 2. ALS data characteristics.

Sensor	ALTM3100EA
Aircraft speed	240 km/h
Data acquisition height	700 m
Swath width	323 m
Max scan angle	25°
Beam divergence	0.3 mrad
Wavelength	1,064 nm
Overlap	75%
Pulse repetition rate	70 KHz
Scan frequency	65 Hz
Number of returns per pulse	4
Point density	11.6 pt./m^2

match the spatial extent of the inventory data. The average first return point density was 11.6 points/m^2. A digital terrain model (DTM) was created using ground returns and applying standard preprocessing routines (Axelsson 2000). The DTM raster layer with pixel size of 1 m was then used to normalize point cloud heights to height above ground level. ALS point clouds for each stand were then summarized to determine dominant height, canopy cover, and canopy complexity as well as terrain characteristics such as elevation, slope (degrees), and aspect. Canopy cover was calculated as the proportion of first returns above a 2-m threshold, relative to all returns. Canopy complexity was characterized with the RUMPLE index (Parker and Russ 2004, Kane et al. 2010), which is a ratio of three-dimensional canopy surface model area to ground area and is sensitive to vertical and horizontal deviations in canopy structure. We calculated the RUMPLE index using normalized point clouds as per Kane et al. (2010) and Stone et al. (2011).

Common Methods for Estimating SI in British Columbia

In British Columbia, SI is calculated for breast height age at 50 years. Breast height age is measured at 1.3 m aboveground and does not account for the time it takes for a tree to attain a height of 1.3 m (which is accounted for in total stand age) (British Columbia Ministry of Forests 1999). Three different methods of estimating the SI are used in British Columbia: Site Index Biogeoclimatic Ecosystem Classification (SIBEC), growth intercept, and height–age curve. The SIBEC method is used for old-growth (>140 years) and very young stands (<3 years) and was developed specifically for observed differences between the growth of regenerating stands and the SI values assigned to previous stands at the same location. With this method, SI values are derived using a model-based approach, related to Biogeoclimatic Ecosystem Classification (BEC) site characteristics (Mah and Nigh 2003). For stands between 3 and 30 years of age, the growth intercept method is used, which is based either on the height and age of the site trees or on the annual growth determined from the distance between branch whorls. The height–age curve method is used for stands between 30 and 140 years old. With this method, SI is determined using a species-specific equation that incorporates age and stand dominant height (British Columbia Ministry of Forests 1999). This height (also known as dominant height) is defined as the average height of the 100 largest (by dbh) trees per ha for the dominant species. Additionally, trees selected for the dominant height measurement (also known as site trees) must be healthy and undamaged (West 2004, Watts and Tolland 2005).

Sample height–age curves for major tree species occurring in the study area are presented in Figure 2. Each curve was calculated for the same SI value (SI = 20) and the same age sequence (30–140

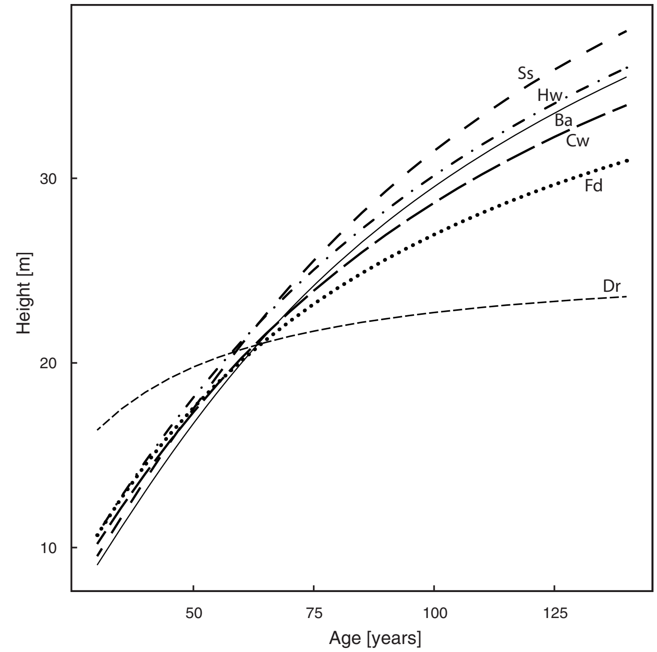

Figure 2. Sample SI curves for six species occurring in the study area. BA—amabilis fir, CW—western redcedar, DR—red alder, FD—Douglas-fir, HW—western hemlock, SS—Sitka spruce.

years). Different species have different height–age curves, most notably the curve for red alder (a deciduous species) is markedly different from that of the coniferous species found in the study area (e.g., Nigh 1997, 2000, Nigh and Courtin 1998). It is also worth noting that because the age used in this example was the total stand age (i.e., age based on time of stand origin), not the breast–height age, the curves do not cross at one point (i.e., where age = 50 years and height = 20 m), as the breast–height age correction was automatically applied by calculating the years-to-breast-height value for each species.

Estimating Stand Height from Inventory SI and Projected Age

We estimated stand height (H_{INV}) using the height–age curve method and the stand-level inventory values for SI and projected age (age projected to the year 2012). To do so, we restricted our analyses to stands that had a projected age between 30 and 140 years and an area greater than 2 ha, resulting in a sample of 2,900 forest stands and representing a total area of 27,859 ha (Table 1). Additionally, species that contributed to less than 1% of the total area (Yc, Hm, Pl) were merged and reported as "other." We used the SiteTools software, developed by the provincial forest management agency of British Columbia to estimate stand height for each stand (British Columbia Ministry of Forests and Range 2004). SiteTools contains the SI and height–growth equations for all major tree species in British Columbia and calculates the stand dominant height as a function of stand age and SI, as well as calculating SI as a function of stand age and dominant height. The software also enables the calculation of breast–height age for each species and will automatically convert total stand age to breast–height age. References for the equations used for the nine species we evaluated in our study area (stands with age between 30 and 140 years) are provided in Table 3.

