

# Implications of differing input data sources and approaches upon forest carbon stock estimation

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**Abstract** Site index is an important forest inventory attribute that relates productivity and growth expectation of forests over time. In forest inventory programs, site index is used in conjunction with other forest inventory attributes (i.e., height, age) for the estimation of stand volume. In turn, stand volumes are used to estimate biomass (and biomass components) and enable conversion to carbon. In this research, we explore the implications and consequences of different estimates of site index on carbon stock characterization for a 2,500-ha Douglas-fir-dominated landscape located on Eastern Vancouver Island, British Columbia, Canada. We compared site index estimates from an existing forest inventory to estimates generated from a combination of

forest inventory and light detection and ranging (LIDAR)-derived attributes and then examined the resultant differences in biomass estimates generated from a carbon budget model (Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3)). Significant differences were found between the original and LIDAR-derived site indices for all species types and for the resulting 5-m site classes ( $p < 0.001$ ). The LIDAR-derived site class was greater than the original site class for 42% of stands; however, 77% of stands were within  $\pm 1$  site class of the original class. Differences in biomass estimates between the model scenarios were significant for both total stand biomass and biomass per hectare ( $p < 0.001$ ); differences for Douglas-fir-dominated stands (representing 85% of all stands) were not significant ( $p = 0.288$ ). Overall, the relationship between the two biomass estimates was strong ( $R^2 = 0.92$ ,  $p < 0.001$ ), suggesting that in certain circumstances, LIDAR may have a role to play in site index estimation and biomass mapping.

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## Introduction

Carbon budget models often rely on forest inventories for assessment of stand type, forest

growth, species composition, and other ecological criteria (Landsberg 2003). The Canadian Forest Service developed the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3), which uses empirical forest inventory growth curves to calculate stand-level biomass and biomass dynamics for Canada's forests (Kurz et al. 2002). Obtaining reliable forest inventory data is a laborious and costly process, and as a result, forest inventories are often based on sampling (Kangas et al. 2006). For example, Canada's new National Forest Inventory is based on a 1% sample of the 401.9 million hectare of Canada's forests and other wooded lands (Gillis et al. 2005). Aerial photography has played an important role in the development of forest inventories (Hall 2003), and more recently, light detection and ranging (LIDAR) instruments have emerged as useful tools for collecting vertical forest structure information (McRoberts and Tomppo 2007).

As the availability of LIDAR data has become more widespread, forest managers have seen opportunities for using LIDAR to meet a wider range of forest inventory information needs (Nelson et al. 2003). LIDAR data are used to produce accurate depictions of tree height (St-Onge et al. 2003) and structure (Lim et al. 2003) and, when collected with an appropriate density of hits on the ground (Lovell et al. 2005), may be used to generate accurate models of stand height (Næsset and Økland 2002).

Stand height and stand age are important attributes of forest inventories that provide a measure of potential site productivity, also known as site index. In British Columbia, site index is defined as the average height that a free-growing, undamaged, top-height tree of a given species can achieve at 50 years growth above-breast height (British Columbia Ministry of Forests 1999). A top-height tree is the largest tree (by diameter at breast height (DBH) (1.3 m)) of a given species in a 0.01-ha plot (British Columbia Ministry of Forests 1999). Site index is an important attribute for forest management, informing inventory, silviculture, timber supply analysis (Nigh and Love 1999), and carbon budget modeling, and is the most commonly used indicator of site produc-

tivity (Hägglund 1981). The concept of site index is premised on the assumption that stand height (combined with age) is closely related to stand volume and is, therefore, a good proxy for assessing productivity (Avery and Burkhart 2002). Height growth is assumed to be sensitive to differences in site quality but not to variations in density, species composition, or thinning regimes.

In a silvicultural context, site index is used to characterize site quality, which in turn is required to formulate silvicultural prescriptions and predict stand growth and yield. In timber supply analyses, site index is used to estimate the number of years required for a harvested stand to be reestablished (i.e., a statutory requirement in British Columbia is that the average height of the tallest 10% of the trees is a minimum of 3 m), the extent of the operable land base, the minimum harvestable age, the yield of regenerated stands, the growth of existing stands, and the supply of wood available for future harvesting. For inventory, site index is also used to characterize site quality, project inventory volume growth, and compare site potential across a range of stand conditions (British Columbia Ministry of Forests 1999; Stearns-Smith 2001; Avery and Burkhart 2002). Although site index is an important attribute for a wide range of forestry applications, the estimation of site index using data sources other than a combination of air photo interpretation and fieldwork has not received much attention from the remote sensing community.

The objectives of this research are to present an approach using LIDAR-derived mean stand top height combined with other photo-interpreted forest inventory attributes to estimate site index ( $SI_{LIDAR}$ ) and then compare these estimates to existing forest inventory site-index values ( $SI_{INV}$ ).  $SI_{LIDAR}$  are used as inputs to CBM-CFS3 to model forest biomass, and the model outputs are compared to model outputs generated using  $SI_{INV}$ , with all other model parameters being equal. Biomass estimates from both CBM-CFS3 model scenarios are compared using all forest stands collectively and using strata defined by dominant tree species.

## Background

### Site index

As a forest inventory attribute, site-index values may be adjusted as part of a forest inventory update process, which is typically conducted on a 10-year cycle in Canada (Gillis and Leckie 1996). Site index is calculated based on breast height age rather than total age; total age is the number of years since seed germination, while years to breast height is the number of years required for a tree to grow from seed to breast height. Breast height age is defined as the number of years of growth above breast height (British Columbia Ministry of Forests 1999). Several different methods are currently used to estimate site index, typically involving either the direct measurement of site trees or, more commonly, indirect estimation based on site factors. For example, in British Columbia, one of the three methods is generally used to estimate site index: height–age models, growth intercept models, and Site Index Biogeoclimatic Ecosystem Classification (SIBEC) models (Mah and Nigh 2003). Each method is most appropriate for a specific stage of stand development, and not all methods are applicable in all areas of the province.

Height–age models (the method applied in this study and hereafter referred to as the site index curve method) estimate site index from tree height and breast height age data and are applicable to stands that have 30 to 140 years of growth above breast height (British Columbia Ministry of Forests 1999). Site index curves are developed either from field measures in permanent sample plots (e.g., Bruce 1981) or from stem analysis (e.g., Nigh and Courtin 1998). A different model must be used for each species, as each species has a different height–age relationship (e.g., Nigh and Courtin 1998; Nigh and Love 1999; Nigh and Mitchell 2003). The site index curve method is known to underestimate site index for old-growth stands, leading to the development of a system of correction equations for several important softwood species (Nussbaum 1998) and the exploration of different approaches for site index estimation (Mah and Nigh 2003).

### Forest inventory

Forest inventories are typically generated by the delineation of homogenous land cover types (i.e., polygons or stands) on aerial photographs, followed by the estimation or interpretation of forest attributes with the aid of ancillary data sources such as silvicultural surveys or ground plots. Typically, stand age and height are estimated directly from aerial photographs, while site index is derived from projected age, height, and species information using one of the aforementioned estimation methods to provide the best available estimate of site productivity (Stearns-Smith 2001). Certain inventory attributes are projected forward to represent stand conditions at a future date other than the date at which the data were originally recorded. Once projected, the inventory may then be used in applications such as timber supply or carbon budget modeling.

