Remote Sensing of Environment 117 (2012) 348–357

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Airborne scanning LiDAR in a double sampling forest carbon inventory

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ARTICLE INFO

Article history:
Received 22 February 2011
Received in revised form 23 September 2011
Accepted 6 October 2011
Available online 9 November 2011

Keywords:
LiDAR
Double sampling
Forest inventory
Carbon
Kyoto Protocol

ABSTRACT

To meet Kyoto Protocol obligations, New Zealand is required to estimate forest carbon stock change over the first commitment period (2008–2012). New Zealand has three subcategories of forest, namely: Natural forest; Pre-1990 forest; and Post-1989 forest. The Post-1989 forest carbon inventory undertaken in 2008 used discrete return airborne LiDAR and ground-based measurements of 0.06 ha circular plots located on a 4-km × 4-km grid. The national carbon stock estimate was based on a double sampling scheme consisting of 246 plots from which both ground and LiDAR data were obtained, supplemented with 46 additional plots assessed using only LiDAR. This paper describes the relationships established between carbon stocks estimated using ground-based measurements and LiDAR metrics. A regression model explaining 74% of the variation in total carbon was developed using LiDAR 30th percentile height (P30ht) and canopy cover (%Cover). The regression estimator improved the precision of the national carbon stock estimate in 2008 by 6% compared to the ground-based estimate. This inventory indicates that it is possible to reduce the cost of obtaining carbon stock estimates to a specified level of precision using a combination of ground-based and LiDAR measurements in a double sampling approach. The theoretical maximum improvement in precision expected in 2012, when additional LiDAR data are expected to be available, is 50–55%.

1. Introduction

New Zealand is a signatory to the Kyoto Protocol and the United Nations Framework Convention on Climate Change. A requirement under Article 3.3 of the Protocol is annual greenhouse gas reporting of carbon stock changes arising from land use, land-use change and forestry (LULUCF) activities. Annual reporting is required for the Protocol's first commitment period, from 2008 to 2012. Good Practice Guidance (IPCC, 2003) for LULUCF activities requires carbon stock changes be estimated in an unbiased, transparent, and consistent manner.

To meet LULUCF reporting requirements, New Zealand has classified forest into three subcategories: Natural forest; forest planted prior to 1990; and forest established after 31 December 1989 onto non-forest land. The latter category is referred to as Post-1989 forest or 'Kyoto forest'. Forest to be measured under the Protocol is defined by New Zealand as meeting the following thresholds: minimum area of 1 ha; at least 30% canopy cover; at least 5 m in height (or the potential to reach this height under current management practices); and a width of at least 30 m. Ninety-five percent of Post-1989 forest in New Zealand comprises planted tree species, with the remaining comprising regenerating native species. Of the planted species radiata pine (*Pinus radiata D. Don*) comprises 89% with Douglas-fir (*Pseudotsuga menziesii (Mirb.)Franco*) and *Eucalyptus* species making up most of the remainder, established in single-species stands throughout New Zealand.

Airborne scanning LiDAR provides a flexible data collection system. High-density LiDAR provides sufficient reflections from the ground to generate accurate digital terrain models under dense conifer forest in mountainous areas (Reutebuch et al., 2003). Further, data collection is independent of sun angle and night collection is feasible. Over the past few years there have been considerable advances in LiDAR systems which have resulted in improved LiDAR positional accuracy and increased surface point density. This has resulted in cm-level ranging accuracies, markedly increased pulse rate frequencies (greater than 150 kHz) and provision for LiDAR intensity signals (as opposed to ranging observation only). The flexibility of airborne LiDAR, coupled with a high level of positional accuracy and point density, makes LiDAR systems an attractive data acquisition tool for estimating a wide range of tree and forest parameters. The use of LiDAR for estimating forest inventory parameters and structural characteristics is reviewed by van Leeuwen and Nieuwenhuis (2010). While numerous studies describe how LiDAR can be used to estimate individual forest parameters, including: tree height (Andersen et al.,

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0034-4257/$ – see front matter
doi:10.1016/j.rse.2011.10.009

2006; Næsset, 2002; Sexton et al., 2009), stem volume (Heurich & Thoma, 2008; Næsset, 2002; van Aardt et al., 2006), tree biomass (Lefsky et al., 2002; Li et al., 2008; van Aardt et al., 2006), and leaf area index (Lefsky et al., 2005; Morsdorf et al., 2006), recent research emphasis aims to identify key metrics that explain most of the variability in stand structural attributes across a range of forest types (Li et al., 2008).

Field-based sampling remains an essential element of forest carbon inventory. The integration of LiDAR into such activities provides an opportunity to reduce total inventory cost by reducing the need for intensive field-based sampling. Investigations into the potential of airborne LiDAR for forest carbon inventory have been undertaken (Drake et al., 2002; Nelson et al., 2003; Patenaude et al., 2004, and Stephens et al., 2007). In temperate deciduous woodland, LiDAR metrics explained 55% of the variation in above-ground plot-level carbon estimates, and 72% of the variation in above-ground estimates at the stand level (Patenaude et al., 2004). For planted forest in New Zealand, a study by Stephens et al. (2007) determined that LiDAR metrics explained 80% of the variation in total carbon.

