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Comparison of high-density LiDAR and satellite photogrammetry for forest inventory

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ABSTRACT

Point cloud data derived from stereo satellite imagery has the potential to provide large-scale forest inventory assessment but these methods are known to include higher error than airborne laser scanning (ALS). This study compares the accuracy of forest inventory attributes estimated from high-density ALS (21.1 pulses m^{-2}) point cloud data (PCD) and PCD derived from photogrammetric methods applied to stereo satellite imagery obtained over a *Pinus radiata* D. Don plantation forest in New Zealand. The statistical and textural properties of the canopy height models (CHMs) derived from each point cloud were included alongside standard PCD metrics as a means of improving the accuracy of predictions for key forest inventory attributes. For mean top height (a measure of dominant height in a stand), ALS data produced better estimates (R^2 = 0.88; RMSE = 1.7 m) than those obtained from satellite data (R^2 = 0.81; RMSE = 2.1 m). This was attributable to a general over-estimation of canopy heights in the satellite PCD. ALS models produced poor estimates of stand density (R^2 = 0.48; RMSE = 112.1 stems ha^{-1}), as did the satellite PCD models (R^2 = 0.42; RMSE = 118.4 stems ha^{-1}). ALS models produced accurate estimates of basal area (R^2 = 0.58; RMSE = 12 m^2 ha^{-1}), total stem volume (R^2 = 0.72; RMSE = 107.5 m^3 ha^{-1}), and total recoverable volume (R^2 = 0.74; RMSE = 92.9 m^3 ha^{-1}). These values differed little from the estimates of basal area (R^2 = 0.57; RMSE = 12.2 m^2 ha^{-1}), total stem volume (R^2 = 0.70; RMSE = 112.6 m^3 ha^{-1}), and total recoverable volume (R^2 = 0.73; RMSE = 96 m^3 ha^{-1}) obtained from satellite PCD models. The statistical and textural metrics computed from the CHMs were important variables in all of the models derived from both satellite and ALS PCD, nearly always outranking the standard PCD metrics in measures of importance. For the satellite PCD models, the CHM-derived metrics were nearly exclusively identified as important variables. These results clearly show that point cloud data obtained from stereo satellite imagery are useful for prediction of forest inventory attributes in intensively managed forests on steeper terrain. Furthermore, these data offer forest managers the benefit of obtaining both inventory data and high-resolution multispectral imagery from a single product.

1. Introduction

Forest managers require detailed, up-to-date, and reliable resource information to achieve their management objectives. Traditionally, this has been achieved through sample-based methods to estimate relevant attributes such as stand density, height, and timber volume. Remote sensing has greatly enhanced terrestrial sampling methods, allowing improved assessment of forest resources at a range of scales (Dash et al., 2015a; Breidenbach and Astrup, 2012). Airborne laser scanning (ALS or lidar) has emerged as a particularly useful technology for accurate characterisation of forest properties at resolutions ranging from stand level (Hall et al., 2005; Naesset, 2002) and plot level (Holmgren et al., 2003; Hyyppä et al., 2001; Lim and Treitz, 2004; Popescu et al., 2004) to individual tree level (Chen et al., 2006; Coops et al., 2006; Holmgren and Persson, 2004; Persson et al., 2002; Popescu and Zhao, 2008; Roberts et al., 2005; Yu et al., 2004).

As ALS provides very detailed three-dimensional information around forest structure and the underlying terrain, this type of data is considered to be the most useful form of remote sensing for forest inventory (Vauhkonen et al., 2014) and ALS can predict inventory metrics far more precisely than satellite imagery (Dash et al., 2015b). Use of ALS is now widespread and operational applications of this technology for forest inventories are in use in Norway (Naesset, 2007), Canada (Woods et al., 2011), Finland (Maltamo et al., 2011), and Sweden

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(Nilsson et al., 2017). Due to the cost of flying, application of ALS is usually limited to local scales and is not affordable as a data source for many countries. While regional scale data is sometimes utilised (Zhao and Popescu, 2009), repeated annual acquisition at this scale is generally cost prohibitive (Hudak et al., 2002).

Research undertaken over the last decade has demonstrated the utility of very high spatial resolution (VHSR) imagery in the prediction of forest inventory metrics. Panchromatic imagery has been successfully used to estimate stand height (Mora et al., 2010, 2013), volume, and biomass Hirata (2008), Leboeuf et al. (2007), Mora et al. (2013). Spectral, textural, and shadow fraction metrics derived from multispectral imagery have also been used to predict tree height (Chen et al., 2012; Peuhkurinen et al., 2008). Predictions have generally been found to be moderately precise for models of tree volume (R^2 of 0.72; RMSE of 52.59 m^3 ha^{-1} (Chen et al., 2012)), biomass (R^2 of 0.72; RMSE of 39.5 tonnes ha^{-1} (Chen et al., 2012)) and tree height (R^2 of 0.76 and RMSE ranging from 1.95 to 3.1 m (Mora et al., 2013; Peuhkurinen et al., 2008)). Comprehensive reviews highlighting the potential of high spatial resolution satellite imagery for forest inventory are given by Wulder et al. (2004) and more recently by White et al. (2016).

