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Quantifying Australian forest floristics and structure using small footprint LiDAR and large scale aerial photography

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Abstract

Light detection and ranging (LiDAR) data and large scale (1:4000) photography (LSP) were investigated for their potential to quantify the floristics and structure of mixed species forests near Injune, central east Queensland, and to scale these up to the region for purposes of baseline assessment and on-going monitoring. For a 220,000 hectare (ha) area, LiDAR and LSP were acquired over 150 500 m × 150 m (7.5 ha) primary sampling units (PSUs) located on a ~4 km systematic grid. Based on LSP interpretation, 292 species combinations were observed, although forests were dominated or co-dominated primarily by *Callitris glaucophylla*, *Eucalyptus melanaphloia*, *Eucalyptus populnea* and *Angophora Leiocarpa*. Comparisons with species distributions mapped using LSP and in the field suggested a 79% correspondence for dominant species. Robust relationships were observed between LiDAR and field measurements of individual tree ($r^2 = 0.91$, S.E. = 1.34 m, $n = 100$) and stand ($r^2 = 0.84$, S.E. = 2.07 m, $n = 32$) height. LiDAR-derived estimates of plot level foliage/branch projected cover (FBPC), defined by the percentage of returns >2 m, compared well (r^2 of 0.74, S.E. = 8.1%, $n = 29$) with estimates based on field transects. When translated to foliage projected cover (FPC), a close correspondence with field measurements ($r^2 = 0.62$, S.E. = 6.2%, $n = 29$) was observed. Using these relationships, floristics and both height and FPC distributions were estimated for forests contained with the PSU grid and extrapolated to the study area. Comparisons with National Forest Inventory (NFI), National Vegetation Information System (NVIS) and Queensland Herbarium data suggested that sampling using LSP and LiDAR aggregated to the landscape provided similar estimates at the broad level but allowed access to a permanent and more detailed record. Observed differences were attributed to different scales of data acquisition and mapping. The cost of survey was also reduced compared to more traditional methods. The method outlined in the paper has relevance to national forest monitoring initiatives, such as the Continental Forest Monitoring Framework currently being evaluated in Australia.

Keywords: Forests; LiDAR; Aerial photography; Floristics; Structure; Monitoring; Australia

1. Introduction

As a signatory to international agreements, including the United Nations Framework Convention on Climate Change (UNFCCC) and the Montreal Process for sustainable forest management, Australia is increasingly required to provide accurate and quantitative information on the species/community composition (herein referred to as floristics), structure and condition of it's forests through time (MPIG, 2001; Barrett et al., 2001). In addition, such information is required by governments, industry, private landholders and the public to detect trends in commercial, biodiversity and greenhouse values (NFI, 1998, 2003; AGO, 2000; Henry et al., 2002), assess the performance of management practices and public policies, guide sustainable development and forecast the future condition of these ecosystems (NFI, 2003). However, undertaking such assessments within Australia represents a significant challenge for two main

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reasons. First, Australia has an estimated 164 million hectares (ha) of native forests, which are distributed largely around the outer margins of the continent. Second, around 70% of these forests are under private management and less than 10% are in commercial public forest estates (NFI, 2003). In the areas under private management, the information available on structure and condition is especially limited (MPIG, 2001). The development of efficient and cost-effective methods for retrieving this essential information is therefore critical if international obligations are to be better fulfilled and the sustainable development and conservation of forest resources optimised.

The overall objective of this research, therefore, was to evaluate whether large scale (1:4000) stereo aerial photography (herein referred to as LSP) and/or small footprint light detection and ranging (LiDAR) data could be used as tools, either singularly or in combination, for routinely sampling, describing and quantitatively assessing the floristics and structure of these forests. Focusing on areas of agricultural land and mixed species forests in central Queensland, which were considered typical of those occurring across large areas of Australia, the study aimed specifically to evaluate whether: (a) floristics could be described through air photograph interpretation (API) of LSP, (b) measures of structure (e.g., height and canopy cover) could be estimated from LiDAR data, (c) the resulting quantitative estimates of each could be extrapolated to the landscape with levels of reliability comparable to or better than those currently available and (d) data from these sensors combined offered a viable and cost-effective alternative or supplement to methods used currently for on-going regional assessment and monitoring of forests.

2. Background

Although LSP has been used as a basic forest inventory tool for some time (e.g., Spencer, 1992), the integration of LSP and LiDAR data has only been possible in the past few years due to advances in sensor design and data acquisition and processing. The following sections therefore provide a brief overview of these two systems and their use in Australia.

2.1. Airborne scanning LIDAR

LiDAR is an active remote sensing technique that directs a near infrared (NIR) laser pulse downwards towards the Earth's surface (Lefsky et al., 2002). This pulse reflects from objects (e.g., tree canopies, buildings and the ground), and is then received by the sensor. The time-delay between pulse transmission and receipt is related directly to distance and hence height, density and areal proportions of objects can be retrieved. The intensity of the return (which has no units) provides information on the pseudo NIR reflectance characteristics of the objects (Wehr and Lohr, 1999; Suárez et al., 2005).

Airborne scanning LiDAR is currently experiencing rapid commercial growth, with small footprint LiDAR being used increasingly for terrain mapping, powerline surveys and vegetation classification (Dowling and Accad, 2003). The number of commercial companies operating LiDAR has increased substantially in recent years, as has the sophistication of instruments. In a period of only 5 years, the industry standard has advanced from systems emitting 5000 pulses per second and measuring a single return to those emitting between 25,000 and 75,000 pulses per second, and measuring up to five returns, with some recording the intensity of each return (Moffiet et al., 2005). In most systems, the laser beam is emitted through a rotating mirror, which creates a zigzag swath of laser returns either side of the aircraft.

Depending upon flying height, the footprint size may vary from 0.1 to 5.0 m and the interval between laser returns may range from 0.25 to 5 m. With the aid of real-time global positioning systems (GPS) and sophisticated inertial navigation systems (INS) that compensate for aircraft pitch, yaw and roll, most LiDAR are now capable of achieving absolute spatial accuracies of $<\pm 1$ m in the x and y directions and <0.25 m in the z direction (i.e., elevation). For forest assessment purposes, such accuracies now makes it possible to "image" individual tree crowns, and to locate the same trees on the ground using, for example, hand-held GPS.

Over the last 15 years, the use of small footprint airborne LiDAR for retrieving ground surface and vegetation parameters have been demonstrated (as examples, see Nelson et al., 1984, 1988; Aldred and Bonner, 1985; Nilsson, 1994; Naesset, 1997; Magnussen and Boudewyn, 1998; Means et al., 1999; Weller et al., 2001; Lovell et al., 2003; Riaño et al., 2004). This work has now matured to the state where direct estimates of structural variables (e.g., tree heights and canopy cover) routinely achieve r^2 values approaching or exceeding 0.90 (e.g., Suárez et al., 2005). Hyyppa et al. (2001) demonstrated that LiDAR could provide more precise stand-based estimates than conventional field-based inventory.