The application of LiDAR to forest inventory has been described, e.g., by Næsset (2002, 2004), Næsset et al. (2004), Parker and Evans (2004), and Corona and Fattorini (2008). These authors used double sampling procedures which combine ground-based plot measurements with auxiliary information from the remote sensed LiDAR data obtained from a larger sample of the population. In the double sampling approach, information from the auxiliary data is used to improve the precision of estimates of forest inventory variables compared with those based solely on the field observations. This improvement in precision is generally achieved using regression or ratio estimators and relies on the good relationships between the remote sensed data and the forest inventory variables. According to Næsset et al. (2004), estimates of stem volume and mean tree height from laser scanned data are better than those from other remote sensing methods such as photogrammetric techniques. This approach can substantially improve the precision of such estimates. For example, Corona and Fattorini (2008) used ratio estimators in a double sampling scheme to obtain 95% confidence intervals for total volume approximately 2/3 smaller than those obtained using information solely from the field plots.

A plot-based forest inventory system has been developed for carbon estimation in New Zealand's Post-1989 forest. Circular plots, 0.06 ha in area, have been located within these forests on a systematic 4-km × 4 km grid. The post-1989 forest estate is comprised of numerous small mainly privately owned woodlots and when planning the inventory, it was believed that ground access to all locations within the estate might not be possible. Therefore, LiDAR was incorporated into the original design as a backup to ground-based measurements. In practice, ground access to almost all locations proved possible, and a conventional double-sampling scheme was therefore adopted for the inventory. Information from both the field measurements and LiDAR data was combined using double sampling regression estimators to calculate average carbon stock per hectare with known precision for the Post-1989 forest estate.

The usual rationale for using LiDAR in forest inventories using double sampling and regression estimators is to reduce costs. This is possible because the LiDAR inventory allows similar precision to be achieved using fewer ground plots than a solely ground-based inventory. Another reason for using LiDAR is that it allows estimates to be obtained for sub-areas of the population which are too small to be adequately sampled by the ground survey, although this was not a consideration in the New Zealand Post-1989 carbon inventory. Only a modest improvement in precision of the regression estimators compared with those based on the ground-based measurements was expected from the design of the New Zealand Post-1989 forest inventory in 2008 because it incorporated only a moderate number of grid locations sampled solely using LiDAR. However, the data obtained makes it possible to assess the potential of using LiDAR to reduced costs in future inventories. This paper describes the use of inventory ground plots to calibrate the regression models, along with the use of data from LiDAR-only inventory plots in a double sampling forest carbon inventory and considers the potential for using LiDAR for reducing costs in future inventories.

2. Method

2.1. Study area

LiDAR data, aerial photographic imagery and ground measurements of inventory plots located throughout New Zealand were acquired for this project. New Zealand is centred on 41° S and 174° E (Fig. 1). When the LiDAR and ground measurements were made, the spatial location and areal extent of Post-1989 forest across New Zealand were not known. Accordingly, a total of 758 inventory plots located on the 4-km × 4-km grid were surveyed with LiDAR and aerial photography (Stephens et al., 2008). The analysis of LiDAR data, and photographic and historical satellite imagery, along with approaches to forest owners, identified 292 of those plots as being located within Post-1989 forest. Of these, 246 were selected randomly for both ground and LiDAR sampling. The remaining 46 plots which were sampled solely using LiDAR were distributed throughout New Zealand (Fig. 1). Subsequently some additional Post-1989 forest areas have been mapped which will be sampled in a future inventory.

2.2. LiDAR and aerial photographic data

The LiDAR survey was flown using a Cessna 207 aircraft between February and April 2008. An Optech ALTM 3100EA LiDAR sensor was mounted in the aircraft, along with an integrated Rollei AIC digital camera. Table 1 summarises the LiDAR and flight parameters used to achieve plot first return densities of at least three points per m^2. The digital camera was used in tandem with the LiDAR sensor. The resulting colour photography had a ground resolution of 0.2 m and a forward overlap of 30%. The system also utilised an Applanix 510 Position and Orientation System (POS) that uses the GPS and IMU sensors, and a GPS-based computer controlled navigation system.

The POS data were processed using Applanix POSPac software and the LiDAR 3D point cloud generation was completed using DASHMap™ software. Automated LiDAR point cloud classification, digital elevation model (DEM) product generation and orthophoto production was accomplished using the TerraSolid suite of LiDAR processing software.

Quality assurance checks and procedures to ensure the data were fit for purpose included: boresight alignment, checking point densities, use of surveyed base stations to monitoring the performance of the Precise Point Positioning algorithms, flight line swath width and location, manual checking of the point cloud data within an 85 m radius centred over the ground plot to verify the quality of the DEM, file naming and establishment of ISO 19115 compliant metadata. These activities are detailed in Stephens et al. (2008).

2.3. Data collected in field

Plot establishment and ground measurement protocols are described in an operational field manual (Payton et al., 2008). Stand records and measurements recorded between June and September 2008 at each 0.06 ha circular plot included: tree ages; stocking (stems per ha); stem diameters of live and dead trees at breast height (1.4 m); a sample of tree total heights including of live and dead trees; pruned heights; and the dates of pruning and thinning activities. Field plot centres were located using a 12-channel differential GPS. Differential correction was implemented with Trimble Pathfinder Office, utilising base stations located throughout New Zealand. The positional accuracy of the survey was generally within ± 1 m of the theoretical