Update of forest inventory data with lidar and high spatial resolution satellite imagery

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Abstract. Most countries with significant forest resources have designed and implemented monitoring systems to inventory, at regular intervals, a range of forest stand attributes such as species composition, age, volume, biomass, and disturbance. These inventory systems are typically based upon the interpretation of air photos supplemented by ground measurements, with digital remotely sensed data often used to capture changes within inventory cycles. Light detection and ranging (lidar) and high spatial resolution digital satellite imagery (e.g., QuickBird) offer additional capacity and complementary data sources for inventory assessment, as demonstrated by this study over a 400 ha area on Vancouver Island, British Columbia, Canada. A range of lidar survey parameters were applied to update an existing forest inventory. Results indicate a strong relationship between the small-footprint lidar-derived heights and stand height as derived from aerial photographic interpretation (API) ($R = 0.79$, $p < 0.05$). In addition, there was no statistical difference ($p < 0.05$) between stand height as predicted from a complete lidar coverage or when sampled as a single 400 m wide transect ($R = 0.89$, $p < 0.001$). These results demonstrate the utility of lidar data, as a full coverage or sample, in combination with high spatial resolution imagery, as useful data sources for capturing forest inventory stand height and cover information.

Résumé. La plupart des pays dotés de ressources forestières importantes ont conçu et mis en place des systèmes de suivi pour inventorier, à intervalles réguliers, divers attributs des peuplements forestiers tels que la composition des espèces, l'âge, le volume, la biomasse et les perturbations. Ces systèmes d'inventaire sont généralement basés sur l'interprétation de photographies aériennes conjointement avec des mesures au sol, les données numériques de télédétection étant souvent utilisées pour mesurer les changements à l'intérieur des cycles d'inventaire. Les images satellitaires numériques lidar (« light detection and ranging ») et à haute résolution spatiale (e.g., QuickBird) offrent des capacités supplémentaires et des sources de données complémentaires pour la conduite de ces inventaires, tel que démontré par cette étude au-dessus d'une zone d'étude de 400 ha sur l'Île de Vancouver, en Colombie britannique, au Canada. Divers paramètres de relevé lidar sont appliqués à la mise à jour d'un inventaire forestier existant. Les résultats indiquent une forte relation entre les hauteurs dérivées des données lidar à petite empreinte et la hauteur du peuplement telle que dérivée de l'interprétation des photographies aériennes (R = 0,79, p < 0,05). De plus, il n'y avait aucune différence statistique (p < 0,05) entre la hauteur du peuplement telle que prédite à partir d'une couverture lidar complète ou lorsque échantillonnée comme un seul transect de 400 m de largeur (R = 0,89, p < 0,001). Ces résultats démontrent l'utilité des données lidar, sous forme de couverture complète ou d'échantillon, en combinaison avec des images à haute résolution spatiale, comme source de données utiles pour dériver la hauteur d'un peuplement ou des informations sur le couvert dans le cadre d'un inventaire forestier.
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Introduction

To meet monitoring and reporting needs, federal governments are often tasked with the generation and production of nationally representative forest inventories and associated statistics. The purpose of these inventories is to assess and monitor the extent, state, and sustainability of forests in a timely and accurate manner (Gillis, 2001). Conventional inventories are based on plot samples and often use a combination of ground measurements and manual interpretation of moderate-scale (1 : 20 000 – 1 : 50 000) aerial photographs for the description of forest stand attributes within each plot (Gillis, 2001). Changes in attributes occurring between inventory cycles are often detected by field inspection, incorporation of harvest plans or silvicultural records, or some form of remote sensing (i.e., aerial photographs or satellite imagery). Recently, a number of remote sensing technologies have emerged that offer alternative approaches for updating forest inventories, with the potential of improving the accuracy and precision of stand-based measurements while reducing data acquisition costs (Wulder and Seemann, 2003; Lefsky et al., 2005; Nelson et al., 2003b; Weller et al., 2003). Key technologies include high spatial resolution satellite imagery and light detection and ranging (lidar).

