Estimating above ground biomass from terrestrial laser scanning in Australian Eucalypt Open Forest

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Abstract

Terrestrial laser scanning (TLS) produces 3D data with high detail and accuracy. In this paper we explore the potential of TLS data in combination with a method for reconstruction tree structure to estimate above ground biomass (AGB) in Australian eucalypt forest. Single trees are isolated from the registered TLS point cloud and are used as input for the reconstruction method. We explore the impact of different input parameters on the reconstruction and compare inferred AGB estimates from volume reconstruction and basic density with destructively sampled reference values. Based on a limited number of samples, regression analysis demonstrated R^2 of 0.98 to 0.99, with an intercept of 110 kg for unfiltered TLS point clouds and 19.8 kg for filtered point clouds. These initial results demonstrate the potential of tree reconstruction from TLS for rapid, repeatable and robust AGB estimation.

1. Introduction

Above ground biomass (AGB) is an important indicator for forest productivity, nutrient cycling and calculations of biomass energy, carbon storage and sequestration of forests (Bi *et al.* 2004). Current methods to estimate AGB of native eucalypt forests are generally based on indirect relationships with tree structural parameters (Hamilton *et al.* 2005; Bi *et al.* 2004). This allometric approach can be very effective when applied within the species and productivity range of the calibration data, but may lead to large uncertainties in broad scale biomass mapping. Van Breugel *et al.* (2011) studied the uncertainties of allometric biomass models in secondary forests and their findings suggest that local allometric models provided a more accurate AGB estimate than foreign models. Direct estimates of AGB involve destructive sampling of trees, which is often impractical and expensive and as such can only be conducted on a limited basis.

Terrestrial laser scanning (TLS) allows for measuring forest structure with high detail and accuracy and has the potential to reduce uncertainties in inferring AGB since it gives a direct estimate of tree volume. Here, we infer tree volume directly from tree models reconstructed from the TLS data, and AGB is derived on the basis of basic density information. A comparison of these direct AGB estimates with harvested AGB gives some insight into the potential and accuracy of TLS for rapid biomass assessments at the plot level, and how this may be used in support of broad scale biomass mapping. In this paper, we present proof of concept based on a limited number of trees from two eucalypt species and evaluate the sensitivity of the tree reconstruction method.

2. Methods

2.1 Study area

The national forest area in Australia is the sixth largest in the world and covers approximately 49 million ha (19.4% national cover; FAO, 2010). Five plots with a 40 m radius were established in a native Eucalypt Open Forest in Victoria, Australia. Three of the plots are located in Toombullup State Forest (TOOM) and two in Rushworth forest (RUSH) (Figure 1).

Figure 1: (left) Overview of harvested plots [source: Google Earth]. (right) RGB image of RUSH07 (Rushworth forest).

2.2 Data collection

These five plots were partially harvested in 2012-2013 to acquire accurate estimates of AGB. Detailed measurements of tree structure and fresh weight were collected for each harvested tree. Dry weight to fresh weight conversion factors and basic density (dry weight per unit green volume) for each species were derived from a limited number of samples across a range of diameters. Pre- and post-harvest TLS data have been acquired in these five plots using five scan locations per plot in a systematic sampling design (figure 2). We used the RIEGL VZ-400 scanner, which records multiple return LiDAR data (up to four returns per emitted pulse) as well as additional waveform data. The wavelength of the instrument is 1550 nm and beam divergence is 0.35 mrad. The angular sampling for both zenith and azimuth angle was 0.06°, azimuth range was 0° – 360° and zenith range was 0° - 130°. Reflecting targets were distributed throughout the plot and were used to register the five scan positions using RIEGL's RiSCAN PRO software (http://www.riegl.com/products/software-packages/riscan-pro/). The average standard deviation of the registered point clouds was 0.0137 m with values for individual scans ranging from 0.0051 m to 0.0226 m.

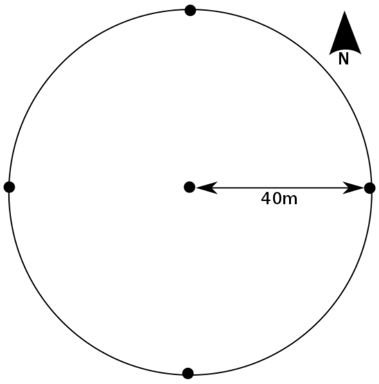


Figure 2: Systematic plot sampling design. Scan locations are indicated with a black dot.

