

QUANTIFYING VERTICAL FOREST STAND STRUCTURE USING SMALL FOOTPRINT LIDAR TO ASSESS POTENTIAL STAND DYNAMICS.

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ABSTRACT:

The vertical distribution of plant elements (e.g., foliage and wood) within a forest can yield important information on stand structure, dynamics and growth stage but such information is often difficult to acquire across landscapes using traditional methods of field survey and aerial photograph interpretation. Recent advances in airborne laser scanning (ALS), however, have facilitated rapid assessment of stand height and cover to levels of accuracy considered acceptable for forest inventory and management. A few studies have extended this analysis to the descriptions of growth stage and retrieval of biomass, particularly in complex forest environments. However, current research has raised issues as to how well the vertical profile can be represented and whether the relative amounts of over and understorey can be quantified accurately. Focusing on subtropical open forests and woodlands, in central Queensland, Australia, this paper provides a better insight into how small footprint Light Detection and Ranging (LiDAR) sensor data can be used to create apparent vertical profiles to describe aspects of vertical stand structure (e.g., overstorey/understorey) and also infer broad successional or growth stages. Such profiles were integrated with field measurements within a common reference matrix (based on 1 m cubes), thereby providing spatially explicit tree/crown maps in three dimensions and allowing validation of those generated from LiDAR. Such interpretations, as well as enhancing forest information retrieval, were considered important in the interpretation of other forms of remote sensing data, including radar and optical data. The conceptual basis for this integration method is outlined with an example utilising one field plot, and the role this method might play in quantifying stand dynamics and carbon sequestration is discussed.

1. INTRODUCTION

As a signatory to international agreements that include the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and the Montreal Process, Australia is increasingly obliged to provide spatial and temporal information on ecosystem biomass, structure and community composition. Such information is particularly necessary for regional assessments of biological diversity and forest condition, supporting sustainable utilisation of ecosystems, and calculating greenhouse gas emissions associated with land use change and forestry (Burrows, *et al.*, 2002). In natural forests and woodlands, or those where a diversity of management practices are imposed, traditional point measurements of structure, biomass and species composition are difficult to extrapolate to the landscape because of the inherent complexity of the system. Such variability arises from natural disturbance; different processes of regeneration, and management practices occurring at a range of spatial and temporal scales. The difficulty in quantifying this inherent variability leads, therefore, to uncertainties in local to regional extrapolations of, for example, species diversity and carbon balances. The integration of remote sensing data, acquired by either airborne or spaceborne platforms, however provides a more appropriate mechanism for extrapolation as data of varying spatial and temporal resolution and information content can be combined.

In recent years, the integration of LiDAR with other forms of remote sensing data has attracted attention as the resulting accuracy of structural attributes (e.g., height, crown cover) are considered to be equivalent or greater than those obtained on

the ground. Furthermore, such data provides a unique perspective on the vertical as well as the horizontal distribution of plant elements and hence the structure, dynamics and growth stage of forest stands. Already, results of landscape-wide estimates of forest biomass generated through integration of LiDAR have been used to parameterise models of carbon partitioning (e.g., Hurtt *et al.*, 2004). LiDAR collected within a sampling framework has also been used to assist the calibration and validation of radar wave scattering models, thereby allowing a better understanding of microwave interaction with plant elements, and facilitating inversion of such models for quantitative mapping of forest structure and biomass (Lucas *et al.*, 2004).

Despite these advances, there is still a need to better understand how the LiDAR beam interacts with vegetation structural components and whether key structural attributes can be derived consistently and to acceptable accuracy levels. Such research is essential as studies, (e.g., Lovell *et al.*, 2003) have raised issues as to whether apparent vertical profiles are truly representative of forest structure. Specifically, such data may not be reflecting the actual vertical distribution of foliage as they may not penetrate to the understorey, particularly where canopy cover is dense, and may over-represent the dominance and closure of the overstorey. The return profile is also affected by the openness of tree crowns and canopies (which varies within and between species), differences in leafing and branching structures and also the number of strata within the vertical profile.