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Lidar is an effective data source for characterizing three-dimensional forest attributes (Lefsky et al., 2000; 2005); however, to date it has rarely been used to pursue large area inventories (with some exceptions including Nelson et al., 2003a; 2003b; 2005; Næsset et al., 2004). This is often due to the prohibitive cost of data acquisition, especially with large areas under consideration in Canada (Wulder and Seemann, 2003; Wulder et al., 2007). One possibility to make lidar more cost effective over larger areas is to combine lidar-derived samples (e.g., transects) with high spatial resolution satellite imagery, which will allow structural information to be obtained over large areas without requiring full lidar coverage (Nelson et al., 2003b; Wulder and Seemann, 2003). Different modeling approaches have been used in the past to extrapolate sampling information to landscape and regional scales. For example, Hudak et al. (2002) combined lidar with Landsat-7 Enhanced Thematic Mapper (ETM+) data to test different aspatial and spatial methods for extrapolating canopy height. Transects were sampled at different lags to determine the optimal sampling strategy to integrate lidar with Landsat. A modeling approach using kriging was found to be most suitable to estimate tree heights, with accuracies significantly above those acquired from aspatial regression models alone (Hudak et al., 2002).

As opposed to previous studies using Landsat imagery with a ground resolution of 15–30 m (panchromatic and multispectral, respectively), this study investigates the potential of using small-footprint lidar, in combination with higher spatial resolution multispectral satellite imagery obtained from QuickBird (ground resolution: 0.61 m panchromatic, 2.44 m multispectral, 4 spectral channels). Our objective is to demonstrate the potential of these technologies for updating forest inventory stand height estimates initially derived from conventional aerial photographic interpretation (API). Using both full-area coverage and transect-based lidar coverage, we compared and contrasted predictions of stand height to API-derived measures using an example photo plot (400 ha) of the Canadian national forest inventory (NFI). In addition to providing an insight into the potential for alternate data sources to augment national inventory approaches, we undertook this research at a NFI photo plot to allow our results to be more relevant and portable on a national basis.

Methodology

Study area

The focus for this study was an NFI photo plot located on Vancouver Island, British Columbia, Canada. The site has a mean elevation of 300 m above sea level and consists of 80% Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), 17% Western red cedar (*Thuja plicata* Donn ex D. Don), and 3% Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (Morgenstern et al., 2004). There are also small stands of red alder (*Alnus rubra* Bong.) in wetter areas. The majority of forest stands within the area, which are industrially managed by the forest companies Timberwest and Weyerhaeuser, consist predominantly of forest regenerating from harvest and are between 0 and 60 years of age (Morgenstern et al., 2004). For the mature stands, a 1998 site survey found that the stand density was 1100 stems/ha, the tree height was 30–35 m, and the average diameter at breast height (DBH) was 29 cm (Chen et al., 2006).

Inventory data

Stand delineation from aerial photographic interpretation

In Canada, API forms the basis of forest inventory development, whereby the derived polygons describing forest attributes are considered homogeneous based upon attributes such as age class, height, crown closure, and species composition. An interpreter typically delineates inventory polygons using visual interpretation of stereo imagery (Leckie and Gillis, 1995), with each inventory polygon assigned a suite of attributes including height, crown closure, dominant and codominant species, and year of stand establishment. In British Columbia, forest inventory polygons are assumed to be positionally accurate to ±20 m, following provincial standards (B.C. Ministry of Environment, Lands and Parks, 1992). In this study, we utilized forest inventory data interpreted from aerial photography acquired in the year 2000 at a scale of 1 : 20 000 (Gillis, 2001). An overview of the existing inventory polygons and the study area is given in **Figure 1**.