2.3 Estimating single tree AGB from TLS data

Tree volume is directly inferred from tree models reconstructed from the TLS data, and AGB is derived on the basis of basic density information. Inferring tree volume consists of two stages: i) extracting single trees from the registered point cloud; and ii) 3D reconstruction of isolated trees. As a proof of concept, the analysis in this paper is limited to only six trees from Rushworth Forest, evenly distributed between two tree species: *Eucalyptus leucoxylon* (Yellow Gum) and *Eucalyptus microcarpa* (Grey Box). The six trees represent a tree AGB range from 102.2 to 2568.9 kg.

2.3.1 Extracting single trees

The isolation of single trees from the registered point cloud is based on a method described in Burt *et al.* (2013). This method uses the open source Point Cloud Library (Rusu and Cousins 2011) and i) identifies and segmentates the ground plane; ii) isolates individual crowns through a Euclidean cluster extraction; and finally iii) uses a second cluster extraction to remove undesired understorey.

2.3.2 Calculating volume of single trees

The point clouds of individual trees are used as input for the tree reconstruction method developed by Raumonen *et al.* (2013). The output of the reconstruction method is a cylinder model of the tree structure, which allows for straightforward calculations of tree volume. The method is relatively fast and a single tree can be modelled within minutes.

The reconstruction method has two main phases: i) segmentation; and ii) surface reconstruction. The method reconstructs the tree structure via an advancing collection of cover sets (i.e. small local point clouds) and does not need prior assumptions about tree architecture. The reconstruction approach was validated by Disney *et al.* (2012) using detailed 3D tree models, where tree structure is known *a priori*. Results showed that, with some constraints, original length and volume could be reconstructed with a relative error of less than 2%. Burt *et al.* (2013) applied the same approach on TLS data from three different forest types in Queensland, Australia. Based on TLS simulation of the reconstructed tree model, they found that total volume could be recreated to within a 10.8% underestimate. The accuracy to which single scans could be globally registered was identified as the greatest constraint in the method.

The reconstruction method requires the maximum size of the cover sets to be restricted by defining its radius (rcov). The other input parameters are the minimum distance between the centers of the cover sets (dmin) and the minimum number of points in a single cover set for it to be used in the reconstruction (nmin). Optional filtering can be applied before the reconstruction to remove isolated points or noise. Filtering happens in two stages and each stage requires the the radius of the cover sets to be specified. Additionally, a threshold number is specified for each stage. In the first stage, this is the minimum number of points in the cover set to pass the filtering stage and in the second stage, it is the minimum number of cover sets forming a connected component (cluster).

3. Results

First we will explore the impact of cover set radius (rcov), minimum distance between cover sets (dmin) and the minimum number of points in a single cover set (nmin) on the volume reconstruction. Next, we look at the impact of prior filtering on the derived tree volumes. Finally, we will present the inferred AGB estimates and compare these with the reference values from destructive harvesting.

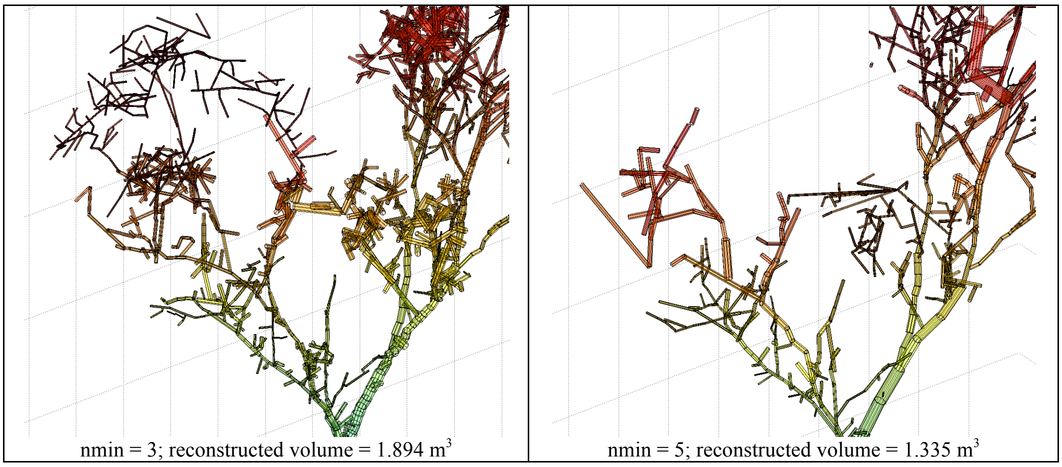
3.1 Impact of the input parameters on the volume reconstruction

Combinations of different input parameters (table 1) are used to make multiple reconstructions of each tree. dmin is generally a little smaller or equal to rcov, with typical values for trees ranging from 1 to 3 cm (Raumonen *et al.* 2013). These parameters should be small enough to reconstruct the details of the surface, but large enough to infer the different characteristics of the tree model.