Estimating Stand Height from ALS Data

To derive estimates of stand height (H_{ALS}) using ALS point clouds, we followed Næsset (1997), who proposed a weighted mean

Table 3. List of references containing SI equations for species in study area (30–140 yr).

Common name	Species code	Reference	Notes
Amabilis fir (Balsam)	Ba	Nigh (2009)	
Western redcedar	Cw	Kurucz (1978)	Updated in 2003
Red alder	Dr	Nigh and Courtin (1998)	
Douglas-fir	Fd	Bruce (1981)	
Mountain hemlock	Hm	Means et al. (1988)	
Western hemlock	Hw	Wiley (1978)	
Lodgepole pine	Pl	Thrower (1994)	
Sitka spruce	Ss	Nigh (1997)	
Yellow cedar	Yc	Kurucz (1978)	Calculated with SI equation for Cw

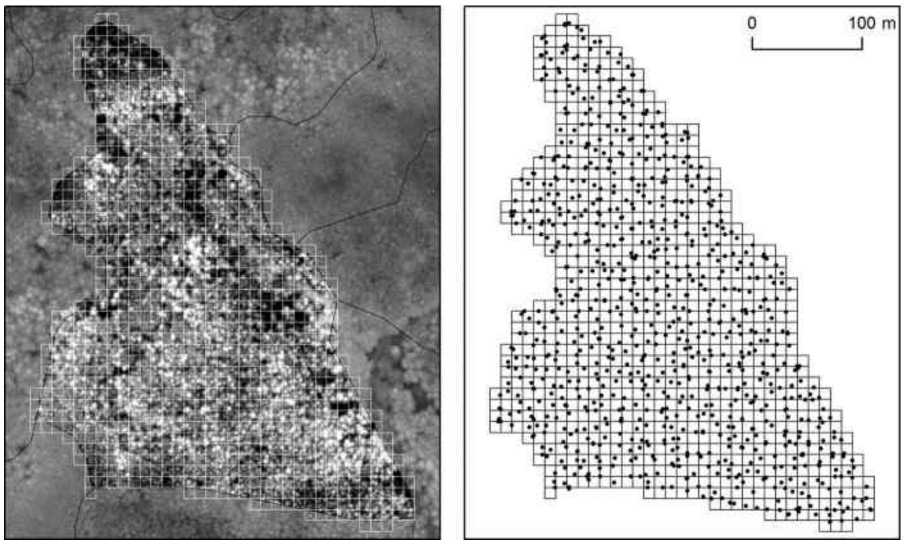

Figure 3. Stand dominant height estimation method. The stand is divided into 10 × 10 m cells (left), and highest point in each cell is then selected (right). The dominant height is an average of these maximums.

approach to estimate stand height where the stand is overlaid with a grid, and maximum height is computed for each of the grid cells (15–30 m size) with the average nonground return count used as weight (Figure 3). Using point count as weight was based on an assumption that tree crown size is proportional to dbh. In our case, the method of calculating the dominant tree height was slightly modified using a smaller cell size (10 × 10 m) as per Wulder et al. (2010). This approach largely follows the accepted definition of dominant height used in British Columbia, however, the tallest (based on height) rather than largest diameter (in terms of dbh) trees are selected. Of note, Gatziolis (2007) found no significant difference in plot SI values estimated using site trees selected using dbh versus height.

This method can be described with the following formula

$$H_{ALS} = \frac{\sum_{i=1}^{n} c_i * h_{max_i}}{\sum_{i=1}^{n} c_i} \quad (1)$$

where

H_{ALS}—dominant height of a stand derived with ALS point cloud

n—number of 10 × 10 m grid cells for a given stand

c—nonground return count within cell

h_{max}—maximum height of points within cell

Examining Differences in Stand Height

As introduced previously, Green et al. (1989) defined a number of factors that govern appropriate SI evaluation, including species composition and canopy cover. Likewise Huang and Titus (1993) concluded that stand structural complexity also highly influenced SI estimation accuracy. We investigated the impact of these factors on difference values between the inventory and the ALS estimated SI. We first calculated the absolute and relative differences between stand heights using following equations

$$\Delta H = H_{ALS} - H_{INV} \quad (2)$$

$$\Delta H\% = \frac{H_{ALS} - H_{INV}}{H_{INV}} * 100 \quad (3)$$

where ΔH and $\Delta H\%$ indicate absolute and relative difference between the ALS (H_{ALS}) and SI-based (H_{INV}) stand dominant height, respectively.

We then used Random Forest (RF) (Breiman 2001) implemented in R (Liaw and Wiener 2002, R Core Team 2014, version 3.1.2), to determine which stand-level forest inventory attributes or characteristics (Table 4), could be drivers of the differences between the H_{INV} and H_{ALS}. RF is a machine learning method that is based

Table 4. **Variables used in Random Forest and multiple regression modeling.**

Variable name	Unit	Description
AGE	Years	Stand age (projected, year of projection = 2012)
SPC	Dominant species	Dominant species (Ba, Cw, Dr, Fd, Hw, Ss, other)
SPC_CNT	Count	Number of unique species in a stand
RUMPLE	–	Canopy structural complexity, rumple index (Kane et al. 2010, Parker and Russ 2004)
COVER	%	Canopy cover estimate (proportion of first returns above 2 m to all returns)
SLOPE	Degrees	Mean slope
ASPECT	Class	Dominant aspect class (N, NE, E, SE, S, SW, W, NW)
ELEV	m	Mean terrain elevation above sea level
INS	WH/m^2	Modeled insolation

on the construction of multiple decision trees, with the output of RF representing the statistical mode of the decision tree ensemble, thereby improving prediction accuracy over that of a single decision tree. RF provides a variable importance measure that indicates the degree to which inclusion of a predictor variable in the model contributes to a decrease in model mean squared error. We used the RF approach to identify the key attributes that may be driving the estimated differences between H_{INV} and H_{ALS}. Finally, we applied a multiple linear regression approach using these attributes to better understand the underlying trends in the differences between H_{INV} and H_{ALS}.