1.1 Conceptual basis for a common reference matrix

The broad aim of the study was to reproduce the 3D structure of the forest as required by some radar simulation models (e.g., Sun and Ranson, 1995) for parameterisation in the third dimension. Airborne Synthetic Aperture Radar (AIRSAR) data were acquired over the study area (see section 2.1) at the same time as the LiDAR, and parameterisation of 2D models utilising the concepts outlined in Durden *et al.*, (1989) has already been undertaken (Lucas *et al.*, 2004). The progression to 3D representations of forest structure from LiDAR was the next step, building on the concepts outlined by Sun and Ranson, (1995) and Lexer and Honninger, (2001), as illustrated in Figure 1. Specifically, the study aimed to a) reconstruct the canopy based on voxels (i.e., volumetric pixels) of varying dimension (e.g., 0.5, 1, 2 m³) with the view to ultimately populating these with quantitative estimates of structural or biomass attributes (e.g., foliage density, branch size, leaf angle distributions, moisture contents) and b) derive ground parameters (e.g., slope and surface roughness) from the LiDAR ground returns. Such attributes can then be used subsequently as input to models such as that described by Sun *et al.* (2002), which simulate microwave interaction and attenuation through the canopy. Through this process, a better understanding of microwave interaction with stand elements can be obtained, thereby refining the understanding and interpretation of the SAR response in complex environments. The results presented in this paper illustrate the representations of the canopy at 1 m³ as this resolution was considered optimal with respect to the average lidar return density.

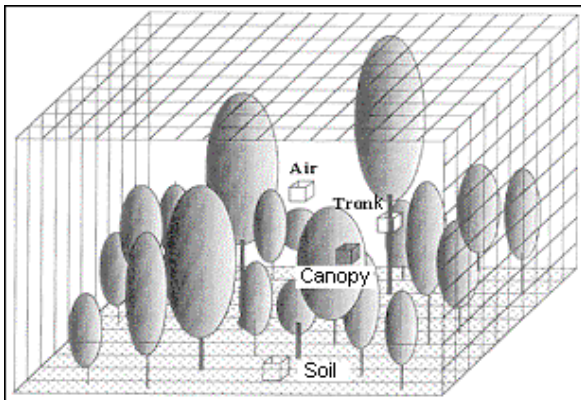


Figure. 1. Conceptual modelling framework for a 3D representation of a forest (after Sun & Ranson, 1995).

This paper presents a subset of the main project aims as outlined previously. Specifically, a conceptual method is presented that validates LiDAR derived apparent vertical profiles by integrating field and LiDAR data within a common reference matrix. This provides a spatially explicit and variable resolution three-dimensional (3D) map of LiDAR returns which can be used to give a better representation of their distribution and the relationship with the actual location of plant elements. Such maps allow better quantitative retrieval of forest structural properties (e.g., foliage, branch and trunk distributions) and hence facilitate the parameterisation of radar and potentially bi-directional reflectance (BRF) models that function in the third dimension. The use of profiles generated from LiDAR data for determining the growth stage of forest stands and hence carbon sequestration potential is described and compared with field

data, in order to investigate if the concepts outlined in Harding *et al.*, (2001) using full waveform large footprint LiDAR could also be undertaken with small footprint LiDAR.

2. METHODS

1.2 Study Area and Data Sources

The study was undertaken over a 220,000 hectare (ha) area containing diverse multi-aged woodlands and open forests located near Injune, central Queensland, Australia. The project design utilised a systematic sampling scheme with 150 Primary Sampling Units (PSUs), arranged on a 4km grid over the 37 x 60km study area. Each PSU was 500 by 150 metres (7.5 ha), where one metre resolution first/last return airborne LiDAR (footprint size 0.09m) was collected. PSUs were subdivided into 30 50 x 50 m Secondary Sampling Units (SSUs) numbered consecutively from 1 to 30. AIRSAR data were acquired across the entire study area. Detailed field surveys were undertaken in 31 square (0.25 ha) ground plots where complete tree maps were generated. These plots were selected using a stratified random field-sampling scheme within 13 selected PSU's, which sampled across broad community and structural types. Core attributes collected included species composition, forest structure, growth stage, biomass, disturbance, and land use. Tree map locations are derived from ± 1 metre GPS recording of plot corners and then a laser rangefinder distance and bearing to tree from the corner coordinate. A more detailed description of the sampling methods can be found in Tickle *et al.*, (2001) and Lucas *et al.* (2004). At the site, the mean annual rainfall is approximately 630 mm per year and the mean annual maximum temperature is 27°C (Bureau of Meteorology, 2004).

1.3 Parameterisation of the common reference matrix

Parameterisation of a common cubic reference matrix can be undertaken for a range of forest types, but this paper provides an example by focusing on a plot in mixed species forest (referred to as SSU 124_19) dominated by white cypress pine (CP-) (*Callitris glaucophylla*), smooth barked apple (SBA) (*Angophora costata*, spp *leiocarpa*), various *Eucalyptus* species, and wattle (*Acacia* species), with a range of growth stages from regrowth to medium height (up to 30m). This forest had established on flat terrain with sandy soils. The plot was contained within an area of State Forest tenure that had been managed for selective native forest timber production (*Callitris*), as well as low intensity beef grazing. The last recorded logging event in the area was 20 years ago, and fire has been actively suppressed for 50-100 years.