2.2. Large scale photography

LSP has long been recognised as a valuable tool for forest inventory, improving the efficiency of ground sampling through improved stratification and plot selection and bridging the gap between ground measurements and other forms of remotely sensed data using multi-phase and multi-stage techniques (Spencer and Hall, 1988). Although LSP has been operational for many years (Spencer and Hall, 1988; Spencer, 1992; Nielson, 1997; Pitt et al., 1997; Spencer and Czaplewski, 1997), its application in Australia has been limited, with the notable exception of a comprehensive inventory of two million hectares of forest in western Australia (Spencer, 1992). This inventory demonstrated that large area inventories could be undertaken at one-tenth of the cost of traditional ground surveys. The reasons for the lack of adoption include the perceived high cost of data capture, film processing, labour cost (for parallax-based measurement of stand variables), establishment of ground control and the requirement of specialised medium format camera systems (often mounted on helicopters). However, with the advent of image motion compensation, specialised aerial films, INS and real-time differential GPS, LSP can now be captured from fixed-wing aircraft (using large format aerial cameras) by the mainstream aerial survey and photogrammetry industry.

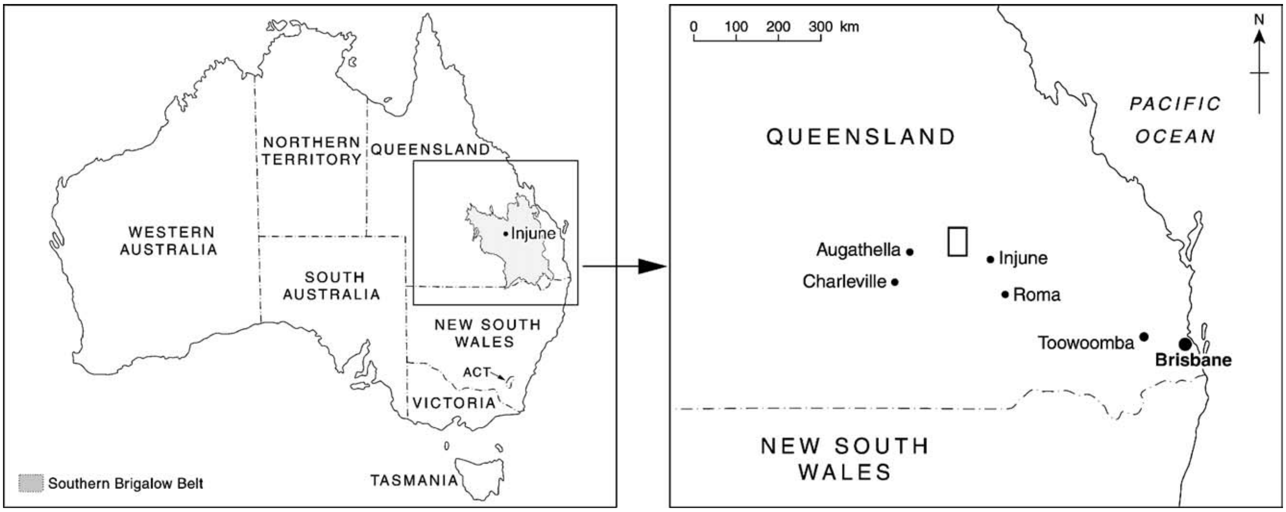

Fig. 1. The location of the 37 km × 60 km study area, central east Queensland.

3. Study area

To evaluate the use of both LSP and LiDAR for quantifying the floristics and structure of forests, an area of 37 km × 60 km (222,000 ha) of private and public land near Injune, central Queensland (Lat 25°32′S, Long 147°32′E), was selected (Fig. 1). The study area was chosen, as the forests are typical to those of much of Australia[1] in terms of floristics and structure. Furthermore, a wide range of regeneration and degradation stages exist, due primarily to past and present agricultural and forestry management practices, creating forest communities that are structurally diverse (Lucas et al., 2004, 2006). The forests near Injune have also been the focus of extensive clearance, particularly in the late 1990s and the early 2000s, and have contributed to the significant losses of carbon associated with vegetation clearance in Australia (Barrett et al., 2001; Burrows et al., 2002; Henry et al., 2002).

The study area was located within the Southern Brigalow Belt (SBB) biogeographic region, and contained a diverse range of forest communities (Queensland Department of Natural Resources (QDNR, 2000)). Based on 1:250,000 broad vegetation mapping (Monteal Process Implementation Group (MPIG, 2001)) and 1:100,000 scale land cover mapping from aerial photography and Landsat TM, the forest communities were dominated by White Cypress Pine (*Callitris glaucophylla*, herein referred to as CP-), Poplar Box (*Eucalyptus populnea*, PBX), Silver Leaved Ironbark (*E. melanophloia*, SLI), Smooth Barked Apple (*Angophora leiocarpa*, SBA) and/or Brigalow (*Acacia harpophylla*, BGL). Common understorey genera included Sandalwood Box (*Eremophila mitchellii,* SWB) and Wilga (*Geijera parviflora,* WIL). In the north of the area, the terrain was hilly and dissected by small gorges in places, and ranged from 400 to 1000 m above sea level (ASL). In the centre and south, undulating hills, plateaux and plains at approximately 200–400 m ASL occurred. The mean annual rainfall was approximately 630 mm year^{-1} and the mean annual maximum temperature was 27 °C (Bureau of Meteorology, 2004).

4. Image and field data collection

The acquisition of image and field data was undertaken in four main stages (Table 1). In stage I, a systematic sampling scheme (Schreuder et al., 1993) was implemented to guide the acquisition of LSP (stage II) and LiDAR data (stage III). Following collection and initial interpretation of these data, forest inventory data were collected from selected areas (stage IV). The majority of the fieldwork was carried out during the period of LiDAR data acquisition and within 1-month of the LSP data acquisition, thereby minimising any seasonal effects and the likely impacts of anthropogenic land cover change at the field sites. The following sections describe these four stages.

4.1. Stage I: sample design

The sampling framework for the collection of the LiDAR and LSP data was implemented to allow comparison with estimates generated using wall-to-wall mapping undertaken as part of other studies (QDNR, 2000) and also to provide operational experience in the implementation of sampling frameworks that may be adopted in future regional and national inventory programs (e.g., the National Forest Inventory (NFI)). A systematic sampling scheme was selected, as knowledge of the floristics and structure of the forests was too limited to allow application of efficient stratified sampling methods. The state of the forests had also changed rapidly over recent years, largely because of extensive clearance of vegetation within the area, thereby preventing the use of historical spatial layers for stratification.

[1] Within Australia, forest is defined as all woody vegetation with a top height equal or greater than 2 m above the ground and a crown cover ≥20%. Woodlands are defined as supporting 20–50% crown cover (equivalent to 10–30% FPC), and open forests as 51–80% crown cover (equivalent to 30–70% FPC; NFI, 1998). Woodland formations such as those found in the study area are representative of over 70% of Australia's forests (Montreal Process Implementation Group (MPIG, 2001)).