Stand age and height are two attributes that are “grown forward” in order to represent current stand conditions, while site index remains static. For example, if a forest inventory was completed in 1958, stand age and height would be projected to represent stand conditions in 2008. It is relatively straightforward to project age by simply adding the appropriate number of years to the original stand age (i.e., if the stand age in our example was 20 years in 1958, 50 years would be added to reflect 2008 conditions, and the projected age would be recorded as 70 years). Stand height is more difficult to project, since the height increment over the time period in question will vary with site conditions (Sharma and Parton 2007).

In general, projected age is used with species-specific site index functions to estimate projected height. There are three problems with this approach. First, site index functions are based on a generalized subsample of sites for a given species and are not site-specific, resulting in bias in the projection of height (Hasenauer and Monserud 1997). Second, research has documented that regenerating stands may have a higher site index than indicated in the forest inventory (which was determined based on the original stand conditions; Boyer 2001; Huang et al. 2004). Thus, site

productivity is not static (Skovsgaard and Vanclay 2007) and in a site with stand replacing disturbance regimes (fire, harvesting), the original site index estimate may no longer reflect true site productivity (Stearns-Smith 2001). Third, photogrammetric methods for estimating tree height are prone to error under certain stand conditions, as it is often impossible to measure ground elevation near trees growing in dense forest (St-Onge et al. 2004; Véga and St-Onge 2008). Any error in the original photogrammetric estimate of height is propagated in the original estimation of site index, thereby impacting height projections when the inventory is grown forward.

## LIDAR

Unlike passive remote sensing systems, LIDAR uses active laser pulses to capture the vertical structure of forest canopies. These emitted laser pulses are reflected from the terrain or from objects on the terrain, such as vegetation or buildings. The reflected pulses can be categorized as either first or last pulse returns (Lim et al. 2003). Although LIDAR pulses interact with the terrain and all materials above the ground to produce a complex cloud of points, increasingly reliable post-processing procedures for distinguishing between ground and object points are being implemented (e.g., Roggero 2001; Sithole and Vosselman 2004; Chen et al. 2007). More advanced LIDAR systems allow multiple returns to be recorded for each emitted pulse.

The distance between the LIDAR source and the point of reflectance is determined by measuring the time required for a light beam to travel from sensor to the surface and back to the sensor. Tree heights can be computed from calculating the difference between the ground (last pulse returns) and top of canopy (first pulse returns) when the position and three-dimensional angle of the instrument is known (either from satellite Global Positioning Systems (GPS) and/or Inertial Navigation Systems (INS) measurements; Véga and St-Onge 2008). The error associated with LIDAR measurements of tree height are typically between 0.5 and 1.0 m (Persson et al. 2002; Næsset 1997, 2002; Magnussen and Boudewyn 1998; Magnussen et al. 1999; Næsset and Økland 2002),

and LIDAR is considered more accurate for height measurement than common field-based measurements (Næsset and Økland 2002).

The greatest advantage of LIDAR is the direct measurement of vertical forest structure (Dubayah and Drake 2000). LIDAR data (either as a direct measure or as a data input for modeling) have been used to characterize forest attributes such as stand height (Næsset et al. 2005), canopy structure (Ni-Meister et al. 2001), crown closure (Lim et al. 2003), biomass (Popescu 2007), and canopy volume (Lefsky et al. 2005; Coops et al. 2007; Heo et al. 2008). Although LIDAR has largely been used for collecting high-resolution geospatial data over vegetated areas, only in the last few years have natural resource scientists begun to use LIDAR for forest structure mapping and inventory purposes (Reutebuch et al. 2003).

There are few examples where LIDAR has been used for large-scale forest inventories (Nelson et al. 2003; Næsset et al. 2005), and analysis procedures for LIDAR in a forestry context are not yet as refined as procedures used for terrain mapping products (Reutebuch et al. 2005). Forest inventory assessment from LIDAR is often based on extraction of individual tree heights (Popescu et al. 2002; Popescu and Wynne 2004) and application of spatial rules for extrapolating this information across the landscape. A first explicit example of site-index estimation from LIDAR was introduced by Gatzliolis (2007) using canopy and ground models for establishing plot-based site-index measures for Douglas-fir from LIDAR-derived canopy and ground models. A recent study by St-Onge et al. (2008) was able to map tree height and aboveground biomass by integrating stereo IKONOS images and LIDAR.

## Carbon budget modeling

Forests exchange large quantities of CO<sub>2</sub> with the atmosphere and make an important contribution to the global biogeochemical cycling of carbon (C) (Hamilton et al. 2002; Denman et al. 2007). Various approaches have been developed to assess forest ecosystem C exchange, from the measurement of temporal changes in biomass (Clark et al. 2001) and soil C (Lal et al. 2001) to the measurement

of C exchanges themselves using eddy covariance flux towers (Baldocchi 2003). Although these approaches have been used to assess C exchange for a large number of forest sites around the world, these measurements are not necessarily representative of entire landscapes (Running et al. 1999); hence, the description of regional or biome-level ecosystem C dynamics remains difficult (Aalde et al. 2006).

A number of simulation modeling approaches have been developed to estimate forest ecosystem C fluxes at different spatial and temporal scales, including both process-driven and empirically driven forest ecosystem simulation models (Landsberg 2003). The latter typically involves the use of empirical information on the growth and yield of merchantable wood volume as input to estimate tree biomass C dynamics. This is the approach that is employed in CBM-CFS3, which takes merchantable wood volume yield tables as input and uses this information together with forest inventory data and a system of biomass estimation models (Boudewyn et al. 2007) to simulate tree biomass C dynamics. In general, yield tables describe merchantable wood volume increment as a function of stand age. Thousands of such tables have been compiled by the forest management community in Canada for timber supply analysis purposes and for use in forest management planning tools (Kurz et al. 2002). These yield tables, based on data collected at thousands of permanent sample plots across Canada, provide the foundation for tree biomass C dynamics in the CBM-CFS3 model. The strength of this approach is that CBM-CFS3 is capable of generating estimates of tree growth that are consistent with field measurements; however, the model cannot account for interannual variability in tree growth or long-term changes in tree growth rates unless additional data and methods are used to apply adjustments to the base growth rates prescribed by the yield tables.