To generate the 3D representation from the LiDAR data and to integrate available field measurements in a common reference matrix, the following method was applied. This simulation method follows the general concepts developed for the FOL-PROF programs as described in Walker & Penridge, (1987).

1. A reference matrix was generated with a 1m² fishnet ESRI ArcInfo polygon layer to cover the maximum geographical extent of field and LiDAR data.
2. Database items were added to the layer for each one-metre height interval, up to the tallest height recorded in the plot (either from field or LiDAR data). This created 'virtual' voxels (for this analysis, a voxel is defined as the combination of cell (XY) and a respective height interval database item (Z)) of 1m³ for the plot volume.

3. The LiDAR point layer was intersected with the matrix layer, and both the height above ground and intensity values for each return were recorded in the corresponding voxel in the matrix. Where multiple returns occurred within one voxel, then the maximum height, mean intensity and number of returns were recorded.
4. The field data tree map layer was intersected with the matrix layer. Those cells that contained the tree point became 'trunk' cells, and were coded thus for all height intervals up to the canopy base height in the database.
5. Crown dimensions (diameter in north-south and east-west directions, canopy depth), species and growth stage were extracted from the tree map layer (i.e., field data), and the whole crown was modelled on a 1m³ basis. An elliptical shape was assumed in the horizontal plane, and shape assumptions in the vertical plane were based on species and growth stage. Here three major shapes were used – the cubic expression of an ellipse (generic crown), a pyramid (conifer or young eucalypt), and an inverted pyramid (senescent eucalypt).
6. A canopy openness factor was then applied to crowns larger than 5 metres in diameter. Here, records were removed randomly from the database until the appropriate openness percentage for that particular crown had been achieved. Crown openness was based on published records for selected species in the literature and through hemispherical photograph interpretation.

Apparent vertical foliage profiles of field simulated and LiDAR data were generated by summarising the number of voxels that were coded with canopy elements per one metre height interval, as a proportion of all canopy voxels in the plot volume. This allowed any obvious strata breaks to be quantified and validated against existing vertical foliage profiles for this environment, as shown in Walker, *et al.*, (1986).

3. RESULTS AND DISCUSSION

1.4 Integrating Field Simulation and LiDAR Data

Within the plot matrix there were 2,367 cells with 27 (1m) height levels, resulting in 63,909 virtual voxels (1m³). The results of the simulated field data, as visualised 3D in ESRI's ArcScene software, are shown in Figure 2. Note that for clarity this image shows the simulation without the canopy openness factor applied.

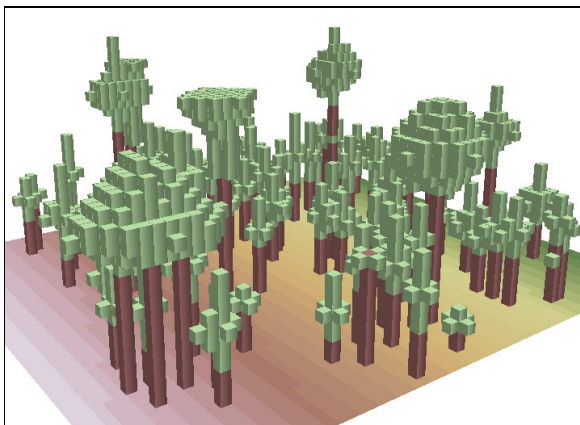


Figure 2. 'Cubic' 3D modelling and visualisation of field tree data from mixed *Callitris* and *Angophora* forests.

Table 1 summarises the direct comparison between field data and LiDAR on a cubic metre basis. Overall there was good correspondence between the two datasets in terms of a two dimensional crown map, with 76% of the field simulated matrix cells also containing LiDAR, although these were not necessarily at the same height above ground. More cells recorded LiDAR returns than field data simulated canopy elements, possibly indicating that there were additional canopy elements not recorded in the field measurements (i.e. small shrub elements). However, more voxels were tagged with field canopy elements than with LiDAR returns, which could indicate that the LiDAR is being occluded from the lower portions of the simulated crowns and trunk voxels. Individual tree comparisons would be required to provide a more conclusive validation.

Attribute	No. Matrix cells	No. Matrix voxels
Field modelled crown elements	557	1,944
LiDAR return elements	981	1,302
Both LiDAR and field elements within the same vertical column (cell)	426	
Both field and LiDAR canopy elements within same voxel		175

Table 1. Summary of matrix results for the field plot area.