Point cloud data obtained from photogrammetric methods applied to multiple overlapping images of the forest canopy have also shown promise for forest inventory assessment. Accurate predictions of stand dimensions have previously been made using point clouds derived from imagery collected by either unmanned aerial vehicles (Dandois et al., 2015; Lisein et al., 2013; Wallace et al., 2016) or, more commonly, by manned aircraft (Gobakken et al., 2015; Nurminen et al., 2013; Pitt et al., 2014; Rahlf et al., 2014; Vastaranta et al., 2013, 2016; Stepper et al., 2014a,b; Wang et al., 2015). Although the aerial images used to generate these point clouds cost about one-half to one-third of airborne LiDAR data (White et al., 2013), this method is not as accurate as laser scanning at predicting stand dimensions (Rahlf et al., 2014) as it suffers from two main limitations. Firstly, laser scanning provides greater penetration into the canopy than imaging technology which allows enhanced vertical stratification of vegetation layers and the terrain. Secondly, as the ground terrain needs to be visible from multiple locations in order to estimate its three-dimensional location, research has shown that accurate generation of canopy height information from imagery often requires the use of a digital terrain model (DTM) supplied from an external source, such as ALS (Dandois and Ellis, 2013; Lisein et al., 2013).

Several modern VHSR-capable satellites offer the ability to capture stereo imagery. These data can be used with photogrammetric techniques to generate point clouds describing the height of the imaged surface. This approach shows considerable promise in predicting stand dimensions at a relatively low cost over broad spatial scales. Multi-sensor comparisons have shown that the digital surface models (DSMs) available from satellite photogrammetry can deliver results similar to those obtained from ALS in complex forest types (Tian et al., 2017). Although recent research has demonstrated that stereo satellite point clouds may have utility in predicting forest inventory attributes, the research around these applications is still sparse and has shown contrasting results. Using an IKONOS stereo pair, St-Onge et al. (2008) were able to accurately predict forest height ($R^2 = 0.91$) and aboveground biomass ($R^2 = 0.79$) in a study site located in Quebec, Canada. Straub et al. (2013) found that WorldView-2 (WV2) provided more accurate predictions of tree volume than Cartosat-1 in a highly structured mixed forest in Germany and that WV2 predictions were only slightly less accurate than LiDAR at the stand level (RMSE = 19.6% vs. 17.1%). Immitzer et al. (2016) found that tree height and spectral variables from WV2 could be used to predict volume with an acceptable, although somewhat lower, accuracy ($R^2 = 0.53$; RMSE = 32%) in conifer, broadleaf, and mixed stands in Bavaria, and that height metrics derived from the CHM had more predictive power than the spectral values. In a study within hemi-boreal and boreal forest in Sweden (Persson and Perko, 2016), WV2 stereo images were used to accurately predict forest height within two study sites (R^2 of 0.94 and 0.91; RMSE of 8.3% and 10.4%).

Stereo satellite point clouds are only capable of characterising the upper portions of the canopy and do not offer the same vertical characterisation as ALS data. For applications such as forest inventory and biomass estimation, the upper canopy, especially measurement of the canopy height, is often most useful (Lim et al., 2003; Dash et al., 2015a). This notion is supported by the widely-demonstrated utility of canopy height models (CHMs) for forest measurement. CHMs describe the spatial variation of the canopy surface and are usually calculated by normalising returns from the top of the canopy against local DTM values. These heights are then filtered and interpolated in a process that results in a useful representation of the canopy surface (Khosravipour et al., 2014). CHMs derived from point cloud data are useful for a range of applications such as individual tree detection (Pont et al., 2015), estimating tree height and crown diameter (Zhao and Popescu, 2009) as well as biomass (Popescu et al., 2003). Metrics derived from CHMs have also been used for prediction of forest inventory attributes (Persson et al., 2013; Hill et al., 2014). The proven utility of CHM metrics suggests that CHMs may be useful outputs from stereo point clouds. Generation of CHMs is well suited to stereo satellite-based point clouds as they utilise the highest elevation points and the process of generating the CHM involves interpolation and smoothing to produce a continuous surface. This may overcome the often irregular representation obtained from photogrammetry where only the height of the upper elements of the canopy surface are estimated, and only for pixels that are successfully matched across multiple images.

The aim of this study was to compare estimates of forest inventory attributes obtained using ALS data with those obtained from point clouds derived from stereo imagery in New Zealand's planted *Pinus radiata* D. Don forests. To overcome some of the limitations of stereo satellite data, we attempt to utilise the statistical properties of a refined CHM. In addition, we investigate the possibility that textural metrics applied to the CHM surface may provide an opportunity to extract important structural information about the canopy. By highlighting the most important predictive metrics, the value of the additional vertical characterisation and improved accuracy of ALS data could be assessed. To the best of our knowledge, this is the first application of this technology in this forest type and a successful application could allow large-scale assessment for forest inventory. Further investigation could validate stereo satellite imagery as a means of providing forest managers with very high resolution imagery, updated forest inventory data, and forest health assessments from a single sensor.

2. Methods

2.1. Study site

The study was carried out in Geraldine forest in New Zealand's South Island (Fig. 1). The terrain is steep and broken, ranging from 200 to 780 masl. The forested area surrounds an area of degraded pasture land, with the steepest forested areas largely located to the north. The nature of the terrain and surrounding land uses created many irregular edges. The forest consists predominantly of *P. radiata* planted and managed for timber production in even-aged stands. Several areas of the forest are subject to occasional snowfall, and several stands showed signs of damage such as broken limbs, double leaders, and toppled stems from past events.

2.2. Field plots

Field data were collected between May and June 2016. Plots were established using a systematic grid with random orientation and origin. Plot centres for each of the 0.06 ha circular, bounded plots were located using a differential GNSS (Trimble Geo6/7 Series, Trimble Navigation, Sunnyvale CA, USA). Within each plot, measurements included