Merchantable volume yield tables are typically produced for forest strata that include a range of forest stand types, and for modeling purposes, these strata are assumed to have the same growth dynamics. Forest inventory polygons are commonly assigned to growth strata on the basis of stand attributes such as site index, species mix,

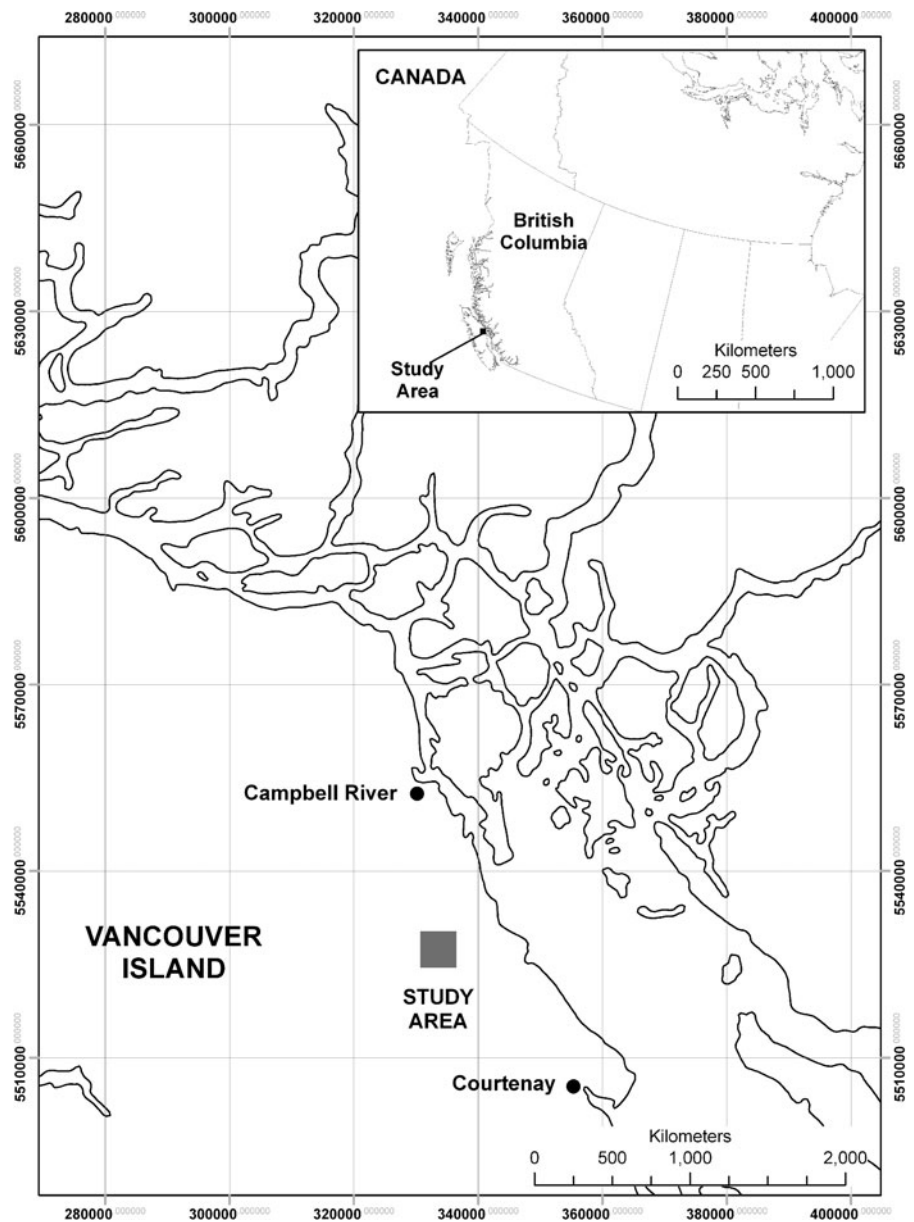
and other ecological criteria. For the purposes of stratification, continuous variables such as site index are often categorized into 5-m site classes or into even more generalized groupings such as high, medium, and poor sites. Errors in the estimation of site index that result in forest polygons being assigned to the wrong site class will also cause the wrong yield table to be assigned to those polygons.

### Study area

The study was conducted in the Oyster River area located between Courtenay and Campbell River on the eastern side of Vancouver Island, British Columbia, Canada (Fig. 1). The bounds of the 5 × 5-km study area were chosen to encompass available inventory data, historic mapped disturbance data, and two flux tower sites (DF1949, HDF2000) and one meteorological tower site (HDF1990) of the Fluxnet Canada Research Network coastal British Columbia station (Humphreys et al. 2006). The Oyster River area is within the dry maritime Coastal Western Hemlock biogeoclimatic subzone (CWHxm) spanning the east (CWHxm1) and west (CWHxm2) variants of the subzone with annual precipitation averaging 1500 mm and a mean annual temperature of 9.1 degrees Celsius (Pojar et al. 1991). This subzone has a maritime climate with typically cool summers and mild winters, though this area can experience significant dry conditions during the summer.

The study area spans the transition from the Nanaimo Lowlands and Leeward Island Mountain Ecosections (Demarchi 1996), ranging in elevation from 120 to 460 m and is within 10 to 15 km from the coast. Douglas-fir (*Pseudotsuga menziesii* var *menziesii* (Mirb.) Franco) is the dominant tree species on dry to mesic site series, though wetter site series will contain western redcedar (*Thuja plicata* Donn ex D. Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), with amabilis fir (*Abies amabilis*) at higher elevations (Green and Klinka 1994). Patches of red alder (*Alnus rubra* Bong.) dominated or hardhack–sweet gale (*Spirea douglasii* ssp. *Douglasii*–*Myrica* gale) wetlands are also

**Fig. 1** Study area location on Vancouver Island, British Columbia, Canada



**Table 1** Summary of leading species by area and by proportion of inventory stands

Leading species	All forest inventory stands in the study area				Forested stands with age 30–140 years			
	Area (ha)	Proportion (%)	# of Stands	Proportion (%)	Area (ha)	Proportion (%)	# of Stands	Proportion (%)
Amabilis fir	30	1.20	31	1.34	18	0.68	9	1.10
Western redcedar	4	0.14	10	0.43	3	0.68	9	0.17
Red alder	259	10.35	334	14.46	203	17.35	229	12.32
Douglas-fir	2050	82.01	1652	71.52	1399	79.24	1046	84.90
Western hemlock	84	3.38	112	4.85	25	2.05	27	1.51
Non-forest	73	2.92	171	7.40	N/A	N/A	N/A	N/A
<b>TOTAL</b>	<b>2,500</b>	<b>100.00</b>	<b>2,310</b>	<b>100.00</b>	<b>1,648</b>	<b>100.00</b>	<b>1,320</b>	<b>100.00</b>



found throughout the area, especially at lower elevations. The distribution of leading species in the study area is summarized in Table 1. Soils within the area range from very gravelly textured duric humo-ferric podzols of fluvial origin at low elevations, to gravelly sandy loam textured duric humo-ferric and ferro-humic podzols of morainal origin at intermediate elevations to shallow stony ortho humo-ferric podzols on colluvium on higher elevation hilltops (Jungen 1985).

