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The uncertainty in conifer plantation growth prediction from multi-temporal lidar datasets

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Abstract

An evaluation of the use of airborne lidar for multi-temporal forest height growth assessment in a temperate mature red pine (*Pinus resinosa* Ait.) plantation over a five-year period is presented. The objective was to evaluate the level of uncertainty in lidar-based growth estimates through time so that the optimal repeat interval necessary for statistically meaningful growth measurements could be evaluated. Four airborne lidar datasets displaying similar survey configuration parameters were collected between 2000 and 2005. Coincident with the 2002 and 2005 acquisitions, field mensuration for 126 trees within 19 plots was carried out. Field measurements of stem height were compared to both coincident plot-level laser pulse return (LPR) height percentile metrics and stand level raster canopy height models (CHM).

The average plot-level field heights were found to be 23.8 m (standard deviation (σ) = 0.4 m) for 2002 and 25.0 m (σ = 0.6 m) for 2005, with an approximate annual growth rate of 0.4 m/yr (σ = 0.5 m). The standard deviation uncertainty for field height growth estimates over the three year period was 41% at the plot-level (n = 19) and 92% at the individual tree level (n = 126). Of the lidar height percentile metrics tested, the 90th (L90), 95th (L95) and maximum (Lmax) LPR distribution heights demonstrated the highest overall correlations with field-measured tree height. While all lidar-based methods, including raster CHM comparison, tended to underestimate the field estimate of growth, Lmax provided the most robust overall direct estimate (0.32 m/yr, σ = 0.37 m). A single factor analysis of variance demonstrated that there was no statistically significant difference between all plot-level field and Lmax mean growth rate estimates (P = 0.38) and, further, that there was no difference in Lmax growth rate estimates across the examined time intervals (P = 0.59). A power function relationship between time interval and the standard deviation of error in growth estimate demonstrated that over a one-year period, the growth uncertainty was in the range of 0.3 m (~100% of total growth) reducing to less than 0.1 m (~6% of total growth) after 5 years. Assuming a 10% uncertainty is acceptable for operational or research-based conifer plantation growth estimates, this can be achieved at a three-year time interval.

Keywords: Lidar; Laser scanning; Red pine; Canopy height; Tree growth; Uncertainty; Plantation

1. Introduction

Airborne lidar (light detection and ranging) data are commonly used to create high-resolution digital elevation models (DEMs) of the ground or digital surface models (DSMs) of vegetation canopy and urban surfaces. Small-footprint discrete-return (SFD) systems are increasingly being adopted in the survey and mapping industry, as the data acquired are analogous to traditional ground survey point data. While data volumes can be high, the resultant point data architecture can be handled in many computed aided design (CAD), geographical information systems (GIS) and image analysis software packages. Current technology can collect multiple laser pulse returns at pulse repetition frequencies (PRF) exceeding 160,000 pulses per second, and can cover a ground swath greater than 3000 m depending on flying altitude and scan angle. The resultant laser pulse return (LPR) data can be dense (up to and exceeding 10 LPRs per m^2) and positional accuracy is typically at the decimetre to metre level (Fowler, 2001). For a more detailed introduction to lidar technology see Baltsavias (1999) and Wehr and Lohr (1999).

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Many studies have investigated the use of lidar for tree height measurement and found good relationships to field measures with r^2 values typically ranging from 0.85 to 0.95 (Maclean & Krabill, 1986; Magnussen & Boudewyn, 1998; Means et al., 2000; Næsset, 1997; Næsset, 2002; Næsset & Økland, 2002; Popescu et al., 2002; Ritchie, 1995; Witte et al., 2001). For example, Næsset (1997) reported that for conifer stands in Norway, sampled grid-based maximum LPR heights (Lmax) above the ground level tended to correlate well with Lorey's mean tree height ($r^2 = 0.91$) despite a range of observed bias from −0.4 m to 1.9 m. Magnussen and Boudewyn (1998) expanded upon this work by finding that a canopy LPR quantile-based approach applied to conifer plots in western Canada could predict canopy height to within 6% of field measurements. Many lidar canopy height estimation studies illustrate a tendency to underestimate height (Lim et al., 2003a,b), and this is typically attributed to: (i) laser pulse penetration into foliage (Gaveau & Hill, 2003; Hopkinson, 2007; Hopkinson et al., 2005); (ii) insufficient representation of canopy apices due to low sample point density (St-Onge et al., 2000) or (iii) ground height overestimation due to minimal pulse penetration through dense vegetation (e.g. Hopkinson et al., 2004a,b; Reutebuch et al., 2003; Weltz et al., 1994).