Additional mismatch error could result from north-south and east-west dimensions, as measured in the field, not correlating with the longest axis of the crown. The modelled crown may not, therefore, reflect the true shape (or the shape as indicated by LiDAR data), especially with very uneven crowns (as is typical of *Angophora* and *Eucalyptus* species). Preliminary comparisons of crown shapes derived from the LiDAR crown delineations versus the simulated field data ellipses have shown this to be a significant issue. Additionally the field data tree map and LiDAR may not line up correctly due to discrepancies in the field-based measurement of tree trunk relative to crown location and also due to GPS and rangefinder error.

Comparisons between field and LiDAR profiles for SSU 124_19 (Figure 3) show that there was little difference between the two, potentially indicating that, for the less dense woodlands and open forests of Queensland, the LiDAR profiles are providing an adequate representation of overstorey and understorey distributions. This analysis is being undertaken on all 31 field plots in order to verify if this conclusion is supported across a range of forest structures. A number of issues were identified when comparing the two profiles. First, a discrepancy of approximately 2 metres exists between the two estimates of maximum top-height, with LiDAR recording taller tree height which most likely results from the inability to identify correctly and measure accurately the top of the tree in the field. Second, field and LiDAR curves diverge significantly at around 22 metres, which suggest that the field crown shapes in the simulation are not creating sufficient canopy elements to match the LiDAR strikes recorded. Testing an inverted pyramid shape for tall overstorey crowns so that proportionally more canopy elements are found closer to the top heights as opposed to the centre of the crown could resolve this issue. Third, there appears to be a 1 metre offset on average between LiDAR and field profiles, with the LiDAR recording the taller value. This could indicate that field measures are underestimated, especially where the density of stems is high

(~600 stems within the 50 x 50m plot), and the measurement of the correct top height and/or canopy base is more difficult. Conversely, this could indicate that the lidar is only striking the upper portions of crowns, and so over-representing their taller portions, which then results in a curve with an apparent taller canopy.

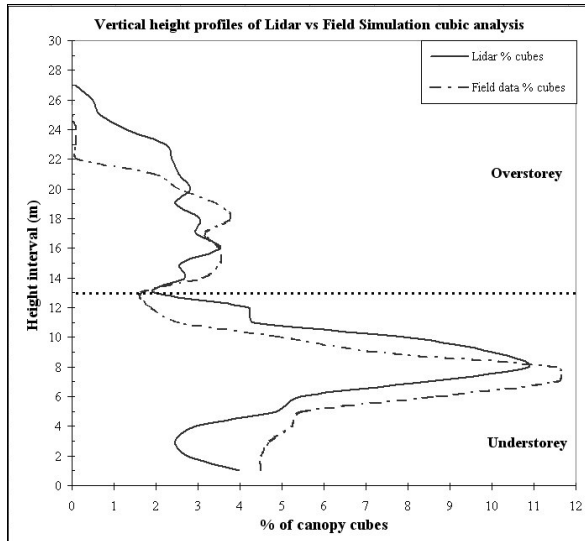


Figure 3. Comparison of apparent vertical profiles generated from the common 3D reference grid, for LiDAR and field simulated data.

Fourth, the difference in lower understorey curves between 2-5 metres could indicate that not many LiDAR returns are penetrating the dense understorey, and therefore the amount of vegetation is potentially under-represented. Conversely, the 1m² size of all field-modelled trunks (regardless of actual size) could be over-representing the amount of vegetation potentially available for the LiDAR to strike. Understorey measurements (i.e., stems 1-5cm diameter at breast height (DBH)) were only sampled in four 5 x 5 metre subplots within the field plot, and scaled up subsequently to the full extent of the plot prior to simulation. Therefore, the presence of a significant understorey component could change the relative distribution of LiDAR percentage cover throughout the vertical profile with respect to field-simulated data. This could introduce some error in very heterogeneous sites, where the samples do not reflect the wider plot. The subplot sampling resulted in a mean stem count of 18 per subplot, with a standard deviation of 9 stems, and a Coefficient of Variation of 50%, indicating that this plot is heterogeneous for stems 1 - 5cm DBH. Checking the simulations against photographs of the plots would also assist in reducing this potential error.

Crown shape has been shown to be important for assessing the interaction between LiDAR and tree crowns (e.g. Nelson, 1997), and this was also identified during the algorithm development phase, where it was observed that crown shape and openness had a significant influence on how field and LiDAR profiles compared. The consistent application of crown shape is being explored through assessment of photographs of field plot trees.