**Data**

Forest inventory

Most of the forest stands within the area are found on private land managed for timber production by Timberwest and Island Timberlands (formerly Weyerhaeuser) and consist predominantly of forests regenerating from clearcut harvest. Each company maintained its own forest inventory data for its respective area within the Oyster River study site, and these inventories (all current to 1999) were harmonized and compiled into a single database (Trofymow et al. 2008) by matching the edges of the inventories with cadastral boundaries and a common 1:20,000 Terrain Resource Information Management (TRIM) base map (British Columbia Ministry of Environment, Lands, and Parks 1992). The combined forest inventory contained information on tree species, year of stand establishment, codes for analysis units, site index, and non-forest land cover. Stands were updated for depletion using 1:70,000 orthophotography acquired in 1995 and 1999 and using spatial information on harvest blocks obtained from the forest companies in 2005. Site index was used to estimate growth and yield over time (Personal communication: Jim McPhalen, Timberwest), and stand volume tables were generated from the British Columbia Ministry of Forests Variable Density Yield Projection (VDYP) (British Columbia Ministry of Forests 1996) program for natural stands or the Table Interpolation Program for Stand Yield (TIPSY; Mitchell et al. 2000) program for managed stands.

LIDAR data and processing

Small footprint laser data were acquired June 8, 2004 using Terra Remote Sensing’s LIDAR instrument on a Bell 206 Jet Ranger helicopter. In Table 2, we provide details on the LIDAR system configuration used for data collection. Based on the pulse frequency and the lowest sustainable flight speed and altitude, hit densities of 0.7 hit/m<sup>2</sup> were achieved with a footprint (spot size) of 0.19 m. Separation of vegetation (non-ground) and terrain (ground) hits was carried out using Terrascan v. 4.006 software (Terrasolid, Helsinki, Finland), which uses iterative algorithms that combine filtering and thresholding methods (Kraus and Pfeiffer 1998; Axelsson 1999) to classify the LIDAR data into either ground or non-ground returns.

From these data, a canopy height model (CHM), describing the three-dimensional canopy structure, was derived in two steps: first, a digital elevation model was developed using ground classified LIDAR returns to establish a triangular irregular network (TIN), which was then rasterized at a 0.5 m spatial resolution. Similarly, a TIN and subsequently a raster (0.5 m spatial resolution) were generated for the non-ground returns. Second, a CHM was generated by subtracting the interpolated ground elevations from the interpolated non-ground elevations.

**Table 2** LIDAR acquisition parameters

Parameter	Performance
Sensor	Mark II
Laser scan frequency	25 Hz
Laser impulse frequency	40,000 Hz
Laser power	<4 W
Maximum scan angle	<20°
Type of scanning mirror	Oscillating
Laser beam divergence	<0.5 mrad
Measurement density	0.5–0.8 hits/m <sup>2</sup>
Datum	NAD83
Projection	UTM Zone 10
Platform	Bell 206 Jet ranger helicopter
Flight altitude above ground	900 m
Flight speed	25–30 m s <sup>-1</sup>
Version of TerraScan used to classify	Version 004.006

## Methods

### Stand height estimation

The correct estimation of top height is critical to the calculation of site index. The Forest Productivity Council of British Columbia (1998a) defines top height as the height of the largest diameter tree in a 0.01-ha plot, providing the tree is suitable (*i.e.*, the tree is healthy, it does not have a broken or damaged top, and its growth is not suppressed by a competitor). The largest diameter tree is used rather than the tallest tree, as the former is easier to identify, measure, and audit in the field, plus there is typically less error associated with measuring DBH. This definition of top height prevents situations where all of the top-height trees are clustered in a single location within a 1-ha area (Forest Productivity Council of British Columbia 1998b). Research on the impact of plot size on the definition of top height has concluded that top height is sensitive to plot size (Magnussen 1999; García and Batho 2005), therefore the application of a consistent top-height definition is an important factor for forest management in general and for site index estimation in particular.

The estimation of tree height and stand height from LIDAR data has been the subject of extensive research (for summary, see Lim et al. 2003). When mean stand height is computed from field measurements, the heights of individual trees are typically weighted according to their basal area (Lorey's mean height); therefore, larger trees have a greater impact on the estimation of mean stand height. A similar approach can be implemented with the LIDAR by using only the largest heights in the stand; however, the  $n$ th largest heights may not be spatially representative of the stand as a whole. Therefore, it is necessary to use a method that can account for spatial variability in the stand. Imposing restrictions for spatial representation may be achieved by superimposing a tessellation of grid cells to the stand and using these grid cells to acquire spatially representative samples of LIDAR hits from across the stand in the calculation of mean stand height (Næsset 1997).

Næsset (1997) found that a direct average of all the non-ground LIDAR hits within a stand re-

sulted in an underestimation of ground measured mean stand height by 4.1 to 5.5 m. By applying a regular sample grid to the stands, systematically selecting only the largest heights within each grid cell and calculating a weighted-average stand height (with the number of non-ground LIDAR hits per grid cell used as weights), the LIDAR estimates more closely matched the field measurements (with errors ranging from  $-0.4$  to  $1.9$  m). Magnussen and Boudewyn (1998) also demonstrated that the use of a sample grid and the maximum height within each grid cell results in mean stand height values that more closely match ground estimates. In this study, we implemented Næsset's approach (1997), applying a  $10 \times 10$ -m grid over the study area and identifying the maximum height within each 0.01-ha grid cell. This approach to estimating mean stand top height from the LIDAR data was used because it most closely follows the operational definition of top height currently used in British Columbia (Forest Productivity Council of British Columbia 1998a, b). Stand height was, therefore, determined for each forest inventory polygon in the study area by determining the number of non-ground LIDAR returns and the maximum tree height within each 0.01-ha grid cell and then calculating the mean of the maximum heights, weighted by the number of non-ground LIDAR hits within each of the 0.01-ha grid cells.

### Site index estimation

Operational procedures used for site index estimation were followed as closely as possible to ensure a robust comparison between the LIDAR-derived estimates of site index and the preexisting site-index values in the forest inventory. SiteTools software (version 3.3, British Columbia Ministry of Forests and Range 2004) was used to calculate site index for each of the forest stands. SiteTools supports both the growth-intercept method and the site-index curve method of site-index estimation (British Columbia Ministry of Forests and Range 2004). SiteTools requires species information and an estimate of stand height and age. Breast-height age is used for site index estimation, and SiteTools adjusts total age input from the forest inventory to breast-height age. For this



study, stands with a projected age between 30 and 140 years were selected for comparison (based on age distribution of stands in the study area) so that the method of site index estimation (i.e., site index curve method) was consistent between  $SI_{INV}$

and  $SI_{LIDAR}$ . Other information required for estimation, such as species and projected age, were taken from the forest inventory. Compilation of ancillary data sources, as detailed in Trofymow et al. (2008), were used to capture disturbance

**Table 3** Merchantable volume yield tables used to simulate aboveground biomass C dynamics in managed Douglas-fir-leading stands