Additional analysis was performed to investigate the differences in SI for stands with different species proportions. We divided stands into five categories: A—pure stands (dominant species percentage equal to 100%); B—mixed stands with dominant species percentage between 75 and 99%; C—mixed stands with dominant species percentage between 51 and 75%; D—mixed stands with two species equally dominant; and E—mixed stands with no dominant species. Using one way analysis of variance (ANOVA) we assessed if the means in each group are equal and applied Tukey honest significant difference (HSD) posthoc test to determine which groups differ significantly.

Examining Differences in Site Class

Different volume yield curves or tables are produced for forest strata, with strata being defined using species and SI, among other criteria. For modeling applications, such as carbon budget modeling and timber supply analyses, these strata are assumed to have similar growth dynamics. To enable stratification, continuous SI values are often categorized into site classes. ALS-derived dominant heights for each stand were used in conjunction with age and species information from the forest inventory to generate a revised SI value for each stand (SI_{REV}), calculated using SiteTools (British Columbia Ministry of Forests and Range 2004). In a management context, the absolute difference between SI_{REV} and the original SI (SI_{INV}) may be more important if the difference is such that it results in a stand being assigned to a different site class and thereby being assigned a different yield curve, which in turn impacts volume estimates. To determine this impact, we assigned SI_{REV} and SI_{INV} to 5 m site classes, with SI values assigned to the closest 5 m interval (e.g., if SI = 7.4, site class = 5; if SI = 7.5, site class = 10).

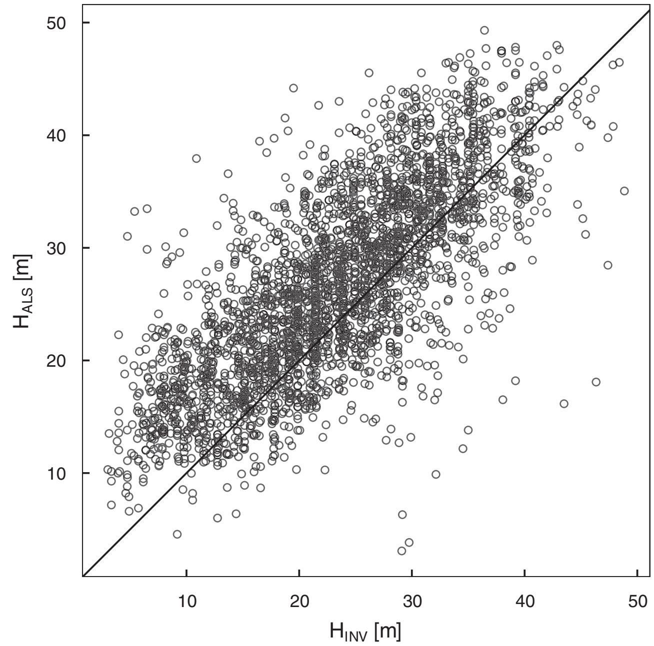

Figure 4. Relationship between predicted and measured height.

Examining Differences in Stand Merchantable Volume Estimates

To assess the impact of differences between the original (SI_{INV}) and revised (SI_{REV}) SI on stand volume estimates, we projected the age of the stands to the local rotation age in the area (80 years). We then used standard provincial inventory models implemented in the software TIPSY (Ministry of Forest, Lands and Natural Resource Operations 2014b, version 4.3) to calculate merchantable volume per hectare for each stand using SI_{INV} (V_{ORG}) and SI_{REV} (V_{REV}). The implemented models are designed to calculate volume for stands with SI values within a specified range, different for each species. In our case, not all of the SI_{INV} and SI_{REV} values were within that range, and therefore, some of the stands were not processed. For example, the minimum and maximum SI for western redcedar dominated stands, reported in forest inventory, was 3 and 41, respectively. The models implemented in TIPSY are limited to process stands with SI value between 10 and 40 only.

We calculated the absolute and relative differences between merchantable stand volumes using the following equations

$$\Delta V = V_{REV} - V_{ORG} \quad (4)$$

$$\Delta V\% = \frac{V_{REV} - V_{ORG}}{V_{ORG}} * 100 \quad (5)$$

We then assessed the significance of the volume differences using the paired *t*-test. To determine the impact of a stand being assigned to a different site class as a result of a revised SI value (SI_{REV}), we analyzed ΔV by changes in site class (i.e., no change, +1 class, +2 class, etc.).

Results

Examining Differences in Stand Height

Stand heights directly estimated from ALS data (H_{ALS}) were compared to stand heights modeled using height–age curves and forest inventory data (H_{INV}). Overall, we observed an absolute mean difference (ΔH) of 3.5 m, and relative mean difference ($\Delta H\%$) of 25.6%; H_{INV} is generally always lower than H_{ALS} (Figures 4 and 5).