Table 1
Main stages in the acquisition, processing and analysis of field and remote sensing data

Stage	Task	Purpose
Sampling and data acquisition		
I	Sample design	To select appropriate field sample locations
II	LSP capture and pre-stratification	To allow description of the species/community composition
III	LiDAR capture	To facilitate retrieval of structural attributes (height, crown, foliage and/or branch cover)
IV	Field sampling	To provide ground truth for interpretation of LSP and LiDAR and validation of products
Post-processing		
V	Georeferencing of LSP to LiDAR	To allow overlay of API vector information
VI	Generation of LiDAR height surfaces	Calculation of a bare earth DEM and vegetation height
Data analysis		
VII	Classification of forest communities based on LSP interpretation	To determine spatial distributions of dominant, co-dominant and sub-dominant species
VIII	Tree height, FBPC, FPC and canopy cover retrieval from LiDAR	To provide individual tree and stand level estimates

Based on these considerations, the systematic sampling scheme for the 37 km × 60 km study area allowed the acquisition of LSP pairs across a grid containing 150 (10 columns and 15 rows) points located 3.7 km × 4 km apart in the east–west and north–south directions, respectively (Fig. 2). The acquisition of LSP was planned such that the 800 m × 800 m (64 ha) area (herein referred to as a primary photo plot or PPP) was centred on each of the 150 grid points. For each PPP and within the 60% stereo overlap area of the LSP, a 500 m × 150 m (7.5 ha) primary sampling unit (PSU) was established. Each of the 150 PSUs was then subdivided into 30 systematically numbered secondary sampling units (SSU) which were 50 m × 50 m (0.25 ha) in area. Using this scheme, data could be analysed and summarised for each of the 150 PPPs and PSUs (4500 SSUs) that represented 5.3% (3.9% for only the stereo area) and 0.5% of the 222,000 ha study area, respectively.

4.2. Stage II: LSP capture

For each of the 150 PPPs, and using pre-defined coordinates, 1:4000 stereo colour aerial photographs (in negative format) were acquired on the 11th July 2000 by QASCO Surveys Pty. Ltd. on behalf of the Queensland Department of Natural Resources and Mines (QDNR&M) Landcare Centre. Photographs were taken using an RC20 large format photographic camera from late morning to mid afternoon. The effective swath width was 920 m and, for each photo principle point, GPS coordinates were recorded to within a nominal precision of ±20 m absolute location. As 150 PSUs were sampled, 300 frames of photographs were obtained.

4.3. Stage III: LiDAR data capture

Airborne scanning LiDAR data were captured over a 1-week period commencing August 24th 2000 using an Optech 1020

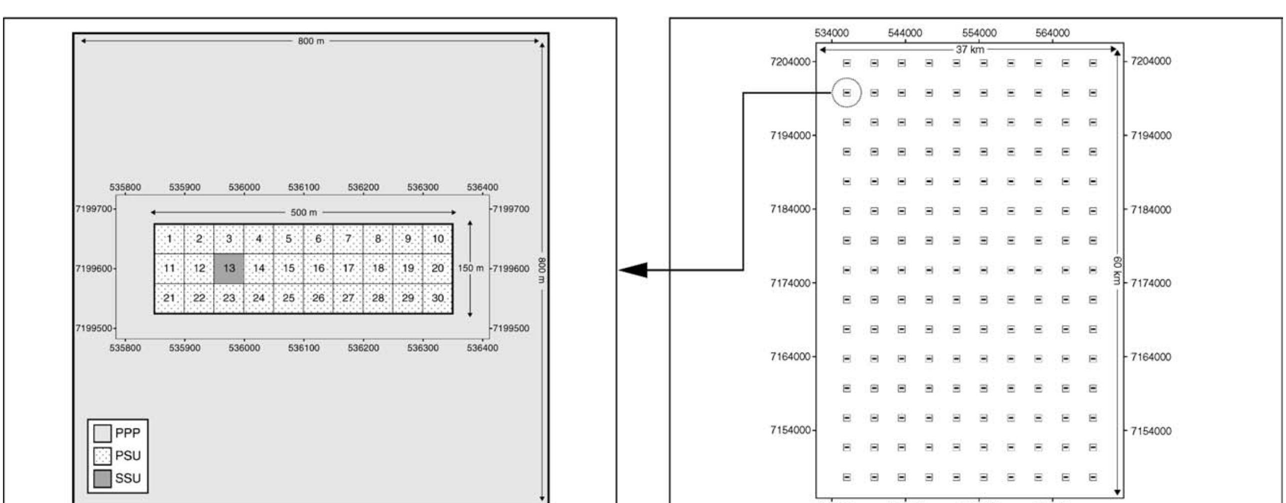

Fig. 2. Layout of the PPP, PSU and SSU grid.

scanning LiDAR mounted in a Bell Jet Ranger helicopter. The Optech 1020 measured 5000 first and last returns and the intensity of each return per second. The LiDAR operated within the NIR spectrum with a beam divergence of 0.3 mrad, a footprint of approximately 7.5 cm and an average sampling interval of <1 m. Data were acquired flying in an east–west direction (and centred on each PSU row), at a nominal altitude of 250 m and a swath width of approximately 200 m. A GPS base station was established for all flights. With full differential GPS corrections, in addition to pitch, yaw and roll compensation from an INS, coordinates were guaranteed to an absolute accuracy of <1 m in the *x* and *y* directions and <0.15 m in the *z* direction.

4.4. Stage IV: field sampling

Field inventory data were collected during August 2000. The collection of field data over the same period as the remote sensing data acquisition was considered necessary to limit the impact of changes in seasonal foliage cover or land cover (associated with disturbance by fire or clearing) on the subsequent development of relationships with remotely sensed data.

Prior to acquisition of the field data, a 100 m × 100 m dot grid was overlain onto the overlap area of each of the 150 hardcopy LSP stereo pairs and used to estimate the proportions of land use, land cover and forest types as well as forest height and cover, disturbance regimes and vehicular access (Jones, 2000). The LSP code allocations were then used to stratify and identify suitable locations for field sampling on the assumption that the vegetation types contained within the 150 PSUs were representative of the proportions across the entire study area. For the purposes of stratification, and based on the vegetation assessment, the API codes were classified into four woodland types: Acacia or sparse vegetation (containing species such as BGL, SWB, *Casuarina cristata*, *Allocasuarina luehmanni*); Callitris (e.g., CP-, *C. preissii*); Eucalypt Ironbark (e.g., SLI, *E. decorticans*, *E. fibrosa* spp. *Fibrosa* and *E. crebra*) and Eucalypt other/Angophora (e.g., PBX, *E. dealbata*, SBA and *Angophora floribunda*). The Eucalypt class was split as the various Ironbark species were seen to contribute a significant proportion of the mapped landscape. Each forest type was then ranked into three (low, medium and high) potential and relative structure/biomass classes, based on structural information obtained from API (Jones, 2000) and a biomass map generated previously using Japanese Earth Resources Satellite (JERS-1) Synthetic Aperture Radar (SAR) data (Lucas et al., 2000), thereby producing 12 vegetation strata. The number of field plots sampled (N_s) was then allocated based on the area of each of the 12 strata (A_S) as a proportion of the total area occupied by the PSUs (where $A_t = 1125$ ha) such that:

$$N_s = \frac{nA_s}{A_t} \tag{1}$$

where *n* represented the number of SSUs available for sampling based on criteria relating to road access, travel times and safety issues. Each of the PSUs (and their contained SSUs) was necessarily scored according to whether road and subsequent foot access was possible, as determined primarily from the LSP interpretation. Landsat-7 Enhanced Thematic Mapper (ETM+) data were also used to identify roads outside of the LSP, thereby assisting assessment of the quality of road access. Knowing that travel times and safety issues would restrict field inventory to 2–4 SSUs per day using 2 field crews of 5 staff, 13 PSUs were selected that contained the necessary strata and met access criteria. Within these, 34 SSUs were sampled across the 12 strata (in proportion to their area within the 150 PSUs). Within each of the 13 PSUs where field measurement took place, SSUs used for field data collection were selected at random from the 390 possible SSUs and according to API-defined classes prior to arriving at the site. Plot coordinates were also calculated and entered into a GPS navigation system to ease location in the field. The final plot allocations per strata are shown in Table 2.

Once located, a 50 m × 50 m square plot, aligned in a north–south direction, was established using GPS survey and laser range finding equipment. Tapes of 50 m length were then laid out to produce a 10 m × 10 m grid to guide the subsequent location of trees for measurement. For three additional SSU's identified as non-forest but containing regenerating vegetation, species and structural measures were conducted in five 10 m × 10 m plots contained within the selected SSU. Within each plot, the location of all trees >10 cm in diameter (at 130 cm above ground level) was recorded digitally by placing reflectors at each of the plot corners and then using either a GEOSCAN or CENTURION Laser Rangefinder to record the distance and angle from each tree to the nearest visible reflector. Using this approach, the Universal Transverse Mercator (UTM) coordinates of all trees were calculated. Trees 5–10 cm in diameter were located by reading the *x* and *y* distances (in cm) from 50 m tapes placed perpendicularly (at 10 m intervals) across the entire plot. The cover and height of trees and shrubs <5 cm in diameter was estimated within five 10 m × 10 m subplots, with the centres of four located at a distance of 10 m from each of the corners and a fifth located at the centre of the plot. Within each plot, each tree was identified to species level and key measurements recorded included trunk diameter (cm, at both 30 and 130 cm) and height (m) to the top of the tree. Transects were established within the field plot to estimate vegetation cover and consisted of three 50 m tapes laid out in the north–south direction at 10, 25 and 40 m, moving eastward from the south–west corner. Along each transect the presence or absence of canopy material was recorded at 1 m intervals. The

Table 2
Allocation of sampled SSUs to each of 12 strata described by floristics and biomass, giving a total of 34

	Above ground biomass (mg ha^{-1})		
	Low (<50; *n* = 10)	Medium (50–100; *n* = 10)	High (>150; *n* = 14)
Acacia (1)	1	0	0
Callitris (12)	2	3	7
Ironbark (12)	3	3	6
Eucalypt other (9)	4	4	1

recording method, after Specht (1970), uses a plastic tube which is attached to a 2 m length rod and contains an internal cross-hair. A mirror situated at the base of the tube at an angle of 45° then enables the operator to record the presence or absence of green leaves or wood (trunk or branches) in the canopy vertically above. Foliage/branch projected cover (FBPC) and foliage projected cover (FPC) is then calculated as the sum of foliage and/or branch records as a proportion of the total. For the purposes of this study, FBPC relates to the amount of light that would reach the ground, and is the percentage of the plot area occupied by the vertical projection of foliage and branches, while FPC only considers light interception by green foliage (McDonald et al., 1998).

5. Post-processing of field and remote sensing

Following collection, the inventory data were analysed primarily to determine the species composition of the forests, so that the API could be better evaluated, and to generate tree and stand level estimates of height and cover that could be regressed against LiDAR data. For this purpose, further stages of LSP (stage V) and LiDAR data (stage VI) processing were necessary (Table 1).

5.1. Stage V: georeferencing of LSP to LiDAR

Following hard copy production of the LSP, photo prints were scanned at 600 dpi. Initial rectification was undertaken using the known locations of the principle points and camera parameters. Comparisons with the LiDAR data confirmed that the photo products were generally accurate to ±20 m without additional registration. The spatial accuracy of the LSP was refined further by collecting ground control points (GCPs) from the LiDAR data. This generally resulted in root mean square (rms) errors of <±2 m within the LiDAR strips, enabling the LSP to be georeferenced with the LiDAR data. Following registration of the LSP, floristic and structural mapping interpreted from the photographs (Jones, 2000; Fig. 3) was also scanned, vectorised and rectified using the same transformation as the digital imagery, to allow GIS overlays over the LiDAR data (3).

5.2. Stage VI: generation of LiDAR height surfaces

Each LiDAR strip was subset to encompass only the areas corresponding to the PSUs. A bare-earth Digital Elevation Model (DEM) was then generated for each PSU using both the first and last return pre-classified ''ground'' LiDAR data, such that all measurements of vegetation height were based upon a reliable ground reference. Both first and last returns were used as in some cases (e.g., bare ground), only one return (i.e., first) was recorded. The DEM was generated for each LiDAR strip by creating a triangular irregular network (TIN) based on a 1 m proximal tolerance. The resultant TIN was then checked visually to confirm correct classification of ground returns and then transformed into a 1 m grid using quintic interpolation methods such that irregularities in the surface, resulting from the high density of first and last returns used, could be smoothed out. The final DEM was checked visually against the LSP to ensure all vegetation was removed and potential mis-registration between LiDAR and LSP was accounted for. Given that ground surface features <20 cm high were easily