Yield tables

Forest inventories often use site index (SI) or yield tables to estimate stand growth and productivity (Mah and Nigh, 2003). SI is a measure that foresters use to quantify the productive capacity of the land to grow a particular species of tree by referencing heights that trees reach at comparable ages. Typically assessed from visual estimation of stereo photography and the use of lookup tables, accuracy requirements for SI estimates in British Columbia are 20% of the tree height at an age of 50 years (B.C. Resource Inventory Committee, 1998). Smoothed site index curves are plotted by averaging the heights of dominant and co-dominant trees of known age (e.g., McArdle, 1961) or by averaging the heights of the tallest 100 trees per hectare (Mitchell and Polsson, 1988). For this study, SI tables were available through the British Columbia Ministry of Forests and Range (Mitchell and Polsson, 1988).

Remotely sensed data

Small-footprint lidar data were acquired on 8 June 2004 by Terra Remote Sensing (Sidney, British Columbia, Canada) on a Bell 206 Jet Ranger helicopter. **Table 1** provides information on the lidar system. Based on the pulse frequency, lowest sustainable flight speed, and altitude, hit densities of 0.7 hits/m^2 were achieved with a footprint (spot size) of 0.19 m. Separation of vegetation and terrain was carried out using Terrascan v. 4.006 (Terrasolid, Helsinki, Finland). The software uses iterative algorithms that combine filtering and

Figure 1. Study area and NFI polygons (from the year 2000) with the lidar transect overlaid over the area.

Table 1. Lidar 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^2
Datum	NAD83
Projection	UTM Zone 10
Platform	Bell 206 Jet Ranger helicopter
Flight altitude above ground	900 m
Flight speed	25–30 m/s
Version of TerraScan used to classify	Version 004.006

thresholding methods (Axelsson, 1999) and classify lidar data into either ground or non-ground returns. A digital elevation model (DEM) was developed using all available ground-classified lidar hits at a spatial resolution of 1.0 m^2.

A near-nadir QuickBird high spatial resolution satellite image was acquired on 4 August 2004 under clear sky conditions. The image was geometrically corrected prior to purchase by DigitalGlobe, with a stated positional accuracy of less than 5 m, which was confirmed using available digital cadastral information.

Approach

To demonstrate the potential for utilizing lidar and high spatial resolution imagery as technologies for updating existing forest inventory data, three different analyses were undertaken.

First, over the entire photo plot, we compared the dominant stand height of each inventory polygon with the lidar-derived heights for that same polygon. As API polygons are generalizations of the actual forest landscape, they can contain significant internal variability that is finer than the observed mapping scale (**Figure 2a**). Consequently, these polygons, when overlaid on high spatial resolution remotely sensed data such as from QuickBird, can contain both positional and