A large number of studies have demonstrated high correlations between certain LPR metrics such as Lmax, and 90th (L90) or 95th (L95) percentile LPR distribution height within the canopy. LPR frequency distributions through the canopy, however, can be influenced by: vegetation structural characteristics such as foliage density (e.g. Magnussen & Boudewyn, 1998); and lidar data acquisition factors such as pulse repetition (Chasmer et al., 2006a), footprint size and energy (Hopkinson, 2006), flying altitude (Goodwin et al., 2006; Hopkinson, in press; Næsset, 2004), and scan angle (Holmgren et al., 2003). The simplest and most robust approach yet adopted to infer canopy height is to isolate the localised maximum LPR elevation and subtract the associated ground elevation (e.g. Næsset, 1997). This approach is often implicitly adopted during the rasterisation of lidar data to create DSMs for grid based canopy height models (CHMs) (e.g. Hopkinson et al., 2005). Canopy height estimates based on upper LPR frequency distribution approaches are simple and robust but pulse spacing and the shape of tree crown apices can influence the probability of the LPR distribution detecting the highest foliage elements within a sample area (Magnussen & Boudewyn, 1998).

With the decimetre level mapping capability of airborne lidar, it follows that the technology can be used for accurate detection of changes in landscape features at a high resolution. This has been demonstrated in several studies. For example seasonal and annual variations in coastal morphology following storm-related erosion events have been observed by comparing lidar DEMs through time (e.g. White & Wang, 2003; Woolard & Colby, 2002). Snowpack depth distribution (Hopkinson et al., 2004b), glacier melt rates and volumes (Hopkinson & Demuth, 2006), and urban building development processes (Vosselman et al., 2004) have all been mapped using lidar DEM inter-comparison processes.

Despite a wealth of literature demonstrating that lidar can be used both for forest mensuration and as an effective means of change detection at the decimetre to metre level, few studies have investigated and quantified the suitability of SFD lidar data for forest growth assessment from multiple datasets collected over a number of years. Yu et al. (2004) provided an assessment of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) canopy growth within a Boreal forest site from two lidar acquisitions 21 months apart. Growth was estimated by observing differences in raster canopy height models (CHMs) for individually segmented tree crowns that could be identified in both datasets. It was found that after adjusting DEM heights to account for observed canopy height underestimations, plot-level growth could be estimated at a precision level of 10 to 15 cm. In a study by St-Onge and Vepakomma (2004) conducted over a five-year period it was shown that changes in forest height and gap fraction estimated from two SFD lidar datasets were generally consistent with expected growth patterns. However, the results were not compared directly to field validation data and the wide variation in survey configuration between the two acquisitions led to some uncertainty in the estimates of dynamic canopy conditions being assessed (St-Onge & Vepakomma, 2004). Næsset and Gobakken (2005) assessed changes in LPR metrics over a two-year time period in mature and immature conifer plots. It was found that while LPR data were able to predict growth at a statistically significant level, the accuracy of the predictions was weak. In most cases the predictions were slightly biased and the precision was low over a two year time period (Næsset & Gobakken, 2005). Finally, Yu et al. (2006) compared two lidar datasets collected 5 years apart to assess the ability to measure growth at the individual tree level. They compared L85, L90 and L95 and the best correspondence with field data achieved an r^2 of 0.68 and an RMSE of 43 cm. From these five lidar forest growth studies, it is clear that growth is detectable over time periods ranging from two to five years but the time interval necessary for an accurate and statistically significant estimation of growth rate is unclear.

This study evaluates the application of lidar for plot-level mean tree height growth assessment within a red pine (*Pinus resinosa* Ait.) conifer plantation over a five-year period using multiple lidar datasets. The specific questions addressed are:

1. Is it possible to accurately estimate conifer plantation rates of height growth from changes in plot-level lidar-derived canopy heights observed over annual and inter-annual time periods?
2. Of the quantile and raster CHM height assessment methods typically employed to assess canopy height, which is most appropriate for growth monitoring?
3. Are lidar estimated rates of growth consistent through time?
4. How does the statistical uncertainty in growth rate prediction vary with increasing time interval between repeat acquisitions?
5. What is the minimum repeat acquisition time interval necessary for an accurate and statistically significant estimate of height growth for the red pine plantation studied?

Any lidar-based investigation of canopy height change through time to quantify forest growth rate is expected to be