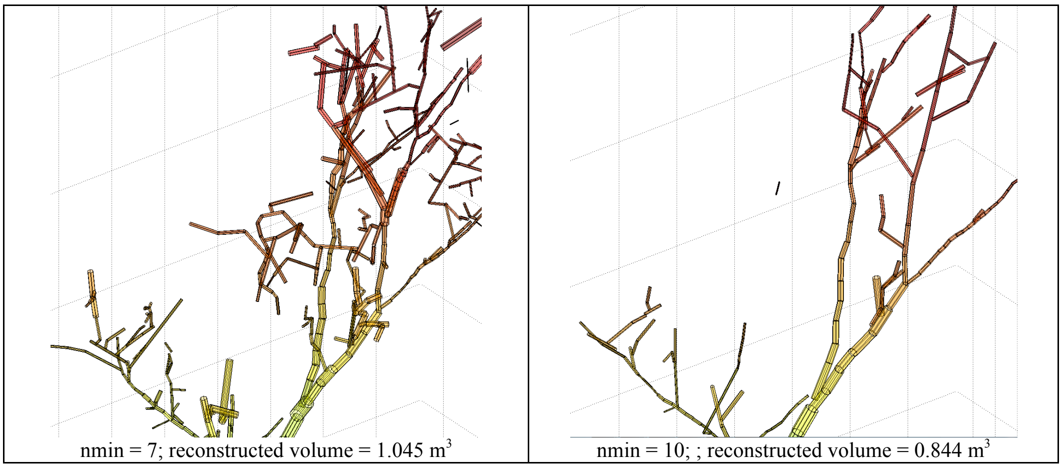
Table 1: Input parameters for the reconstruction method; each of the rcov – dmin combinations was reconstructed with nmin values of 3, 5, 7 and 10.

Input parameter	**Different combinations**				
rcov [m]	0.01	0.02	0.01	0.03	0.015
dmin [m]	0.01	0.02	0.02	0.03	0.03

The impact of nmin on the tree reconstruction is illustrated in Figure 3. Larger values of nmin lead to smaller estimates of tree volume. This is not unsurprising since the value of nmin is a threshold for which cover sets are kept and which ones are discarded in the reconstruction. For this example tree, it can be seen that too many cylinders are modelled in the crown when nmin is too small (3), but too few are modelled when nmin is too large (10).