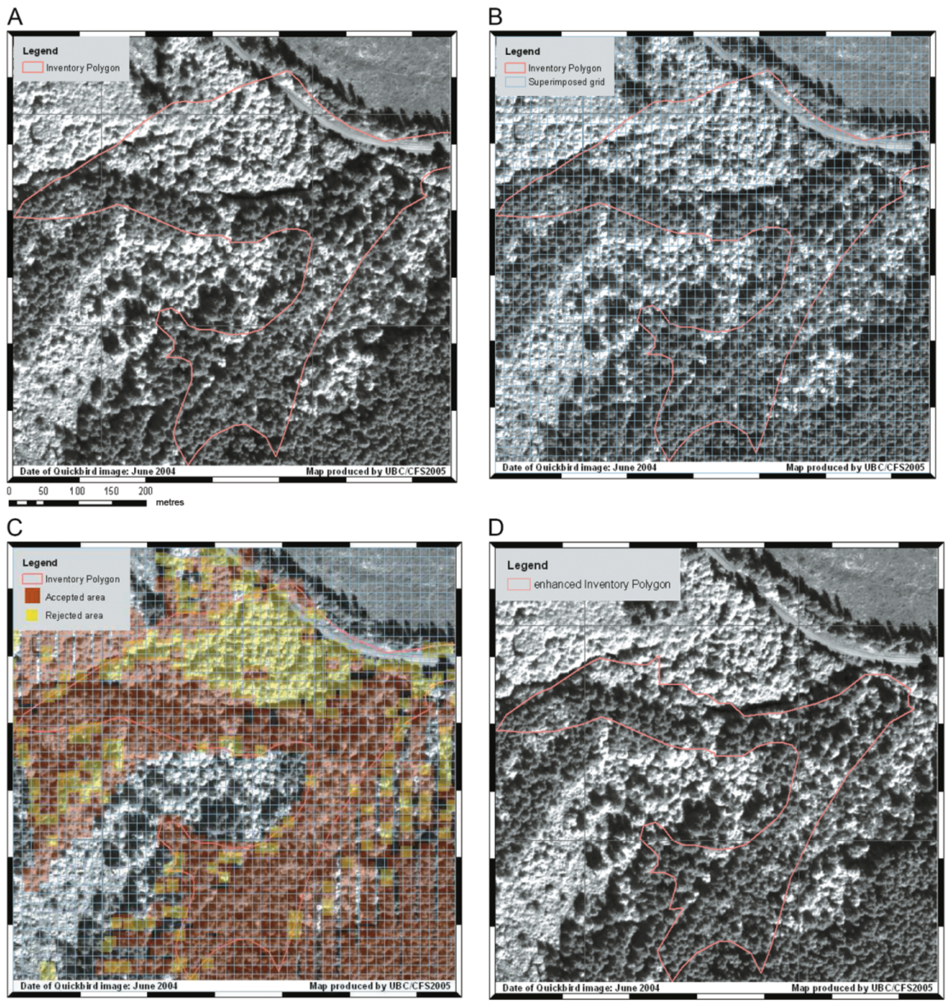

Figure 2. Adjusting spatial scale of inventory boundaries within forested areas using the lidar filter: (a) original inventory polygon, (b) superimposed grid, (c) rejected and accepted areas, and (d) redefined inventory boundary.

generalization ambiguities. An image-based mask was therefore developed to ensure compatibility between the generalized forest inventory polygons and the coincident lidar-based estimates.

Second, to investigate the potential for acquiring cost-efficient inventory updates, the predictions of stand height from lidar over the complete 2 km × 2 km study area were compared with lidar heights acquired along a single 400 m wide transect placed in north–south orientation through the centre of the photo plot (**Figure 1**).

Finally, height information data obtained from the transect lidar were extrapolated across the entire plot using high resolution QuickBird imagery.

Height estimation from full-area coverage lidar

Small-footprint lidar height measurements generally tend to underestimate tree heights, especially in coniferous forests, because most of the laser pulses are returned from locations below the tree tops (Magnussen and Boudewyn, 1998), and as a result stand-based maximum and mean height will be biased (Næsset, 1996). This bias, however, can be mitigated by subdividing a plot into fixed-area cells and then selecting the maximum laser canopy height from each cell (segment) (e.g., Ritchie, 1995; Nilsson, 1996; Næsset, 1996). In this study, stand heights from full-coverage lidar data were estimated following a grid-based procedure (Næsset, 1996). A 10 m × 10 m grid was superimposed on each polygon and the average of the two top-most hits within each grid cell was used to define the height of this specific cell. After Næsset (1996), average and maximum stand heights were then computed using the arithmetic mean and maximum value of all grid cells within a given forest inventory polygon.

To match the scales of the API-derived polygons and the higher spatial resolution lidar data, lidar returns from non-forested areas (such as canopy gaps, openings of reduced canopy cover, roads, and small clearings) were masked out from inside the inventory polygons (**Figure 2**). First, a lidar-based site index (SI_{lidar}) was computed for each grid cell (**Figures 2a, 2b**) using the lidar-measured cell height, age, and species information as attributed by the inventory. Second, SI_{lidar} was compared with the inventory-defined site index (SI_{NFI}) (**Figure 2c**) and grid cells were automatically removed from a polygon if the two site indices (SI_{lidar} and SI_{NFI}) varied by more than a given threshold (35%) (**Figure 2d**). This filter effectively masks out canopy gaps and ensures a meaningful spatial and attribute correspondence between measurements from the original forest inventory values and the new lidar-based measures based on objectively measurable criteria.