Similar trends were observed across all species, with western redcedar (Cw) having the largest significant difference ($\Delta H = 5.4$ m, $P = 0.000$) and Sitka spruce (Ss) having the smallest significant difference ($\Delta H = 1.7$ m, $P = 0.023$) (Table 5). Spatial distribution of SI differences for two key subareas is showed on Figure 6.

The analysis of variable importance with RF showed that the most important variables influencing ΔH were canopy complexity (RUMPLE) and canopy cover (COVER), both increasing the mean square error by more than 10% (17.3 and 13.5%, respectively) when randomly permuted (Figure 7). Species count (SPC_CNT) was the least important variable, increasing the mean square error by only 0.2%, followed by solar insolation, which increased mean square error by 4.2%. Overall, the RF model explained 37.6% of the variance in ΔH.

The multiple regression results show how ΔH is influenced by the explanatory variables, taking into account their relationship to each other. Using this approach, almost all variables, with the exception of species count were significant ($P < 0.05$); however, the sign of the coefficients indicating their influence on the height difference values varied (Table 6). The results indicate that one unit change in canopy complexity (RUMPLE) or canopy cover would result in a 2.02 or 0.09 m change in ΔH, respectively. The effect of other variables can be assessed in a similar manner, although their influence on the modeled ΔH is lower. The model resulted with regression coefficient equal to 0.18 (adjusted).

Allowing species information to enter the regression approach enables the coefficients for the species to be interpreted in reference to western hemlock (Hw), the dominant species in the study area (Table 7). For example, when $\Delta H = 1$ m for Hw, the relative ΔH for western redcedar (Cw) is 4.8 m, and for Douglas-fir (Fd)-dominated stands is −2.3 m. For amabilis-fir- and Sitka-spruce-dominated stands, the coefficients are not significant, indicating no difference in the independent variable. The regression coefficient was slightly higher ($R^2 = 0.22$).

Using ANOVA to compare ΔH among stand categories defined according to the relative dominance of a single species in the stand indicated that the mean differences between stand categories are not equal ($F = 12.1$, $P < 0.0001$). The results of posthoc Tukey HSD test (Table 8) indicated significant differences ($\alpha = 0.05$) between most of the pure (A) and mixed (B, C, E) species stands but no significant differences between pure stands and stands with two equally dominant species (D). The largest differences occurred for stands without a single dominant species (E; true mixed stands), with a mean ΔH of 3.85 m when compared to stands that were mixed but largely dominated by a single species (C), and a mean ΔH of 3.68 m for stands with two equally dominant species (D).

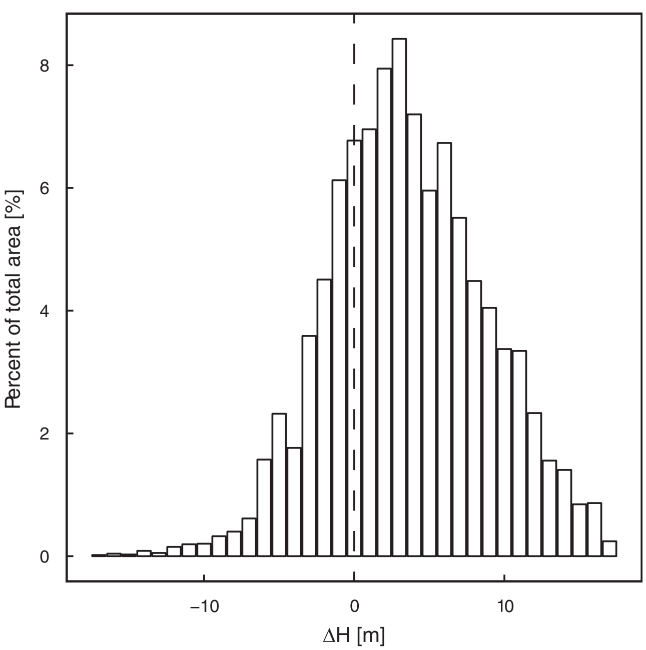

Figure 5. Histogram of height differences (ΔH) between heights derived with ALS (H_{ALS}) and calculated using SI (H_{SI}).

Examining Differences in Site Class

We assessed whether differences between SI_{INV} and SI_{REV} resulted in stands being assigned to different site classes. Of the 2,900 stands considered, 30.8% did not change site class assignment, with the majority of stands (32.0%) changing by one site class (Figure 8). Overall, 56.8% of stands increased site class, while 12.3% experienced a decrease in site class, and 73.1% of stands were within ± 1 site class of their original SI class. The results of *t*-test indicated that these differences were significant and varied by species ($\alpha = 0.05$). The greatest shift in SI class was observed for western-redcedar-dominated stands where the majority of stands changed by two site classes. In contrast, there was no site class change for stands dominated by Ba, Douglas-fir, and Sitka spruce. For the most common species, western-hemlock-dominated stands, the majority of SI_{REV} differed by one class when compared to SI_{INV}.

Examining Differences in Stand Volume

The overall comparison of stand volume per hectare calculated for stands at age 80 years is presented in Figure 9 and Table 9. Stand volume was, on average, 198.8 m^3ha^{-1} greater (SD = 343.9 $m^3 ha^{-1}$, when calculated using SI_{REV} (V_{REV}) than when calculated with SI_{ORG} (V_{ORG}). The mean $\Delta V\%$ was equal to 51.47% (SD =

Table 5. Differences in site index predicted height and observed height from LiDAR.