nmin = 3; reconstructed volume = 1.894 m^3

nmin = 5; reconstructed volume = 1.335 m^3

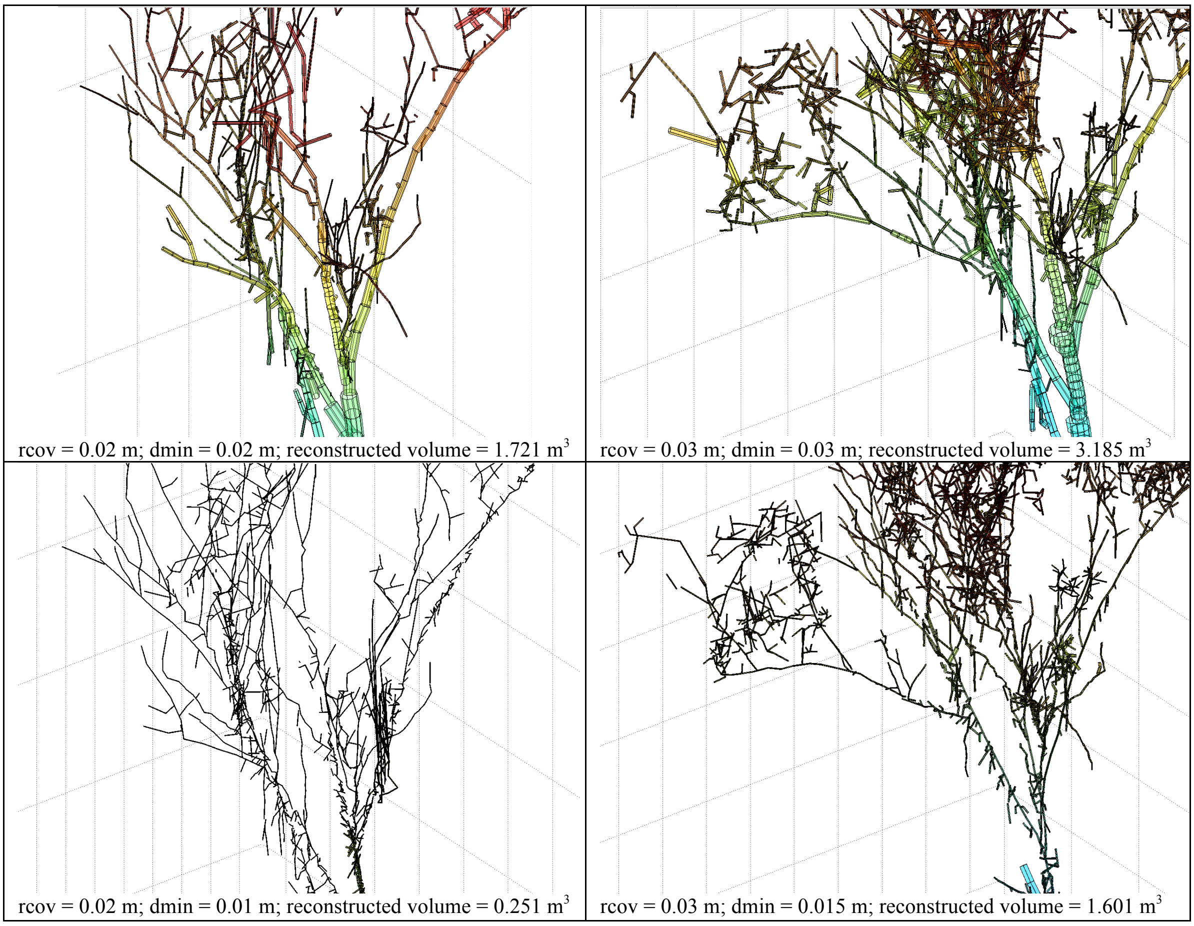


nmin = 7; reconstructed volume = 1.045 m^3

nmin = 10; ; reconstructed volume = 0.844 m^3

Figure 3: Crown view to illustrate the impact of nmin on the tree reconstruction (no filtering). Example of a *Eucalyptus leucoxylon*, rcov and dmin were 0.03. Reference volume for this tree was 1.079 m^3.

Figure 4 illustrates the impact of rcov and dmin on the reconstructed trees. The tree reconstruction with rcov 0.03 m results in the best reconstruction, with an estimated volume of 3.185 m^3, which relates well to the reference value from destructive harvesting (3.283 m^3). Cover sets with radius 0.02 m (nmin = 5) fail to pick up some of the branches in the crown, resulting into an underestimate of the tree volume.



rcov = 0.02 m; dmin = 0.02 m; reconstructed volume = 1.721 m^3

rcov = 0.03 m; dmin = 0.03 m; reconstructed volume = 3.185 m^3

rcov = 0.02 m; dmin = 0.01 m; reconstructed volume = 0.251 m^3

rcov = 0.03 m; dmin = 0.015 m; reconstructed volume = 1.601 m^3

Figure 4: Crown view to illustrate the impact of rcov and dmin on the tree reconstruction (no filtering). Example of a *Eucalyptus microcarpa* with nmin set to 5. Reference volume for this tree was 3.283 m^3.

3.2 AGB calculations via volume reconstruction

For all the possible combinations of input parameters in Table 1, the best performing combination was visually identified by overlaying the tree model with the LiDAR point cloud. Once the optimal parameters (rcov, dmin & nmin) were identified, the reconstruction was run again with prior filtering applied to the point cloud. For the first filtering stage we used a radius of 2 cm with a threshold of 3 and for the second stage a radius of 3 cm with a threshold of 5. Table 2 compares the reference AGB with the inferred AGB from volume reconstruction.

Table 2: Summary of the optimal input parameters per tree, reference AGB (derived from destructive harvesting) and inferred AGB via volume reconstruction.

	rcov [m]	dmin [m]	nmin	Reference AGB [kg]	Inferred AGB (no filtering) [kg]	Inferred AGB (filtering) [kg]
Yellow Gum 1	0.03	0.03	5	2568.9	2726.9	2619.9
Yellow Gum 2	0.03	0.03	5	1906.6	2135.0	1819.7
Yellow Gum 3	0.03	0.03	5	717.6	868.6	635.2
Grey Box 1	0.03	0.03	5	2493.2	2418.9	2031.7
Grey Box 2	0.02	0.02	7	1871.9	1902.9	1793.7
Grey Box 3	0.02	0.02	7	102.2	157.5	150.4

Regression analysis shows a strong relationship between the reference and inferred AGB (Figure 5). Volume reconstruction without prior filtering of the point cloud relates with an R^2 of 0.99 and with prior filtering the R^2 is 0.98. The estimates from the filtered point cloud are consistently lower compared to estimates from the raw LiDAR point cloud. The intercept of the regression from the filtered data is also smaller: 19.8 kg versus 110 kg.