Age	TI0110 Site class 10 m <sup>3</sup> ha <sup>-1</sup>	TI0115 Site class 15 m <sup>3</sup> ha <sup>-1</sup>	TI0120 Site class 20 m <sup>3</sup> ha <sup>-1</sup>	TI0125 Site class 25 m <sup>3</sup> ha <sup>-1</sup>	TI0130 Site class 30 m <sup>3</sup> ha <sup>-1</sup>	TI0135 Site class 35 m <sup>3</sup> ha <sup>-1</sup>	TI0140 Site class 40 m <sup>3</sup> ha <sup>-1</sup>	TI0145 Site class 45 m <sup>3</sup> ha <sup>-1</sup>
0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
15	0	0	0	0	0	1	21	48
20	0	0	0	1	23	53	95	155
25	0	0	5	35	71	131	197	271
30	0	1	30	78	138	213	297	410
35	0	13	59	132	202	292	413	542
40	0	28	88	182	261	383	521	668
45	1	43	125	225	324	470	620	788
50	1	59	158	264	388	544	717	888
55	7	74	185	302	449	617	802	977
60	13	89	210	344	501	685	875	1,053
65	19	108	233	382	548	749	941	1,121
70	24	124	254	419	595	802	998	1,194
75	29	139	274	453	638	850	1,049	1,261
80	33	153	293	483	679	893	1,094	1,320
85	38	165	314	510	716	933	1,141	1,361
90	43	176	333	534	750	967	1,187	1,361
95	47	185	350	557	779	999	1,229	1,361
100	52	195	367	579	805	1,027	1,268	1,361
105	56	203	383	601	829	1,053	1,298	1,361
110	60	211	399	620	851	1,076	1,322	1,361
115	63	218	413	638	872	1,101	1,343	1,361
120	67	226	426	655	891	1,126	1,343	1,361
125	70	232	438	671	908	1,149	1,343	1,361
130	73	238	449	686	923	1,170	1,343	1,361
135	75	244	459	699	937	1,189	1,343	1,361
140	78	249	468	712	950	1,206	1,343	1,361
145	81	254	476	723	961	1,223	1,343	1,361
150	85	259	484	732	972	1,237	1,343	1,361
155	88	263	491	741	982	1,246	1,343	1,361
160	91	267	498	749	991	1,254	1,343	1,361
165	94	272	504	757	999	1,262	1,343	1,361
170	97	277	510	764	1,007	1,269	1,343	1,361
175	99	281	516	771	1,014	1,269	1,343	1,361
180	102	286	522	777	1,020	1,269	1,343	1,361
185	104	290	528	782	1,028	1,269	1,343	1,361
190	106	293	533	787	1,035	1,269	1,343	1,361
195	108	297	537	792	1,042	1,269	1,343	1,361
200	110	300	542	797	1,048	1,269	1,343	1,361

All input data and modeling parameters used to conduct these simulations are described by Trofymow et al. (2008)

information and update the “date of stand establishment” attribute. Current-age information was then determined by subtracting this revised date of stand establishment from 2006. There were 2310 forest stands in the study area; 1320 of these stands were productive forest with a projected total age between 30 and 140 years, with sufficient LIDAR data (>200 non-ground LIDAR hits/ha) to estimate stand height. This subset of 1320 forest inventory polygons was used to compare the site-index values and subsequent CBM-CFS3 outputs.

### Estimation of stand biomass and C stocks

Total stand biomass and C stocks and components (i.e., above- and below-ground biomass, dead wood, litter, and soil organic matter) were estimated using the CBM-CFS3, an annual time-step model that uses forest inventory data along with merchantable volume yield tables to drive stand-level biomass C dynamics (Kurz et al. 1992; Kurz and Apps 1999; Kurz et al. 2002; Kull et al. 2006). In this study, stand-level biomass carbon dynamics were simulated using merchantable volume yield tables derived for natural and managed stands in Coastal British Columbia, stratified by leading species and 5-m site index classes. The yield tables used for managed Douglas-fir leading stands (the most common stand type present in the study area) are provided in Table 3. Other yield tables were used for other stand types present in the study area, including hemlock-, red cedar-, amabilis-, and alder-dominated stands. These yield tables were developed by the British Columbia Ministry of Forests and Range using the Table Interpolation Program for Stand Yields (TIPSY) developed from the TASS individual tree growth model (Mitchell et al. 2000). In this application of the CBM-CFS3, each forest cover polygon in the forest inventory is treated as a separate database record and is assigned a yield table on the basis of stand type (defined according to species mix) and 5-m site class (Kurz et al. 2002). For CBM-CFS3, the continuous site-index values for  $SI_{INV}$  and  $SI_{LIDAR}$  were categorized into 5-m site classes (SC), with the site-index values assigned to the closest 5-m interval (e.g., a site index of 12.4 is assigned a site class of 10; a

site index of 12.5 is assigned a site class of 15) to generate  $SC_{INV}$  and  $SC_{LIDAR}$ .

Merchantable volume yields are converted in the model to annual above-ground biomass carbon (C) increments referenced to projected stand age using stand-level biomass estimation models (Boudewyn et al. 2007) and assuming a C content of 0.5 t C t<sup>-1</sup> biomass. Below-ground (root) biomass is estimated in the model as a function of aboveground biomass and species group (Li et al. 2003). CBM-CFS reports in units of tonnes C, and this is multiplied by two to get biomass (tonnes). The entire study area has been logged at least once since 1920, so the entire stand history was simulated for all stands present on the landscape.

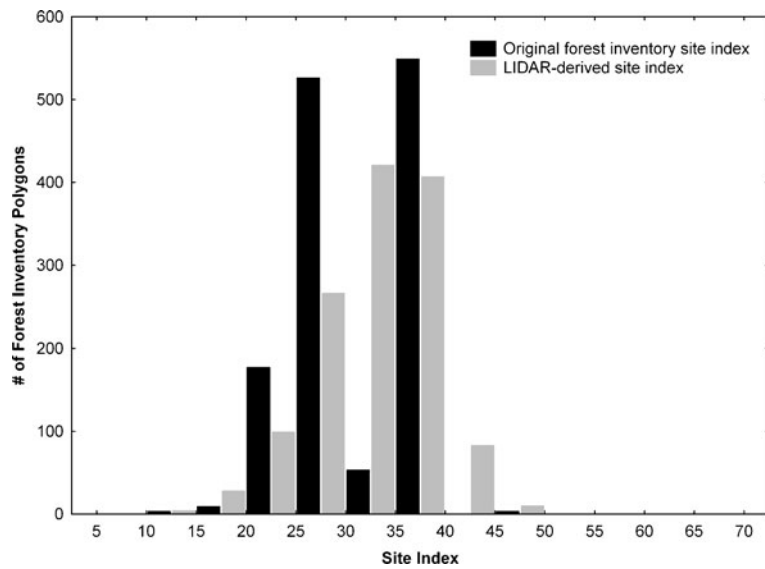
## Results

### Stand height and site-index estimation

Mean stand heights were determined for each forest stand. Although no field measures were available for comparison at this study site, Coops et al. (2007), working in a similar area with similar species, data, and methods for establishing mean plot height from LIDAR, found that LIDAR estimates of plot height were consistently lower than field-measured plot heights. As both the site index and modeled biomass estimates were generated from different data sources, they were expected to vary. The distribution of  $SI_{INV}$  and  $SI_{LIDAR}$  for all 1320 stands is shown in Fig. 2. Regressions of  $SI_{INV}$  on  $SI_{LIDAR}$  produced a low overall  $R^2$  value of 0.03 ( $p < 0.001$ ; Fig. 3) and the stand-level differences between  $SI_{INV}$  and  $SI_{LIDAR}$  were found to be statistically significant (dependent samples, two-tailed  $t$ -test,  $\alpha = 0.05$ ,  $t = -9.224$ ,  $p < 0.001$ ,  $df = 1, 319$ ). Figure 4 characterizes the differences between site index estimates by leading species; statistically significant differences were found for all leading species except western red cedar leading stands, which also had the largest standard error (Table 4).  $SI_{LIDAR}$  are greater than the  $SI_{INV}$  for all stands sampled and for all species groups.