1.5 Assessing Stand Dynamics and Carbon

Figure 4 presents a summary of the field data for SSU 124_19, outlining tree growth stage and species by relative percentage of basal area and stocking per DBH class. Plot growth stage could be interpreted as complex with an overstorey canopy of large crowns reflecting, multiple successional phases (based on Florence, 1996). *Eucalyptus* and *Angophora* species occurred throughout the DBH class and growth stage range, and have a mean tree height of 9.1 m (Standard deviation, SD, of 7.6m, range 2.5 – 24.0 m). Four distinct cohort age groups were evident with these most likely relating to major disturbance and regeneration episodes in the past. However, these species have relative few stems (only 1 - 3 stems per DBH class above 25cm), indicating that they have been on this site for possibly hundreds of years and have self-thinned to a woodland climatic equilibrium. *Acacia* species constitute 67% of all stems, but only 6% of stems greater than 10cm DBH, and have a mean tree height of 1.1m (SD 1.5 m, range 0.5 – 12.3 m). *Callitris* has the majority of stems greater than 10cm DBH (77 %) but they are all less than 20cm DBH and, with a mean tree height of 7.4 m (SD 3.1m, range 2.7 – 14.0 m), and are identified with the developing growth stage. Therefore, they would be relatively recent recruits to the plot, possibly as a result of past logging and fire suppression, given this genus is fire intolerant when young.

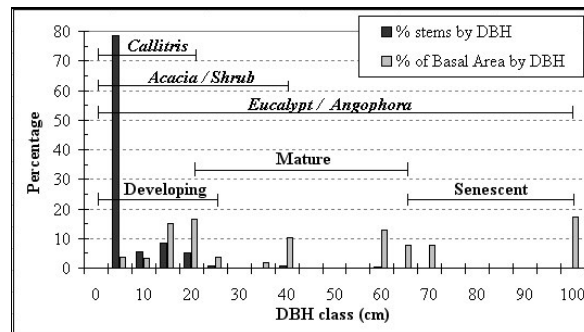


Figure 4. Field data summary illustrating tree growth stage and genus distribution by basal area (total BA = 4.30m²) and stocking (n = 603).

In terms of inferring potential stand growth stage and therefore carbon sequestration potential from the vertical profiles, a number of elements can be related to the field data. A distinct strata break between understorey and overstorey could be inferred at 13 metres, which broadly corresponds to the previously described plot growth stage. There are 13 stems with a top height greater than 13 metres (2 % of all stems), but these stems account for 55 % of the total basal area, so the strata break is reasonable. The dominant understorey proportion visible in the curve would indicate a dense understorey layer that is capturing a significant number of returns (75 % of non ground returns are <14 m). Further lidar analyses indicate this is from many small crowned stems, rather than a few stems with dense and wider crowns, which again reflects the field data. The less dominant overstorey (in terms of cover) is likely to be quite open as evident by the relatively few voxels with canopy elements, compared to the understorey. Also, comparisons between this plot and other field and lidar plots indicate that the tallest trees in this plot are near the maximum height for this environment. Based on this stand structure, carbon sequestration potential is likely to reduce from

the current stock of 143 Mg ha⁻¹, as the few large senescent individuals are anticipated to die eventually and the growth of the other larger DBH cohorts is likely to be slow. There is potential for increased sequestration from the large number of CP-regrowth stems present. However in this environment they can 'lock-up' and remain small for long periods of time (decades) unless disturbance (e.g. fire) leads to thinning of individuals.

4. CONCLUSION

To date LiDAR has mainly been used to produce maps of the two-dimensional height and cover of forests. In this study, we have shown that by distributing LiDAR returns within a voxel matrix, and simulating actual vertical and horizontal foliage distributions, a 3D representation of forest structure can be generated. As each voxel can be populated with information on plant structural elements (e.g., foliage density), these representations can be used as input to models of microwave or radiation interaction with forests, thereby facilitating better interpretation of their radar response or even bi-directional reflectance, as recorded by airborne or spaceborne remote sensing instruments. Voxels (1 m³) within the matrix were found to correspond to simulated crown elements and were summed per one metre height interval, producing vertical foliage profiles similar to those generated with LIDAR for the same forests. The vertical strata identified in the LiDAR profiles appeared to match qualitative assessments of disturbance history and quantitative field measures. However there is a requirement for adequate field and ancillary data to effectively calibrate and validate the analyses. The methods investigated in this paper provide insight into the utilisation of small footprint LIDAR for determining potential stand structural dynamics (e.g., forest structure, biomass, potential growth stage, types of disturbance and succession stage), and further research is underway to improve the consistency of forest attribute estimates across a wider range of structural and environmental types.

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