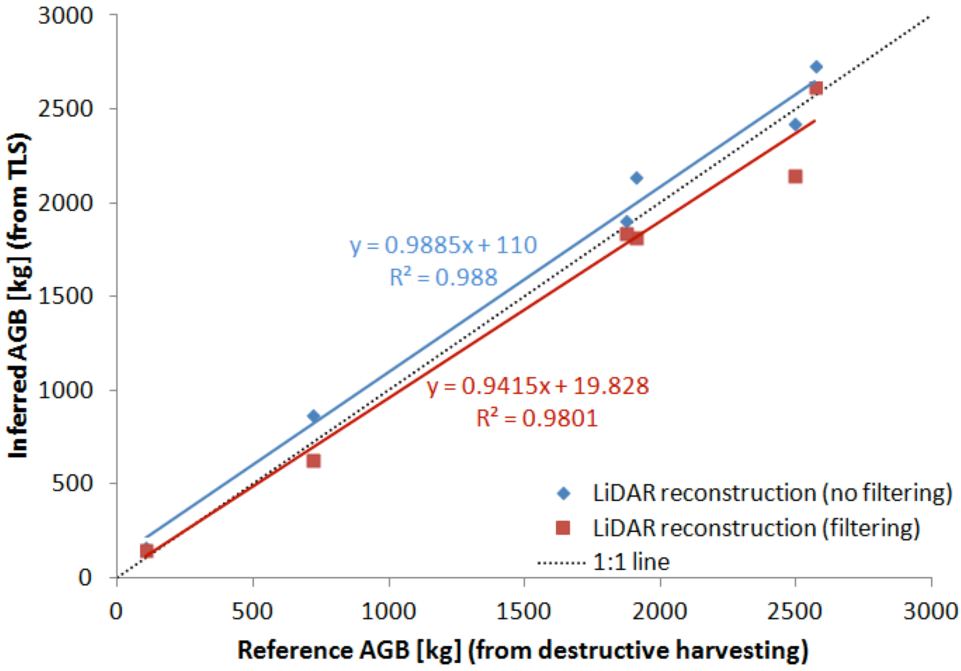


Figure 5: Regression plot of reference AGB vs. inferred AGB (from TLS)

4. Discussion & Conclusions

Varying the input parameters (rcov, dmin and nmin) mainly influenced the reconstruction of the crown constituents (Figure 3 and Figure 4). The stem and main branches are generally well sampled by the LiDAR instrument and are less susceptible for variations in the reconstruction method input. This is important since the main part of tree biomass is located in the stem and the main branches. In this study, we used visual assessment to determine the optimal input parameters. Future work will include a more automated assessment to achieve this. For the six trees in this study, only two different optimal combinations of input parameters were identified (Table 2).

AGB inferred from the filtered point cloud were consistently lower (Figure 5). Filtering removes isolated points in the LiDAR data, so it is not surprising that estimates are lower. Isolated points lead to erroneously modelled cylinders, which increase the AGB estimate.

As a proof of concept, the work in this paper was limited to only six trees (from two species) from Rushworth Forest. Further analysis will include all the harvested trees from the five plots. Approximately 150 trees from multiple eucalypt species were harvested and cover the whole range of single tree AGB for these species. We will also compare the reconstruction approach with indirect estimates of AGB derived from allometric equations that depend on structural parameters such as diameter at breast height (DBH) and tree height. We will use both field inventories and TLS derived parameters as input for these allometric equations. A comparison of these three methods with the harvested AGB will give some insight into the potential and accuracy of TLS for rapid biomass assessments at the plot level, and how this may be used in support of broad scale biomass mapping.

In conclusion, we have used TLS point clouds of single trees to infer AGB via volume reconstruction and basic density. These estimates were compared with destructively sampled AGB and regression analysis demonstrated R^2 of 0.98 to 0.99, with an intercept of 110 kg for unfiltered TLS point clouds and 19.8 kg for filtered point clouds. With a limited number of samples, we have demonstrated the potential of tree reconstruction from TLS for rapid, repeatable and robust AGB estimation.

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