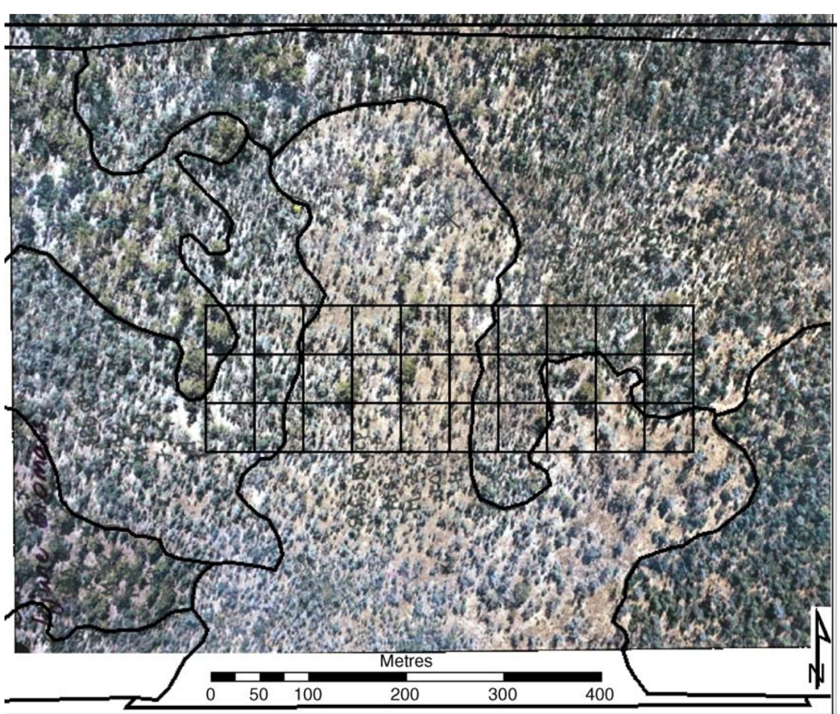

Fig. 3. True colour 1:4000 stereo aerial photograph of PSU 138 overlain with the 500 m × 150 m PSU boundary, contained SSUs (50 m × 50 m) and polygon vectors associated with different forest communities (based on species composition and cover), as mapped through aerial photography interpretation (API).

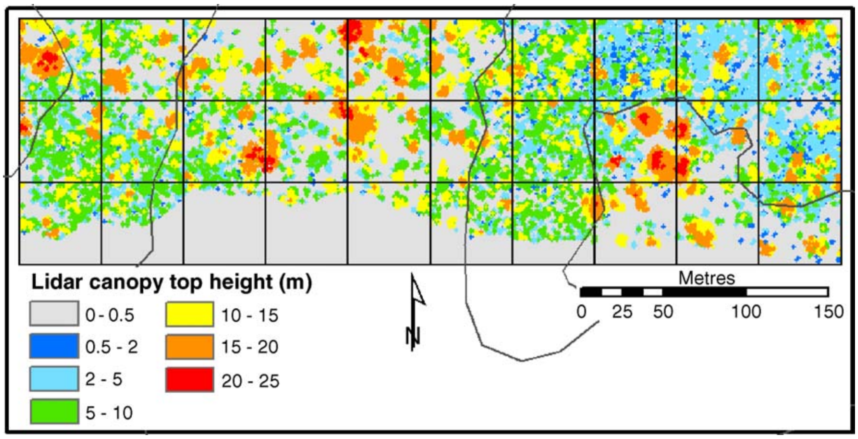

Fig. 4. LiDAR data representing tree crown heights acquired over PSU 138 and rasterised to a 1 m spatial resolution grid.

discernable, the relative elevation accuracy of the final DEM was considered to be <1 m. The height above ground of each LiDAR vegetation return was then calculated as the elevation difference between the ground DEM and the vegetation return. Canopy surfaces were interpolated using a TIN from all vegetation returns, and this was converted subsequently to a 1 m^2 grid (Fig. 4) for further analysis.

6. Data analysis

To provide summary information on the forests, their floristic composition was described using LSP (stage VII) whilst estimates of tree and stand height and cover were retrieved from LiDAR data (stage VIII).

6.1. Stage VII: classification of forest communities

Based on API, polygons interpreted from the LSP were allocated between one and three dominant tree species which, herein, are referred to as D1–D3. However, it should be recognised that D2 and D3 could be co-dominant or sub-dominant (e.g., common in the understorey). This resulted in 292 unique combinations of species code sequences (e.g., CP-SLI or PBXSLISWB) throughout the study area. For reporting clarity, these 292 species combinations were aggregated into five broad genus groups based on the dominant species: Acacia, Callitris, Eucalypt Ironbark, Eucalypt other and Angophora. Areas of non-forest were also distinguished. Angophora was identified as a separate class as the distribution of this species is poorly documented in regional datasets, particularly as these species are often mixed with other genera.

6.2. Stage VIII: tree height and cover retrieval

More than 2300 individual trees with diameters >10 cm (at 130 cm) were measured for diameter and height in the field. From this pool, the heights of ~100 clearly identifiable trees were extracted from the LiDAR data. Adjustments were required in some cases, as the centres of many tree crowns (particularly *Eucalyptus* species) did not correspond to the locations of the trunks. Field and LiDAR measurements of height were then compared. At the plot level, relationships were also established between field-based estimates of FBPC and FPC, which represented the percentage of the SSU occupied by the vertical projection of foliage and branches (Carnahan, 1990) and foliage (excluding branches), respectively. Both FBPC and FPC were compared against the number (for each SSU) of (a) actual vegetation LiDAR returns with a height >2 m above ground level and (b) interpolated vegetation cells (based on a 1 m^2 pixel grid) as a proportion of all cells to determine whether stand level estimates of both cover attributes could be retrieved. Crown cover (CC) was also estimated through interpretation of the LSP, and considered the area occupied by the whole crowns (which are considered opaque), with respect to the polygon area.

7. Results: tree and stand level estimates

Based on the analysis outlined above, the use of both LSP and LIDAR for tree and stand level assessment, in terms of floristics, tree height and canopy cover was evaluated.

7.1. Species/community composition from LSP

The discrimination of species from LSP required skills in API with knowledge of the appearance (in terms of colour and texture) of different species. Although individual trees were not mapped or identified by the interpreter, and so a tree-by-tree comparison was not possible, a close correspondence (24/34 = 70.5%) between the dominant species within the field plot SSUs and that assigned by the API was observed (Table 3). Forests dominated by *Callitris* species were identified in all cases. SSUs identified through API as non-forest typically contained remnant trees and regrowth stands of BGL but also non-forest, and hence the API classification was deemed correct in this case, increasing the overall correspondence to 79%. API identified 40 and 17.6% of D2 and D3 genera correctly. However, all SSUs inventoried in the field contained the same species identified as D1–D3 through API. Therefore, although the exact order of dominance differed, the species

Table 3
Count of field plots classified through API vs. tree basal area estimates, for D1–D3 species

API	Based on field (basal area) data					
	Non-forest	Acacia	Angophora	Callitris	Eucalypt other	Eucalypt Ironbark
D1 = dominant						
Non-forest		3				
Acacia		1				
Angophora			3			
Callitris			2	9	1	
Eucalypt other			1		7	1
Eucalypt Ironbark					2	4
Total						34
D2 = co-dominant						
Non-forest						
Acacia		2		4	2	
Angophora			2		1	
Callitris				3	2	
Eucalypt other		4		1	2	3
Eucalypt Ironbark			1			3
Total						30
D3 = co- or sub-dominant						
Non-forest						
Acacia				2		
Angophora		1			1	1
Callitris				1		2
Eucalypt other		2		1	3	
Eucalypt Ironbark		1		1	1	
Total						17

composition was correctly identified in the majority of cases. Such a strong correspondence gave confidence in the subsequent classification of dominant species and communities within each of the 4500 SSUs.