Height estimation from transect-based lidar

Lidar transects, rather than full-area coverage, can potentially lead to significant cost and time savings and may therefore facilitate the collection of inventory information where regular updates might otherwise not occur (Gillis and Leckie, 1993). However, the reduced spatial coverage of transect data is a challenge to inventory assessment because it results in a large number of polygons for which no lidar observations are available. To investigate the potential of using such transect-measured lidar data for updating forest inventories, lidar observations from a single 400 m wide transect were extracted through the centre of the 2 km × 2 km photo plot. QuickBird imagery was used to extrapolate the lidar-derived stand heights from this central transect to the entire photo plot using an object-based classification algorithm (eCognition, Definiens Imaging GmbH, München, Germany), subsequently clustering pixels into objects of similar characteristics with respect to spatial, spectral, textural, and areal (i.e., size and shape) characteristics (Wulder and Seemann, 2003). Parameters may be set to weight the impact of a given characteristic upon the segmentation; for example, if the scale parameter is larger, then the image objects will be larger (Baatz and Schape, 2000). Based upon visual testing and iteration, the following eCognition settings were used: scale (10), color (0.7), shape (0.3), smoothness (0.5), and compactness (0.5).

Once each segment was defined, the image clusters were classified using supervised classification to produce a simple forest/non-forest mask. For each forested segment inside the transect, the height was determined from lidar and this height information was transferred to any other clusters outside the transect following three key rules:(1) the two clusters contain identical species composition (as derived from the API), (2) the two clusters contain identical site indices (also from API), and (3) the two clusters have the same spectral properties (i.e., brightness values). To assess the accuracy of this method, the extrapolated heights were validated against the full-coverage lidar data.

Results

Comparing full-coverage lidar heights versus inventory heights

Figure 3a shows the relationship between average maximum stand heights derived from all of the full-coverage non-ground lidar returns and the stand heights obtained from the year 2000 inventory (plus the additional 4 years of growth as estimated from SI curves). Although the heights are moderately correlated (R = 0.71, p < 0.05), it is apparent that the relationship contains a significant bias from the 1:1 line, with an over-prediction of the lower heights in the canopy by up to 7 m (**Figure 3a**), which was statistically confirmed using a *t*-test. Removing lidar hits that did not intersect with overstorey vegetation (**Figure 2**) yielded a much stronger relationship between stand height estimates from the API and lidar data (**Figure 3b**). The relationship is statistically significant