The site-index values were reclassified into 5-m site classes for input into CBM-CFS3. The relationship between  $SC_{INV}$  and  $SC_{LIDAR}$  was weak ( $R^2 = 0.02$ ,  $p < 0.001$ ), and there was a significant

**Fig. 2** Comparison of the distribution of site index estimates in the original forest inventory and the site index estimates made using LIDAR-derived mean stand heights



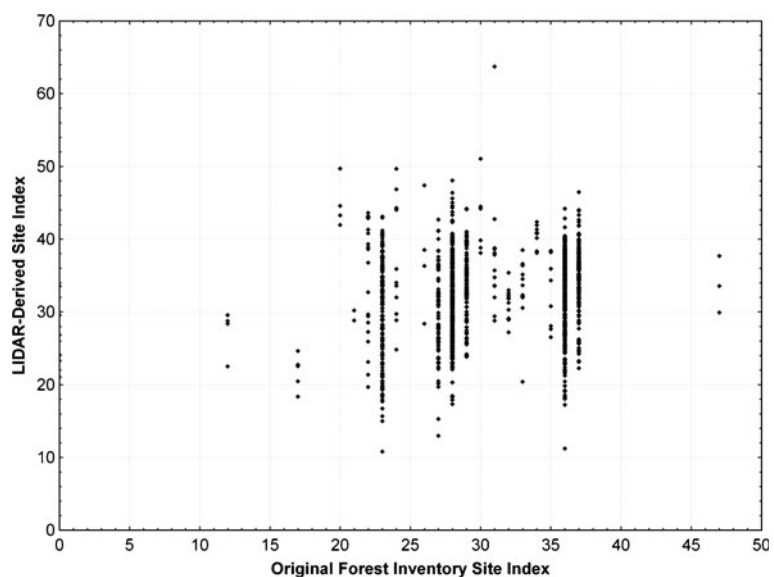
difference between the two site class estimates (dependent samples two-tailed  $t$ -test,  $\alpha = 0.05$ ,  $t = -8.972$ ,  $p < 0.001$ ,  $df = 1, 319$ ) (Table 4). Figure 5 shows the distribution of site class differences ( $SC_{INV} - SC_{LIDAR}$ ); the LIDAR-derived site classes were greater than the corresponding inventory site classes for 42% of stands. The majority of stands (77%) were within  $\pm 1$  class of the site class estimated from the original site-index values. Figure 6 illustrates the differences in site class by leading species (sample sizes in Table 1) and

indicates that for all species,  $SC_{LIDAR}$  was greater than  $SC_{INV}$ . Amabilis fir dominated stands had the greatest difference in site class, followed by western hemlock; Douglas-fir dominated stands had the smallest difference in site class.

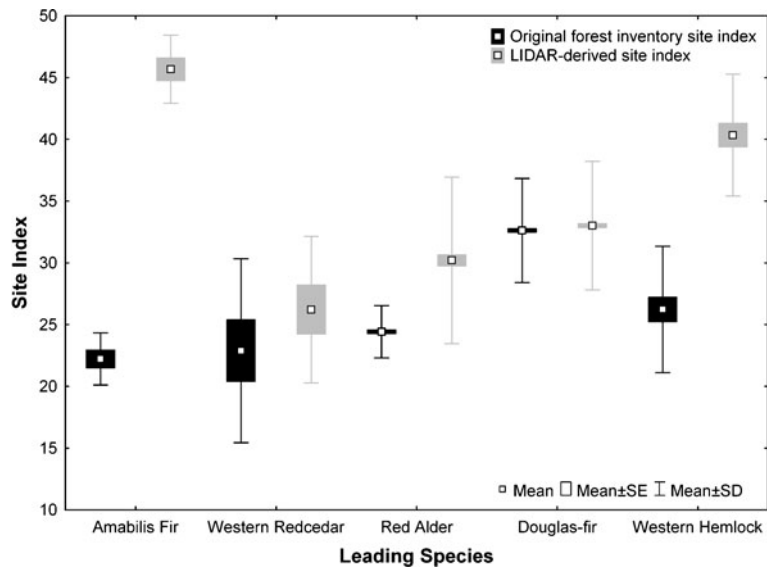
Estimation of stand biomass and C stocks

Two separate model runs were conducted using the CBM-CFS3 model; all parameters were identical with the exception of site class. Figure 7

**Fig. 3** Scatterplot showing  $SI_{INV}$  versus  $SI_{LIDAR}$



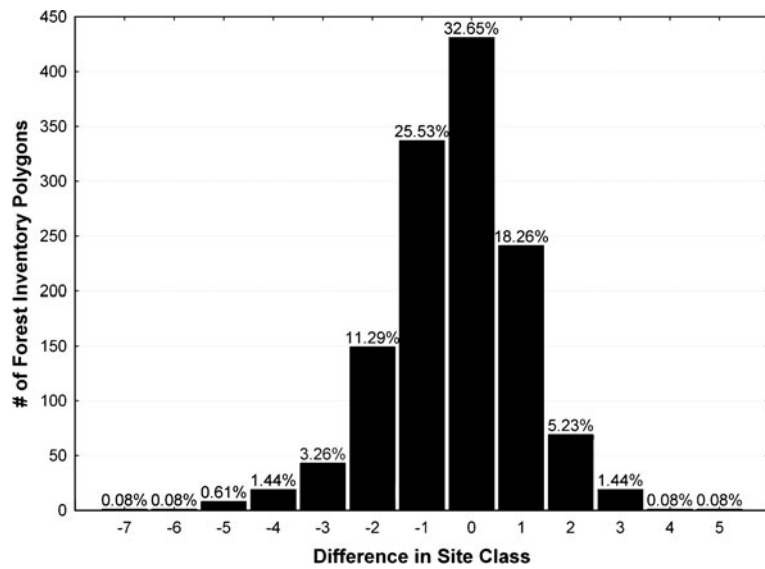
**Fig. 4** Comparison of the distribution of site index estimates in the original inventory and those made using LIDAR-derived mean stand heights, by leading species. Sample sizes are provided in Table 1. Mean, mean  $\pm$  SE (box), and mean  $\pm$  1 SD (whisker)