7.2. Tree and stand height estimates from LiDAR

A close correspondence ($r^2 = 0.91$, S.E. = 1.34 m, $n = 100$) between tree heights derived from both field measurements and LiDAR data was observed (Fig. 5a). The comparison suggested, however, that the height was more reliably estimated for trees with more hemispherical crowns (e.g., Eucalypt and Angophora species) compared to those that were more pointed (i.e., *Callitris* species). The estimates of height, both from the field and LiDAR measurements, were within largely ±1 m of each other, although discrepancies as high as 4 m were observed, which suggested some over-estimation by field measurement or under-estimation from LiDAR. The height estimates provided by the LiDAR were, however, considered to be more reliable for several reasons. First, height measurements were obtained from a greater area of the canopy and therefore the highest point of the canopy could be located objectively. This is particularly significant as the interpretation of the highest point of the tree from the ground varies with the observer and can lead to errors of the order observed between LiDAR and field measurements. Second, the field-based height measurements were often considered to contain errors as the highest point of the tree was not always visible. Even so, a disadvantage of the LiDAR was that the wind effects on the crown might lead to minor errors. For the stand, a close correspondence between the maximum ($r^2 = 0.84$, S.E. = 2.07 m, $n = 32$) height (excluding non-forest) estimated from the field and LiDAR data was observed (Fig. 5b).

7.3. Foliage cover estimates from LSP and LiDAR

From LSP, CC was interpreted and also categorised into four forest cover classes: 10–30, 30–50, 50–70 and 70–100%, and a non-forest class (<10%). All classes were observed, but the majority of cover was from 30 to 70%, which equates to open forests under the Carnahan (1990) classification (Specht and Specht, 1999). A close relationship between field-based measurements of FBPC and FPC was observed (Fig. 5c) which indicated that, on average, FPC was 67.7% (range 50–92%) of FBPC. In general, the percentage of leaf material was lower within forests with a greater proportion of Angophoras and Eucalypt other and was greater within those containing Callitris, Ironbarks and Acacia.

On average, there were approximately 5000 LiDAR point measurements in total per 0.25 ha field plot, with an average of 1700 vegetation returns from objects greater than 0.5 m in height. In comparison, there were only up to 150 canopy measurements from the three 50 m transects per SSU. Exploratory data analysis was undertaken to identify which field measures were most closely explained by the LiDAR vegetation returns. In this analysis, 29 of the 34 field plots were

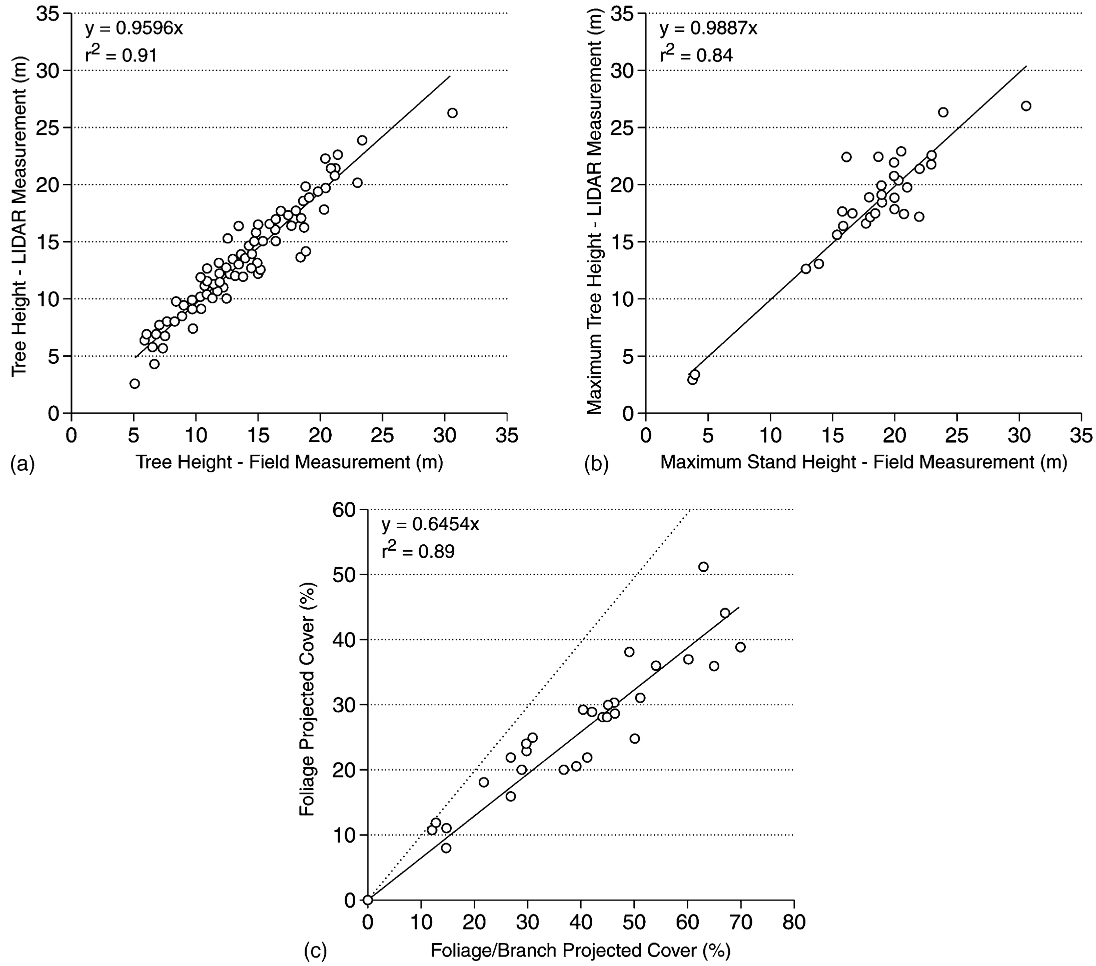

Fig. 5. Relationships between (a) individual tree height and (b) maximum stand height (based on SSUs), as estimated in the field and from LiDAR, and (c) field-based assessments of FBPC and FPC (with 1:1 line in grey).

compared, as field measurements were not obtained for plot 142_02, and plot 138_28 was missing significant LiDAR data as a result of errors in data acquisition caused primarily by adverse wind conditions. Three plots were located in sparsely vegetated short regrowth areas and were not therefore included. For those plots with partial loss of LiDAR data, transects were clipped to the extent of the available LiDAR data. The strongest relationship between LiDAR data and field estimates was that between field FBPC and LiDAR returns 2 m height and above (Table 4; $r^2 = 0.74$, S.E. = 8.1%, $n = 29$). In order to compare LiDAR derived cover estimates with existing regional scale data, which was based on FPC field calibration alone, a relationship between field FBPC and FPC was necessarily applied to the LiDAR vegetation returns, as the LiDAR is responsive to both leaves and branches. This relationship suggested a good correspondence ($r^2 = 0.89$, S.E. = 4.0%, $n = 29$) between these parameters. The LiDAR-predicted estimates of FPC, when plotted against the field-estimates of FPC, suggested that this cover measure could be estimated with a reasonable degree of certainty ($r^2 = 0.62$, S.E. = 6.2%, $n = 29$; Fig. 6), particularly given the disparity between respective number of measures per method, and also the measurement coverage within the plot (field = ~3% of plot; LiDAR = 100% of plot). The lower outlier identified in Fig. 6 was associated with an SSU in which one of the three field transects passed through a particularly open section, suggesting that the ground measurements were not adequately capturing the variability within the plot. The upper outlier was associated with a SSU