Dominant species	Correlation coefficient (Pearson)	Mean difference (ΔH)	SD of difference (ΔH)	Mean difference ($\Delta H\%$)	SD of difference ($\Delta H\%$)	t	Df	*P* value (*t*-test)
Ba	0.91	0.94	5.38	0.82	21.71	−1.16	43	0.2519
Cw	0.48	5.40	5.52	69.32	82.25	−13.56	191	0.0000
Dr	0.35	3.95	6.68	20.86	32.34	−11.26	362	0.0000
Fd	0.76	2.46	3.86	11.70	17.68	−3.50	29	0.0015
Hw	0.76	3.44	6.07	23.41	43.92	−26.32	2,154	0.0000
Ss	0.53	1.66	7.19	16.87	45.96	−2.31	99	0.0229
Other	0.85	2.79	4.08	58.05	69.35	−2.73	15	0.0153
All	0.75	3.52	6.16	25.63	47.63	−30.81	2,899	0.0000

Paired *t*-test used to assess the differences; t indicates value of the test statistic, Df indicates degrees of freedom.

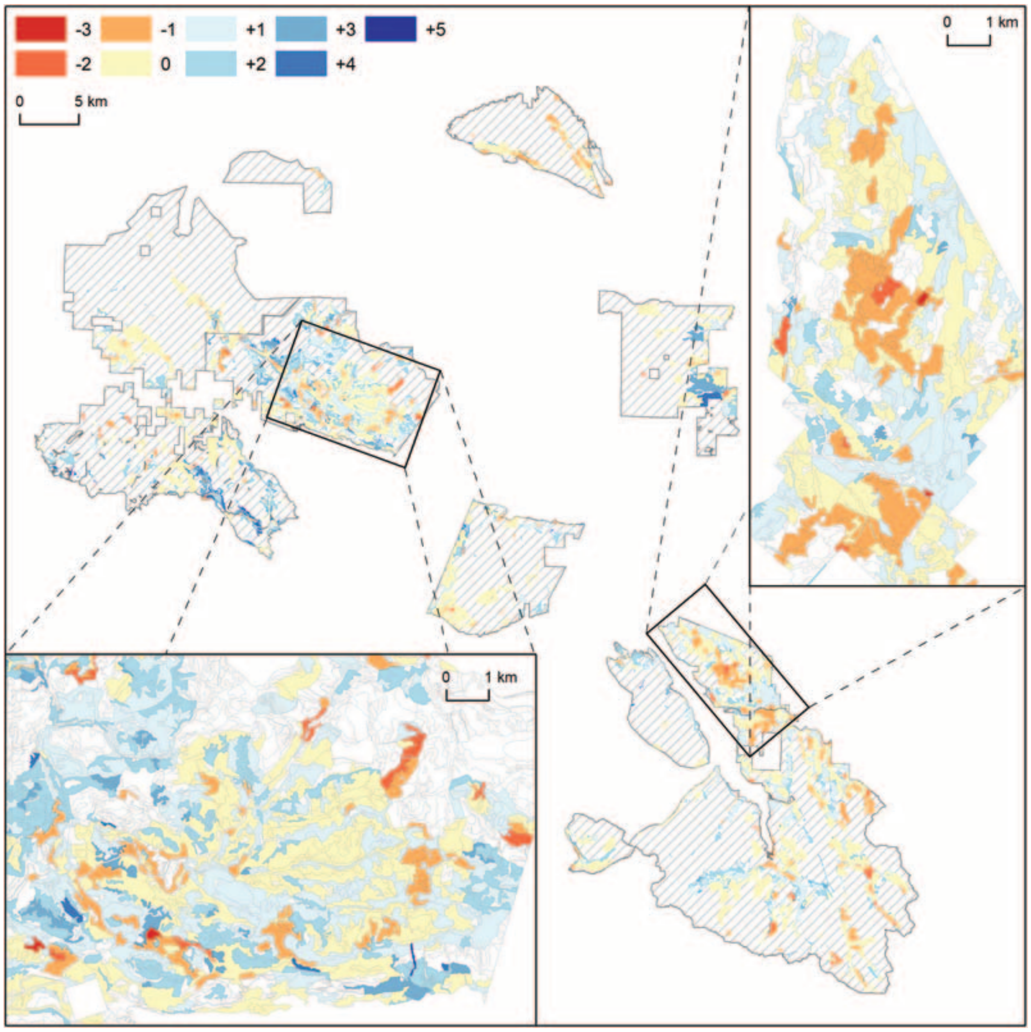

Figure 6. Examples of the site class differences for key subareas of the study area.

104.32%). The greatest differences occurred for western-redcedar-dominated stands where mean $\Delta V\%$ was 148.46%, indicating that the use of SI_{ORG} resulted in significantly underestimated volumes. The paired *t*-test indicated that the mean ΔV was not zero for all dominant species, with the exception of amabilis fir ($\alpha = 0.05$).

To explore the impact of site class differences on volume projections, we grouped ΔV by changes in site class. The results show that the greatest stand-level differences in projected volume occurred in those stands that increased site class, with ΔV increasing with increasing site class differences (Figure 10). This trend is similar across all species with range of volume differences markedly larger for stands with positive difference between SI_{INV} and SI_{REV}.