**Table 4** Comparison of site index, site class, and biomass/ha, by leading species

Leading species		Mean	SD	t	Df	p
<b>Site index</b>						
Amabilis fir	SI <sub>INV</sub>	22.22	2.11	23.791	8	0.000
	SI <sub>LIDAR</sub>	45.67	2.75			
Western red cedar	SI <sub>INV</sub>	22.88	7.44	-2.286	8	0.052
	SI <sub>LIDAR</sub>	26.22	5.93			
Red alder	SI <sub>INV</sub>	24.42	2.12	-12.633	228	0.000
	SI <sub>LIDAR</sub>	30.19	6.75			
Douglas-fir	SI <sub>INV</sub>	32.62	4.21	-2.060	1045	0.039
	SI <sub>LIDAR</sub>	33.02	5.21			
Western hemlock	SI <sub>INV</sub>	26.22	5.12	-25.512	26	0.000
	SI <sub>LIDAR</sub>	40.34	4.96			
<b>Site class</b>						
Amabilis fir	SI <sub>INV</sub>	22.78	2.64	-18.81	8	0.000
	SI <sub>LIDAR</sub>	45.56	3.00			
Western red cedar	SI <sub>INV</sub>	21.67	8.29	-2.683	8	0.027
	SI <sub>LIDAR</sub>	26.67	5.59			
Red alder	SI <sub>INV</sub>	25.09	1.55	-11.922	228	0.000
	SI <sub>LIDAR</sub>	30.37	6.85			
Douglas-fir	SI <sub>INV</sub>	32.60	3.04	-2.167	1045	0.030
	SI <sub>LIDAR</sub>	33.01	5.53			
Western hemlock	SI <sub>INV</sub>	27.78	6.41	-16.901	26	0.000
	SI <sub>LIDAR</sub>	40.74	4.94			
<b>biomass/ha (tonnes)</b>						
Amabilis fir	SI <sub>INV</sub>	109.55	0.45	-3.811	8	0.005
	SI <sub>LIDAR</sub>	228.48	94.03			
Western red cedar	SI <sub>INV</sub>	180.09	37.08	-2.395	8	0.043
	SI <sub>LIDAR</sub>	209.40	20.13			
Red alder	SI <sub>INV</sub>	134.59	49.75	-8.914	228	0.000
	SI <sub>LIDAR</sub>	150.72	63.64			
Douglas-fir	SI <sub>INV</sub>	268.82	98.64	-1.061	1045	0.288
	SI <sub>LIDAR</sub>	271.41	110.29			
Western hemlock	SI <sub>INV</sub>	200.94	36.03	-16.098	26	0.000
	SI <sub>LIDAR</sub>	349.95	32.97			

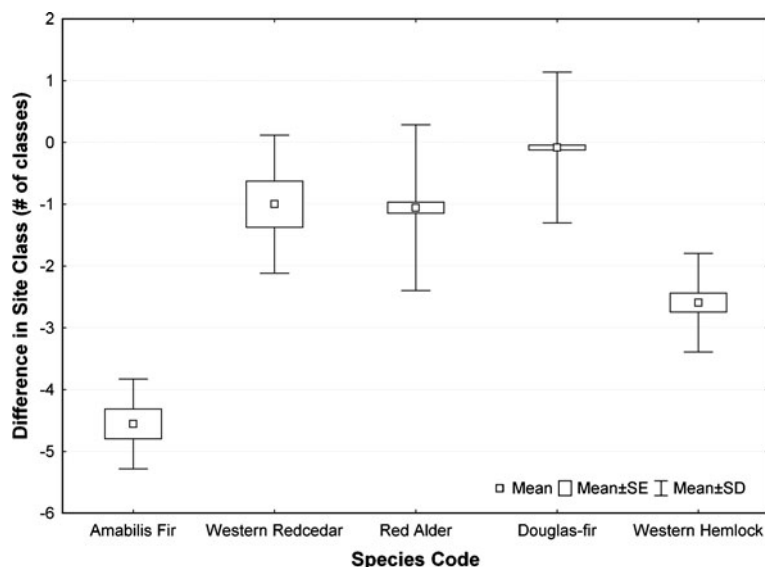
**Fig. 5** Distribution of the site class difference values (original site class—LIDAR-derived site class)



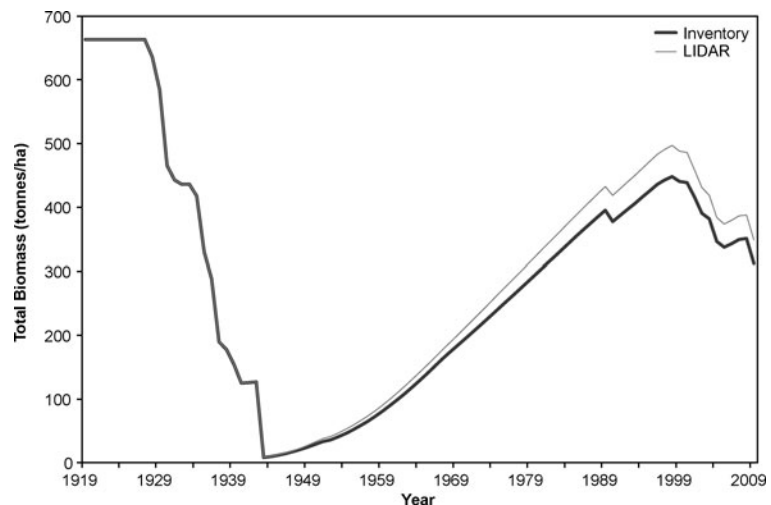
shows differences in the total biomass per hectare for the entire study area as modeled from 1920 to 2006. Total biomass does not differ greatly until the 1940s—most of the stands sampled were established in the 1940s, and when growth is modeled for these stands, the higher LIDAR site-index values (representing more favorable site conditions) result in greater estimates of biomass. Biomass estimates prior to 1940 were unaffected by differences in site index because site index was not used to assign yield tables to

the old-growth stands that were present prior to logging. Instead, old-growth biomass in 1920 was estimated using stand-level merchantable volume estimates derived from a 1919 timber cruise as described by Trofymow et al. (2008). Old-growth biomass increments were simulated by assigning natural stand yield tables in a manner that provided appropriate starting volumes and subsequent annual increments that were consistent with our assumptions about old-growth biomass increments in these ecosystems.