Table 4
Relationships between FC and FPC and the proportion (x) of LiDAR vegetation returns (≥2 m)

Cover descriptor	r^2	Adjusted r^2	S.E. (%)	n	Equations
Field FBPC vs. LiDAR veg returns	0.74	0.73	8.1	29	$Y = 1.09x + 6.24$
Field FPC vs. field FBPC	0.89	0.88	4.0	29	$Y = 0.6454x + 3.23$
Field FPC vs. LiDAR FPC (returns)	0.62	0.61	6.2	29	$Y = 1.08x + 3.46$

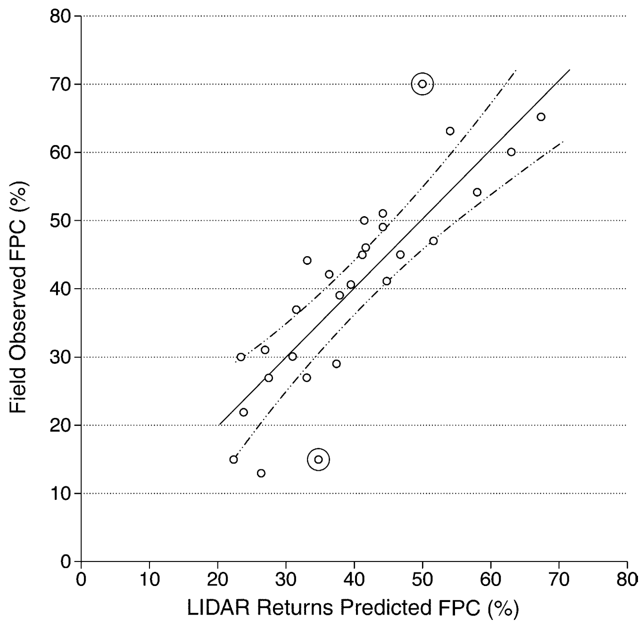

Fig. 6. Estimates of LiDAR predicted FPC vs. actual field estimates. Outliers associated with open ground or less dense LiDAR returns are circled. Dashed lines indicate 95% confidence intervals.

with high cover, but poor LiDAR coverage (2 m spacing) compared to other SSU's, as a result of adverse wind conditions. With these plots removed, the strength of the relationship increased further ($r^2 = 0.68$, S.E. = 4.9%, $n = 27$). The various relationship values for field to LiDAR cover conversions are summarised in Table 4.

8. Scaling up to the landscape

On the basis of the plot level relationships established with LSP (floristics) and LiDAR (height and canopy cover), predictions of mean attribute values and distributions at both the PSU (150 predictions) and SSU (4500 predictions) level for the entire 220,000 ha study area were generated. The following sections present a summary of the extrapolations and then compare the sampled distributions with the mapped distributions based on datasets currently used by both the Queensland and Federal Governments.

8.1. Species distributions

The floristic composition was established by summarising the occurrence of species associations within the 4500 SSUs. Approximately 70% of the D1 species were represented by CP-, SLI, SBA and Eucalypt species, with CP- being the most common. Only 10% of the study area was non-forest. Within the remaining 20%, species such as *Eucalyptus dealbata* (TDG), *E. fibrosa* sp. *Fibrosa* (BRI) and *E. decorticans* (GTI) were commonplace. Of the D2 species, SLI, EUS, CP- and SBA continued to account for the majority (55%), with the remaining co-dominant including GTI, TDG and PBX. D3 species were absent from 35% of the PSUs and, where they did occur, these were dominated by *Eucalyptus* species (particularly SLI), although a diversity of other species were present. Such species, many of which are understorey, included BGL and SWB. Species associations were commonplace. Based on the presence of D1 and D2 species (e.g., PBXSWB, which represents and association of PBX and SWB), CP-SLI formed the most extensive association although CP-SBA, SBA-CP- and SLI-CP- were common. However, these associations (together within non-forest) represented only 31% of all associations. Other associations, including SLI-EUS and CP-EUS, dominated within 61% of the PSUs with non-forest occurring in the remainder.

Within the existing regional datasets (i.e., 1:250,000 broad vegetation mapping; MPIG, 2001) and 1:100,000 scale land cover mapping based on Landsat TM, the equivalent detail at a species level was not available. Therefore, species information for the SSUs were extracted from Queensland Herbarium data and based primarily on the dominant species according to the main categories of Acacia, Callitris, Eucalypt/Ironbark, Eucalypt (other), Angophora and non-forest. It should be noted that the regional datasets were also generated partially from the Herbarium data, but the final aggregation classes were too broad for our needs. The distribution of species/communities within the study area, as sampled using the field plots, the PSUs and also the PPPs, was then compared (Table 5). Areas of Angophora and non-forest mapped using the Herbarium data (for the PPPs and PSUs) were similar to those mapped using API. The mapped area of Acacia was far lower within the Herbarium data, although this may have been attributed to the extensive clearance

Table 5
Comparison of dominant genus groups as sampled from the 4500 SSUs and mapped using Queensland Herbarium data for the SSUs and also the region

Data source	Percentage area of dominant genus group					
	Acacia	Callitris	Eucalypt Ironbark	Eucalypt other[c]	Angophora	Non-forest
Field plots (7.75 ha)[a]	8.8	30.3	15.7	30.3	15.1	–
API-PSU (1125 ha)	3.1	35.6	24.3	16.1	10.9	10.0
API-PPP (8713 ha)	2.8	36.8	25.2	15.1	9.5	10.7
Qld Herbarium (PSU area)	0.0	18.8	54.5	4.6	12.4	9.7
Qld Herbarium (PPP area)	0.3	17.5	54.5	5.4	12.7	9.7
Qld Herbarium (study area)	1.1	18.6	51.9[b]	6.8	11.0	10.7

[a] Percentage based on basal area (for trees 10 cm DBH+) and not crown area.
[b] 28% could also be included in the ‘‘Eucalypt other’’ class.
[c] Includes unknown species in the field plot and LSP data.

of woodlands and subsequent regrowth of Acacia in the period between the Herbarium (1995) and the LSP survey (2000). The area of Callitris were under-estimated (by ~50%) by the Herbarium and a greater area of Eucalypt/Ironbark was mapped compared to just Eucalypt and other genera. The combined area of Herbarium-mapped forests with Eucalypt dominance was, however, greater (by about 20%) compared to the 2000 survey. The relative proportion of Herbarium classes within the area of the PSUs and PPPs, was similar to that observed across the entire study area, suggesting that the proportion of species observed in the LSP for the PSUs and PPPs should be representative of the area as a whole.