Discussion

In this research, we compared predicted stand dominant heights derived using height–age curves and forest inventory data (H_{INV}), with stand dominant heights derived from ALS data (H_{ALS}). We found that in 73.7% of stands, H_{ALS} was greater than H_{INV}. Although ALS-derived heights have demonstrated accuracy (Means et al. 2000, Maltamo et al. 2004), we acknowledge that in cases of steep slopes and dense canopies these estimates can be biased (Gatziolis et al. 2010). The average absolute height difference for all stands (ΔH) was 3.5 m, with the greatest difference for stands dominated by western redcedar (5.4 m). Results of our regression analyses indicated that ΔH increased with increasing stand canopy complexity, canopy cover, and slope, and decreased with age and the number of unique species in the stand. The importance of these variables as drivers of ΔH varied, with canopy complexity being the most important variable and species count being the least important. RUMPLE, the measure of canopy complexity derived from the ALS data, is known to be correlated with both stand age and structure (Kane et al. 2010). As the height–age curve method for determining SI is designed for pure, even-aged stands, it is therefore not surprising that stands with greater canopy complexity, indicative of an uneven age structure, would have larger values for ΔH. We investigated the impact of species composition on ΔH across stands with different proportions of dominant species, including stands with two equally dominant species and mixed stands without any dominant species. We found that there were significant differences in ΔH, especially between pure stands (100% single species) and other stand categories of species composition, and there was a significantly larger ΔH for stands with no dominant species. Thus, our findings that ΔH is greatest in mixed stands and stands with an uneven age structure affirms that the existing height–age curve

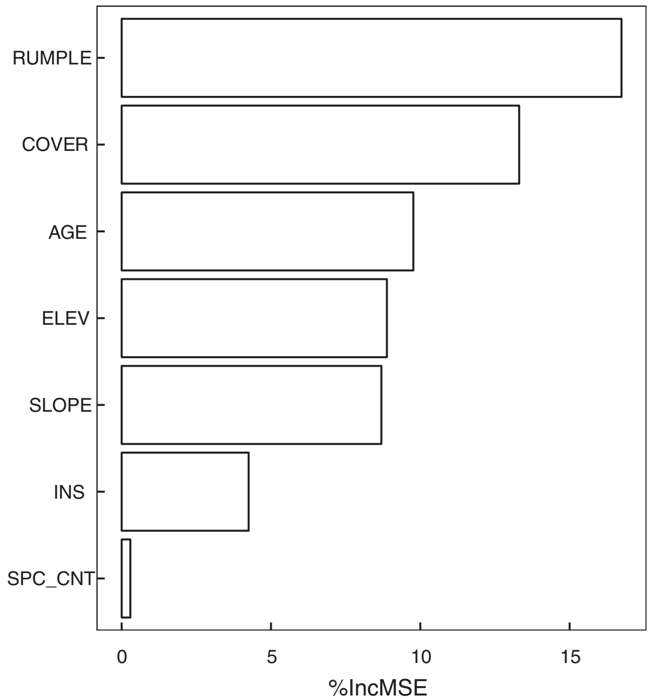

Figure 7. Importance of variables used in random forest modeling. %IncMSE indicates the increase of the mean squared error when given variable is randomly permuted.

Table 6. Multiple linear regression results. Stand height difference modeled against listed variables.

Variable	Coefficient value	Std. error	*t* value	Pr(> t)
(Intercept)	−24.70	2.76	−8.95	0.0000*
RUMPLE	2.02	0.18	11.13	0.0000*
COVER	0.09	0.008	11.77	0.0000*
AGE	−0.05	0.006	−8.32	0.0000*
ELEV	−0.007	0.006	−9.34	0.0000*
SLOPE	0.20	0.02	12.55	0.0000*
INS	0.000016	0.000003	5.35	0.0000*
SPC_CNT	−0.04	0.13	−0.31	0.7600

* $P < 0.001$.

Table 7. Multiple linear regression results. Stand height difference modeled against listed variables. Species modeled using dummy variable (western hemlock).

Variable	Coefficient value	Std. error	*t* value	Pr(> t)
(Intercept)	−29.70	2.79	−10.66	0.0000***
RUMPLE	2.26	0.18	12.56	0.0000***
COVER	0.12	0.008	15.12	0.0000***
AGE	−0.05	0.006	−8.76	0.0000***
ELEV	−0.01	0.001	−8.81	0.0000***
SLOPE	0.21	0.02	13.23	0.0000***
INS	0.000018	0.000003	5.86	0.0000***
SPC_CNT	−0.09	0.13	−0.71	0.4795
Ba	−0.16	0.86	−0.18	0.8541
Cw	4.77	0.43	11.1	0.0000***
Dr	0.85	0.33	2.58	0.0098**
Fd	−2.30	1.00	−2.29	0.0222*
Ss	−0.76	0.58	−1.31	0.1889
Other	8.95	1.43	6.27	0.0000***

Significance levels are as follows: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Table 8. Results of the Tukey HSD test.

Compared stand categories	Difference	*P* value
B-A	−1.13	0.0184
C-A	−1.23	0.0079
D-A	−1.07	0.3119
E-A	2.62	0.0009
C-B	−0.11	0.9943
D-B	0.06	0.9999
E-B	3.75	0.0000
D-C	0.17	0.9971
E-C	3.86	0.0000
E-D	3.69	0.0000

Significant differences showed in bold. A—pure stands (dominant species percentage equal to 100%); B—mixed stands with dominant species percentage between 75 and 99%; C—mixed stands with dominant species percentage between 51 and 75%; D—mixed stands with two species equally dominant; E—mixed stands with no dominant species.