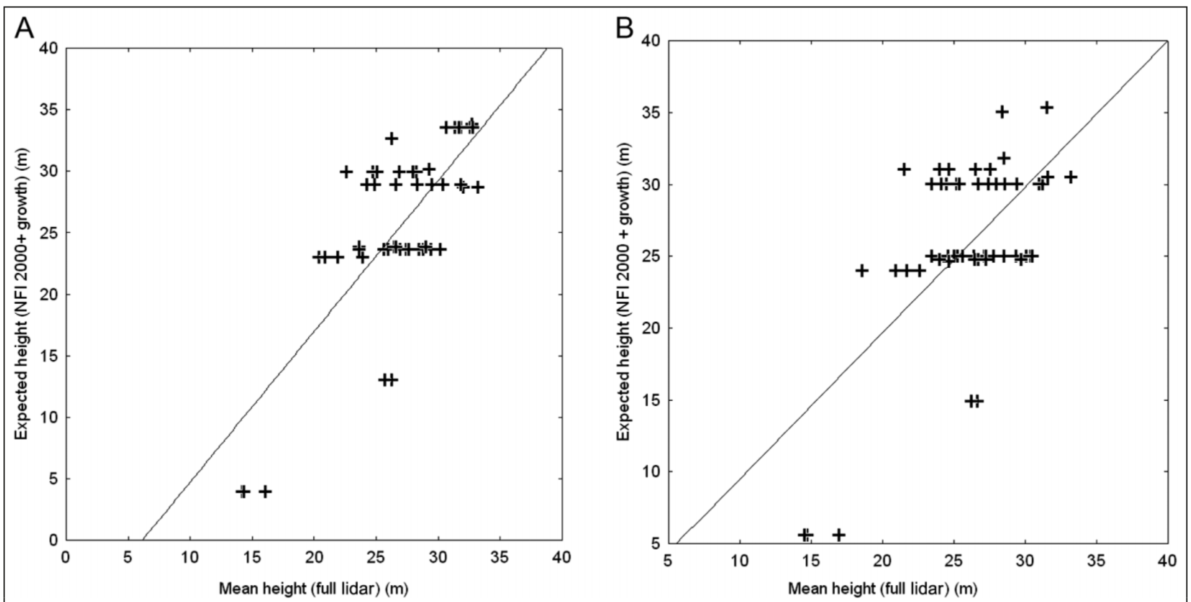

Figure 3. Correlation between inventory heights and full-coverage lidar (a) unfiltered and (b) filtered.

($R = 0.78$, $p < 0.05$) and, importantly, a *t*-test confirmed that the stand height estimates are not statistically different ($p > 95\%$).

Comparison of full-coverage and transect lidar heights

The comparisons between maximum, average maximum, and median stand heights derived from full-area coverage and transect-based lidar respectively, for those inventory polygons that spatially intersected the lidar transect are shown in **Figures 4a–4c**. As anticipated, the transect-derived height values were highly correlated with the full-coverage lidar data ($R = 0.98$, $p < 0.001$). The slope of the line in all relationships was not statistically different from 1:1 ($p < 0.001$), indicating that there is no significant bias. In addition, the variances around the stand height values were also highly correlated and unbiased ($R = 0.98$, $p < 0.05$) (**Figure 4d**).

Figure 5a shows a comparison between the spatially extrapolated stand heights, as derived from the transect data in combination with QuickBird imagery, and the heights obtained from the full-area lidar data. The extrapolated height values and the full-coverage lidar derived heights were significantly correlated ($R = 0.89$, $p < 0.05$), with predicted height values underestimating the stand height by 3.5 m compared with the reference dataset (a 25.2 m average maximum height for the sample compared with 28.7 m for the full lidar data). A *t*-test indicated that this difference is significant ($p < 0.05$). Variation in tree height was 14.19 m for the interpolated polygons compared with 28.15 m for the reference data.

Spatially extrapolated stand heights were also compared with inventory height measures, computed from NFI plus the anticipated growth between inventory data to lidar acquisition