**Fig. 6** Distribution of site class difference values, by leading species (original site index–LIDAR site index). Mean, mean ± SE (box), and mean ± 1 SD (whisker)



**Fig. 7** Relationship between total study area biomass (in tonnes/ha) as estimated from the two separate CBM-CFS3 model runs. A model run estimated total annual biomass for each year from 1920 to 2006 and model inputs were identical with the exception of site index class

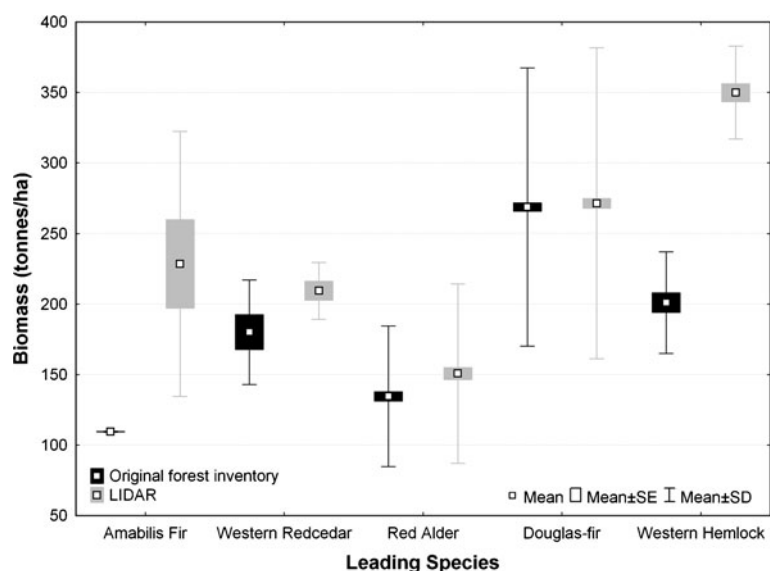


Once the stands were harvested, the old-growth stand attributes and natural stand yield table associations were replaced with stand attributes provided in the forest inventory data and the resulting managed stand yield table associations. Our biomass estimates for stands that were on site prior to the stands present in 2006 had no effect on our estimates of stand biomass in 2006. As expected, the different site class estimates used in the two model scenarios contribute to increasingly larger differences in biomass estimates over time.

Differences in biomass estimates between the two model scenarios in 2006 were statistically sig-

nificant for both total stand biomass (dependent samples two-tailed t-test,  $\alpha = 0.05$ ,  $t = -6.26$ ,  $p < 0.001$ ,  $df = 1, 319$ ) and stand biomass per ha (dependent samples two-tailed t-test,  $\alpha = 0.05$ ,  $t = -4.28$ ,  $p < 0.001$ ,  $df = 1, 319$ ) (Fig. 8). Total, above- and below-ground biomass in 2006 for the subset of stands considered in the analysis was 398,445 tonnes (242 tonnes per ha) for the inventory site-index scenario and 442,640 tonnes (269 tonnes/ha) for the LIDAR site index scenario. The total difference was 44,195 tonnes (27 tonnes/ha). The difference in estimated stand biomass per ha, by leading species, is illus-

**Fig. 8** Distribution of biomass estimates (tonnes/ha), by leading species. Mean, mean  $\pm$  SE (box), and mean  $\pm$  1 SD (whisker)





trated in Fig. 8. Significant differences in estimates of biomass per ha (dependent samples  $t$ -test,  $\alpha = 0.05$ ) were found for amabilis fir ( $t = -3.81$ ,  $p = 0.005$ ,  $df = 8$ ), western red cedar ( $t = -2.395$ ,  $p = 0.043$ ,  $df = 8$ ), red alder ( $t = -8.913$ ,  $p < 0.001$ ,  $df = 228$ ), and western hemlock ( $t = -16.098$ ,  $p < 0.001$ ,  $df = 26$ ). The difference in biomass estimates for Douglas-fir were not statistically significant ( $t = -1.061$ ,  $p = 0.288$ ,  $df = 1, 045$ ) (Table 4).

## Discussion

All of the stands included in our analysis were disturbed in the last 100 years, either by harvest or fire (the maximum age is 72 years), and while some of the stands were left to regenerate naturally, others were planted with Douglas-fir, which is an important commercial species in Coastal British Columbia forests. Douglas-fir plantations have limited variation in tree size and have a more uniform structure than naturally regenerated stands (Wilson and Oliver 2000). Douglas-fir stands in our study area are more structurally uniform than stands dominated with cedar, hemlock, and red alder, which typically have greater diversity in stand composition, age, and height. The variability in the non-Douglas-fir-dominated stands is most clearly evidenced by the differences in site class shown in Fig. 6. These results not only indicate that mean stand heights, as calculated from the LIDAR, are representative of stand conditions in the more uniform Douglas-fir stands but also that height-age models of site index are best suited to these even-aged pure species stands (British Columbia Ministry of Forests 1999).

The implications of these findings are two-fold. First, the use of LIDAR to capture local variability in stand height may be most useful in characterizing the site index of naturally regenerated stands or forest stands with more complex structure. Second, site index is dynamic (Skovsgaard and Vanclay 2007) and may require periodic update (Stearns-Smith 2001), as site index values in the forest inventory may not accurately reflect conditions for regenerating stands (Mah and Nigh 2003). LIDAR can be an effective

sampling tool (Reutebuch et al. 2005) and the use of LIDAR data to enhance the robustness of species-specific height-age methods (and other methods) of site index estimation warrants further investigation. Furthermore, methods have been developed to integrate LIDAR and optical imagery to obtain stand height and map above-ground biomass (St-Onge et al. 2008) and such an approach holds promise for areas such as Canada's north, where there is a lack of pre-existing forest inventory and logistical challenges to acquiring aerial photography (Wulder et al. 2004; Gillis et al. 2005).

## Conclusions

Two different methods of forest-stand site-index estimates were applied to the study area: the first method used original forest inventory site-index values and the second method used LIDAR-measured tree heights, combined with inventory information, to estimate site-index values. Significant differences were found between the original and LIDAR-derived site-index values for all species types and for the site class groupings derived from the estimates. Site classes were input into independent CBM-CFS3 model runs to generate stand-level estimates of biomass. Of the stands analyzed in this study (i.e., with a stand age between 30 and 140 years), 85% were dominated by Douglas-fir. For these stands, no significant difference was found between the biomass estimated from the original forest inventory site index and the LIDAR-derived site index (when estimates were normalized by stand area). Overall, the relationship between the two estimates of biomass are strong ( $R^2 = 0.92$ ,  $p < 0.001$ ), and the strength of this relationship suggests that LIDAR may have a role to play in site index estimation and biomass mapping in areas where there is no comprehensive forest inventory (assuming other data sources, such as optical remotely sensed data, can deliver the other attributes required for site index estimation), where an audit of site-index values is desired for operational or research purposes or where existing forest inventory site-index values are considered out-of-date.

LIDAR may be a useful and economical source of calibration and validation data for site-index models across a range of species and sites and, as the results of this research suggest, may be particularly useful for characterizing the site index of naturally regenerated stands or stands with a more complex structure. Costs for LIDAR data acquisition and processing over large areas are currently high and may limit the application of LIDAR to that of a sampling tool for areas where current and site-specific estimates of site index can result in statistically significant refinements in biomass estimates. However, costs for transporting and maintaining ground crews in inaccessible areas are also high, and LIDAR may have a role to play in estimating stand heights and site index in these remote areas. Finally, the collection of aerial photography concurrently with LIDAR greatly expands the utility of the LIDAR data, facilitating the interpretation of range of forest attributes, including stand age, which is required for site-index estimation.

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