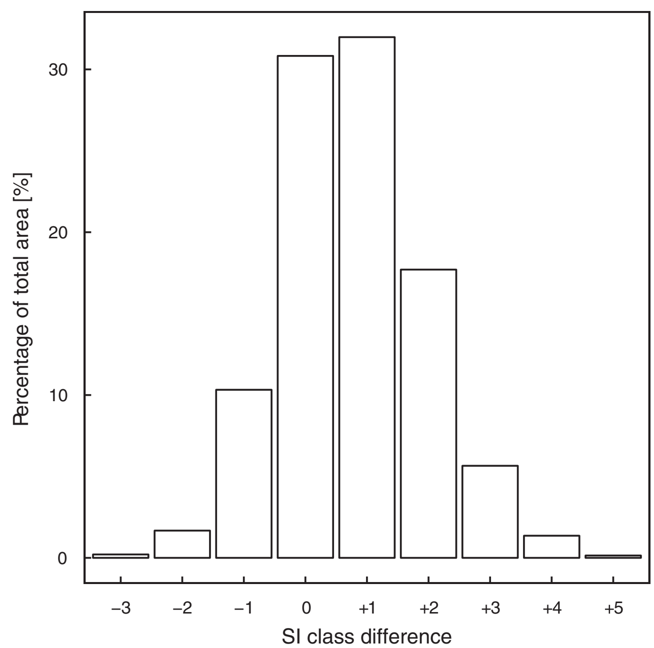

Figure 8. Changes to stand site class assignment from the original SI (SI_{INV}) and the revised SI (SI_{REV}).

models used to estimate SI are not suitable for stands with these characteristics.

As a function of stand dominant height and age, the accuracy of SI is dependent on the accuracy with which height and age are estimated. Although height–age curves are developed using ground samples, where measurements of height and age can be done robustly, stand-level estimates of SI in most strategic inventories are made using photo-interpreted estimates of stand height and age (and species) in concert with appropriate height–age curves. SI based on photo-interpreted attributes has been found to be consistently lower than those based on ground measures (Sandvoss et al. 2005). The consistent underestimation of SI values by conventional methods identified in our study area has also been found by others. Ham et al. (2013) derived SI using ALS data for pine and oak stands in South Carolina, USA, and reported significant differences when compared to forest inventory and a digital soil database. The underestimation was on average 5.6 m (SD = 3.8 m) with extreme differences exceeding 10 m for pine stands. Wulder et al. (2010) found that SI estimates from ALS are greater than the SI from inventory for all stands and for all species groups. They report the differences determined for 5-m site classes, with site classes derived from ALS being greater for 42% of stands; but with the majority (77%) of stands being within ± 1 class of their original site class. The authors also describe a species-specific effect, with SI estimates for stands dominated by Douglas-fir found to be more similar to the reference values than stands dominated by western redcedar, western hemlock, red alder, or amabilis fir. A similar effect was observed in our study, with larger ΔH observed for stands dominated by western redcedar, with smaller ΔH for stands dominated by western hemlock, Douglas-fir, or Sitka spruce.

The larger mean difference for western-redcedar-dominated stands may be partly due to their species composition. Only 0.6% of the stands are pure, single species stands. Most are composed of two or more species, with western hemlock as the main co-occurring second species (90% of western-redcedar-dominated stands). Western redcedars are usually shorter than western hemlocks at a given age (Smith et al. 1961, Minore 1983). From the example SI curves shown on Figure 2, we observe that calculating Cw heights with equations designed for western hemlock will lead to overestimation of up to several meters for mature stands.

Differences between SI values derived from height–age curves and ALS point clouds were articulated in Wulder et al. (2010). First and foremost, height–age curves are not site specific; they are developed using a limited number of samples that are representative of homogenous stand conditions (British Columbia Ministry of Forests 1999), whereas ALS-derived SI values represent a direct measurement that is site specific. The small sample size commonly associated with the development of height–age curves results in a bias in the projection of stand height (Hasenauer and Monserud 1997). Indeed, the sample sizes used to derive height–age curves are highly variable between species in our study area. For example, height–age curves for Douglas-fir were developed using more than 13,000 plots in Washington, Oregon, and British Columbia (Bruce 1981). In contrast, height–age curves for Sitka spruce were developed using a sample size of 40 (Nigh 1997), while height–age curves for western hemlock, which is the most common species in our study area, were developed from 90 plots acquired in Washington and Oregon (Wiley 1978). As indicated, ALS provides a direct estimate and is able to capture small variability in canopy cover and precisely determine height of the tallest tree in the stand. The accuracy with which ALS can measure stand height therefore results in improved estimates of SI—assuming stand age and dominant species has been (or can be) correctly interpreted from air photos.

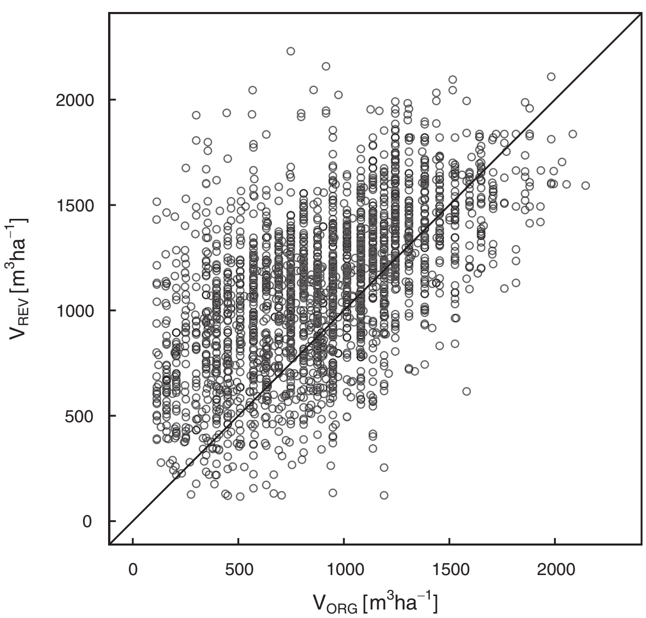

Figure 9. Scatterplot of volume per hectare calculated for each stand with original (V_{ORG}) and revised (V_{REV}) SI value.