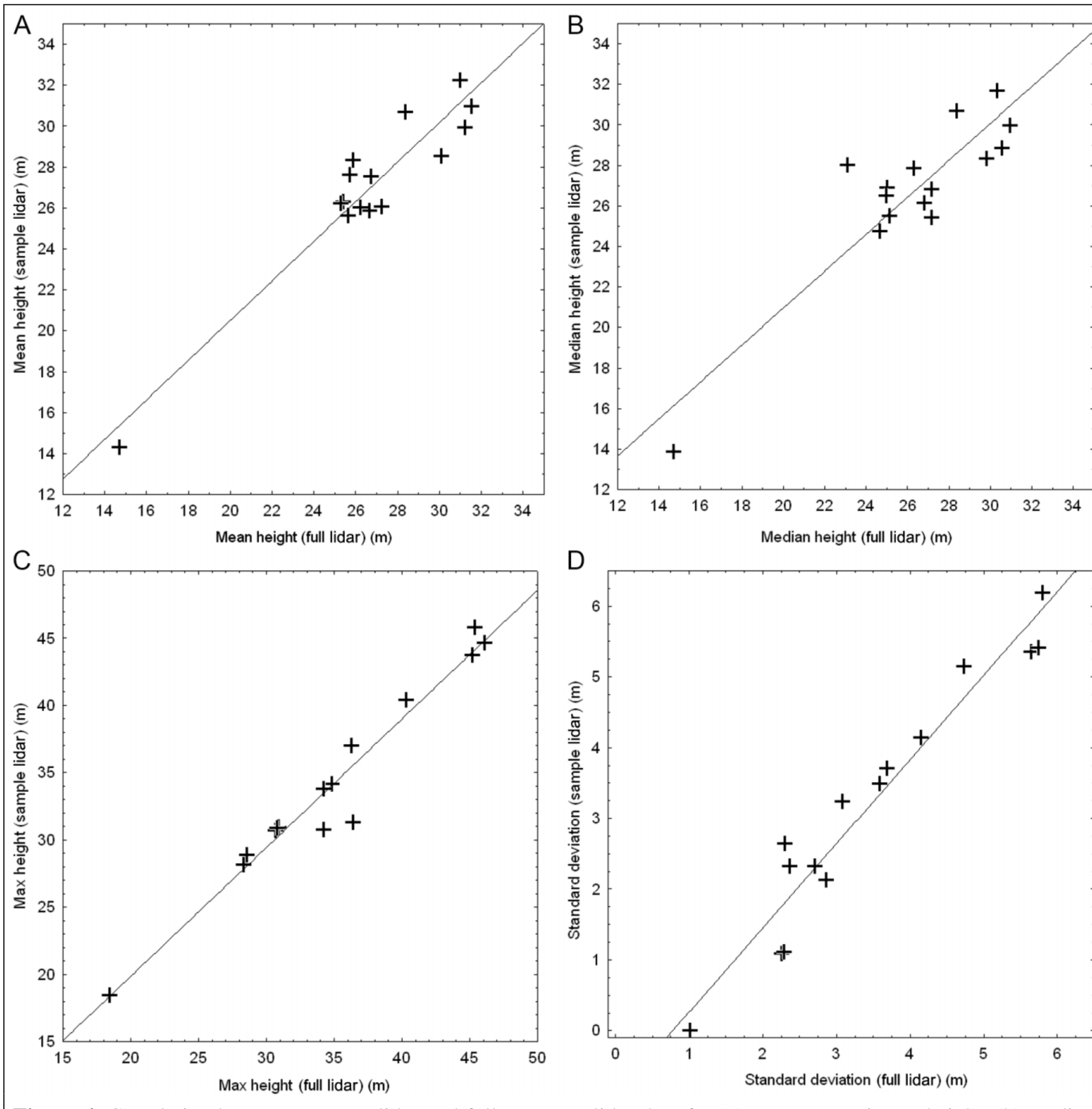

Figure 4. Correlation between transect lidar and full-coverage lidar data for (a) average maximum height, (b) median height, (c) maximum height, and (d) standard deviation.