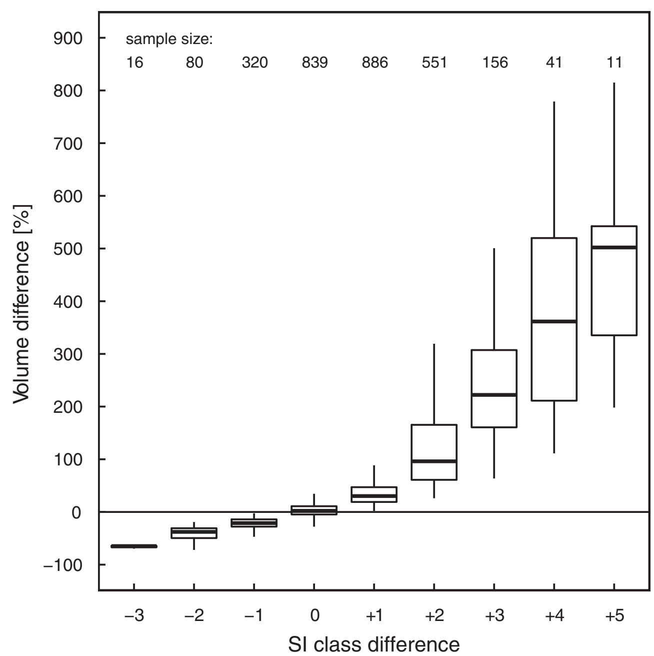

Figure 10. Box plots of volume difference by site class difference.

Table 9. Comparison of volume per ha calculated using SI values from forest inventory and ALS-derived.

Dominant species	Correlation coefficient	ΔV [m³]		ΔV% [%]		t	Df	*P* value (*t* test)
		Mean	SD	Mean	SD			
Ba	0.22	26.09	278.31	8.66	41.37	−0.62	43	0.5373
Cw	0.16	420.85	450.00	148.46	195.30	−11.64	154	0.0000
Dr	−0.04	21.32	37.28	44.54	63.71	−8.09	199	0.0000
Fd	0.77	140.57	216.23	20.78	34.42	−3.56	29	0.0013
Hw	0.58	208.12	334.85	47.85	97.16	−28.43	2091	0.0000
Ss	0.29	120.32	485.71	20.78	57.53	−2.46	98	0.0155
Other	0.49	−14.83	244.89	11.97	36.30	0.15	5	0.8878
All	0.70	198.80	343.90	51.47	104.32	−29.62	2625	0.0000

Paired *t*-test used to assess the differences; t indicates value of the test statistic, Df indicates degrees of freedom.

Through our analyses, we confirmed many of the known weaknesses associated with conventional SI estimation. Using the ALS-derived stand dominant heights and the stand age, we generated a revised SI value for each stand. We then assessed the impact of using this revised SI to estimate stand volume by "growing" the stands to 80 years and calculating the stand merchantable volume. On average, stand volumes calculated with SI_{REV} were 51.47% larger than stand volumes calculated using SI_{INV}. This demonstrates the sensitivity of the volume models to the input SI value and the potential impact this may have on timber supply models. This sensitivity is also evident in the relation between the variability of the volume differences and changes in site class assignment. The range of volume differences for stands that were assigned to a higher site class is markedly larger than for stands that did not change or were assigned to the lower site class. The impact of revised SI on stand volume is also not constant across all species, with extremely large volume differences for western-redcedar-dominated stands equal to 148.46%, or more than three times the second largest value observed for western-hemlock-dominated stands.

In this study, we incorporated age and species information directly from a forest inventory database with ALS data to investigate the robustness of SI estimates. This type of investigation is enabled by very accurate measures of stand height that are derived from the ALS data. However, ALS data alone cannot be used to estimate site productivity in the absence of age and species information. Research has indicated that the estimation of forest age with only ALS data is challenging, requires complex statistical modeling, and is only possible when a link exists between age and forest structure (Racine et al. 2014). More attention has been given to species identification with ALS data with some promising results. Typically, however, species identification is limited to distinguishing between conifer and deciduous species (Reitberger et al. 2008) and requires extremely dense point clouds (Li et al. 2013) or multitemporal acquisitions (Brandtberg 2007, Kim et al. 2009). In time, it may be possible to derive all the information needed to estimate SI directly from ALS data; however, at the present, this study has demonstrated that there is value in combining accurate measures of stand height from ALS data with existing inventory information to derive improved estimates of SI.

Conclusion

In this study, we used ALS data, in concert with species and age information from a forest inventory, to investigate the robustness of existing SI estimates in the inventory. The SI estimates in the inventory were derived from height–age curves, which were developed using ground sampling. Although the height–age curves themselves are developed using a network of ground samples, the curves are applied in the inventory using attributes that are photo-interpreted (i.e., species, age, height). Our analyses indicated that the current SI estimates in the forest inventory consistently underestimate site potential, and this finding is in keeping with what others have reported in the literature. We explored factors that may be driving this underestimation and found that canopy complexity, which may be indicative of an uneven age structure in the stand, was the most important factor driving the underestimation of SI. This result further affirms that height–age curve models are most appropriate for pure, even-aged forest stands. We then used accurate stand heights measured from the ALS data, along with species and age information from the forest inventory, to produce a revised SI value for each stand. We demonstrated the impact this revised SI would have on projected merchantable volumes for each stand and showed that SI has a significant impact on volume projections. From this, we conclude that there is utility in combining ALS data and forest inventory information to provide improved estimates of SI and thereby improving estimates of volume or biomass for applications such as carbon accounting or timber supply analysis. In Canada, there is growing interest among forest managers to acquire ALS data to enhance their existing forest inventories (White et al. 2013). The capacity to improve SI estimates with ALS data is yet another potential application that can be of great benefit for forest planning and reporting—providing information of high value to both industry and government.

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