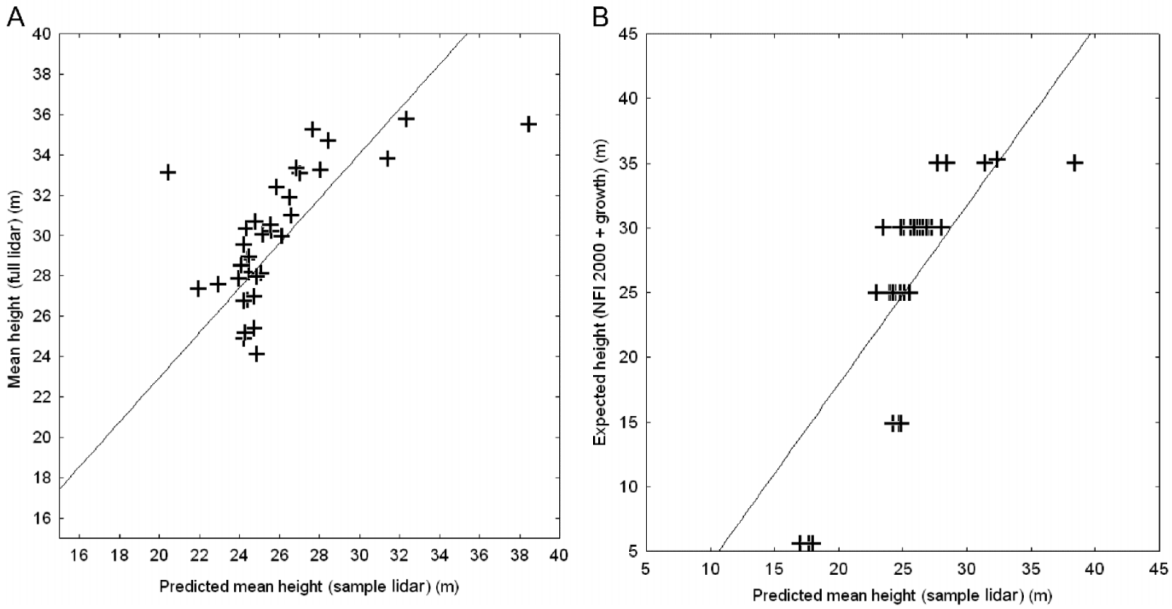

Figure 5. Height prediction using the image segmentation-based model: (a) predicted mean height (sample lidar) versus mean height observed from full lidar coverage, and (b) predicted mean height from sample-based lidar versus inventory heights (last NFI + growth obtained from SI-curves).

derived from the relevant SI curves. Results indicate that the heights are significantly correlated ($R = 0.87$, $p < 0.05$) (**Figure 5b**).

Discussion and conclusion

In this study we demonstrated the potential of integrating high spatial resolution satellite imagery and lidar for the purpose of updating conventionally derived forest inventory polygons, using a Canadian NFI photo plot as an example of forest inventory data that can be considered as typical for Canada.

The comparison between the lidar-derived stand heights (full-coverage lidar) and the inventory year 2000 stand heights (plus the expected growth from the SI curves) demonstrates that lidar technology is capable of estimating stand heights similar to API estimates. When using lidar as an updating tool, however, it is critical to match the spatial resolution of API- and lidar-derived inventory polygons (**Figure 2**). Using the filtered lidar dataset, the height estimates from lidar and API were strongly correlated and exhibited no significant bias (**Figure 3b**). The use of lidar transect data, rather than the full-coverage approach, is more cost effective and therefore has a potential for application over large areas. The results of this study indicate that stand height predictions for all polygons that were intersected by the transect were not statistically different from stand heights derived using the full-coverage lidar data (**Figure 4a**). The significant correlation for the segmentation-based prediction of stand heights for those polygons that did not spatially intersect the lidar transect has been successfully applied to extrapolate lidar stand heights to polygons with similar stand properties (i.e., similar species composition, age, and SI) (**Figure 4b**). For the applied method of extrapolating height information to polygons that were not intersected by the lidar transect, however, it is important to ensure the transect is placed in such a way that it covers API polygons that are representative of the entire area, as the applicability of the method can be expected to decrease with an increasing heterogeneity of the forest stands. The forests on Vancouver Island are more variable and complex than those found elsewhere in Canada, especially the more northern locations. The long inventory cycles and homogeneous forest conditions typical to boreal regions indicate an operational potential for the procedures presented in this study.

Additionally, stand heights can only be predicted for those forest types that are also represented in the transect sample. For example, in this study, the method was not able to estimate stand height information for API polygons delineated as red alder, as the lidar transect did not intersect any alder stands. Other methods and models may need to be investigated, developed, and tested for less common situations as required.

Overall, the stand height relationships developed in this study using the combination of satellite imagery and lidar data are higher than those of previous studies undertaken with large-footprint lidar and Landsat-5 TM data in northern Saskatchewan (Wulder and Seemann, 2003) and with small-footprint lidar and Landsat in Oregon (Hudak et al., 2002). These increased correlations may be due to the higher spatial resolution of the satellite imagery used, which allows the heterogeneity of forest stands to be assessed prior to the development of relationships between API and lidar observations, in comparison with Landsat, which has a spatial resolution of 30 m and therefore averages multiple crowns and much of this heterogeneity within a single pixel. Although this study successfully demonstrated the application of an extrapolation technique over a 400 ha sample area, further investigation is required to validate these results for different forest types and stand conditions. These findings are intended to illustrate the utility of, and foster, incremental inclusion of new data sources, such as lidar and high spatial resolution imagery, into forest inventory generation and updates.

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