The discrepancies observed between the two surveys were attributed partly to the differing scales of the datasets rather than to the different approaches to mapping (i.e., wall-to-wall mapping and systematic sampling). Specifically, the Herbarium classifications were generated from a combination of Landsat sensor data with API of 1:80,000 scale photography and some field survey, and hence less detail was able to be resolved. Also, the Herbarium classifications were designed for describing community mosaics, so that the relative dominance of species in any one polygon may not match a field survey plot in that same polygon; however, the overall landscape composition will be robust. The differences in the extent of Callitris are of concern, however, as these are spectrally most distinct from other communities within the Landsat sensor data. The analysis suggests that the LSP API provided a good estimate of the extent of dominant species within the study area and also a better identification of the composition of the communities.

8.2. Height and FPC distributions

A comparison of height estimates for the 13 PSUs with those estimated through the NFI (2003; Table 6) indicated a general correspondence between classes but demonstrated the greater detail that could be obtained using LiDAR (as only two height categories were stated by the NFI). Within Australia, forests are defined as being >2 m in height and supporting a canopy cover of ≥20% and, within this vegetation type, woodland, open forest and closed forest are regarded as having an FPC between 10 and 30%, 30 and 70% and greater than 70%, respectively (Carnahan, 1990; Specht and Specht, 1999). These broad categories were therefore used to summarise the spatial distribution of FPC (and also height), as estimated using the regression equations with LiDAR outlined above, across the 4500 SSUs (Table 7).

Heights, in this case, were defined as the maximum height within each SSU, as estimated using LiDAR, whilst FPC was defined as the total FPC of the SSU. Based on the FPC classes, approximately 10% of the area represented by the SSUs was defined as non-forest, whilst 17.7 and 72.2% were defined as woodland and open forest, respectively. Within the non-forest areas, the maximum height of vegetation was <9 m (for approximately 85% of the class) with greater heights associated with large and relatively isolated trees (e.g., remnant within paddocks). Within the woodlands and also the open forests, the maximum height of the trees was distributed relatively evenly between the 10–19 and 20–29 m classes. Few PSUs with trees 30–39 m tall were observed.

The distribution of height by genus group (Table 8) suggested that different height classes were dominated by different genera, namely Acacias (2–9 m), Callitris and Eucalyptus (10–19 m), Callitris (30%, 20–29 m) and Callitris/Angophoras (30–39 m). Within the 20–29 m height class, Callitris predominated (36.5% of the category) but Eucalypt/Ironbark, Eucalypt/other and Angophora occurred in moderate (~20%) and roughly equal proportions.

LiDAR FPC estimates were also generated for each of the 4500 SSUs. The distribution of FPC by community (Table 9) suggested that within the non-forest category (i.e., FPC < 10%), Acacia was more abundant, with BGL dominating. Within woodlands, all other genus types were equally represented. However, within the open forest, Callitris and Eucalypt other/Ironbark represented over 70% of the dominant genera occurring.

Estimates of forest cover by type (based on either API or LiDAR) for the area were compared subsequently against prior estimates generated by the State Land Cover And Trees Survey (SLATS) land cover change analysis (1991/1999; QDNR,

Table 6
Estimates of the maximum and range (top 10%) of heights as estimated using LiDAR and by the NFI (2003)

PSU	LiDAR height		NFI (2003) height
	Maximum[a] (m)	Range[b] (top 10%, m)	Range (m)
114	30	16–30	11–30
124	29	17–29	11–30
83	29	17–29	11–30
111	29	16–29	11–30
81	27	18–27	11–30
58	25	14–25	11–30
23	24	14–24	11–30
138	23	15–23	11–30
148	23	13–23	11–30
144	24	15–24	0–30
142	20	13–20	0
59	20	11–20	0
131	15	10–15	0

[a] The highest LiDAR return above the ground.
[b] 10% of returns sorted highest to lowest.

Table 7
Percentage distribution of 4500 SSUs within different height and FPC classes

Height interval (m)	Non-forest (<10%)	Woodland (10–<30%)	Open forest (30–<70%)	Total
<2	3.5	0	<0.1	3.5
2–9	5.0	<0.1	0	5.1
10–19	1.3	9.3	38.2	48.8
20–29	0.2	8.2	33.6	42.1
30–39	0	<0.1	0.4	0.5
Total	10.1	17.7	72.2	100.0

Table 8
Proportion of different dominant genera within the 4500 SSUs

Height interval[a] (m)	Percentage of SSU's by dominant genus group						
	Non-forest	Acacia	Callitris	Eucalypt Ironbark	Eucalypt other	Angophora	Total
<2	2.64	0.80	0.04	0.0	0.04	0.0	3.53
2–9	4.58	0.36	0.13	0.0	0.02	0.0	5.09
10–19	2.11	1.58	20.04	15.38	8.20	1.53	48.84
20–29	0.64	0.40	15.18	8.82	7.78	9.22	42.04
30–39	0.02	0.0	0.18	0.09	0.07	0.13	0.49
Total	10.0	3.13	35.58	24.29	16.11	10.89	100.0

[a] Max LiDAR height of SSU.

Table 9
The percentage distribution of FPC by dominant genus group across the 4500 SSUs

FPC	Percentage of SSU's by dominant genus group						
	Non-forest	Acacia	Callitris	Euclaypt Ironbark	Eucalypt other	Angophora	Total
Non-forest (<10%)	8.47	1.22	0.20	0.09	0.09	0.2	10.09
Woodland (10–<30%)	1.31	0.36	3.60	4.13	4.20	4.09	17.69
Open forest (30–70%)	0.22	1.56	31.78	20.07	11.82	6.78	72.22
Total	10.0	3.13	35.58	24.29	16.11	10.89	100

Table 10
Forest extent estimates (FPC) as a percentage of the 220,000 ha study region based on existing regional mapping compared to those generated using LSP and LiDAR

Data source	Date	Non-forest (% of area)	Woodland (% of area)	Open forest (% of area)
SLATS	1991[a]	12	17	71
NFI (SOFR)	1997	11	30	60
NVIS[b]	1999	11	70	19
NFI[c] (Montreal reporting)	2000	13	67	20
LSP sample (3.9% of study area)[d]	2000	11 ± 5	43 ± 5	38 ± 5
LIDAR sample (0.5% of study area)	2000	10 ± 2	18 ± 2	72 ± 2

[a] The FPC value (i.e., woodland/open forest) is based on 1991 estimates, whilst the non-forest area is based on 1999 land cover change mapping.
[b] For Queensland, the NVIS is derived from the Herbarium data.
[c] The NFI provides information only on broad vegetation classes (e.g., Callitris, Acacia and Eucalpyt) and is a combination of Landsat cover estimates plus regional ecosystem mapping (including Queensland Herbarium data).
[d] Translation of LSP estimate of CC to FPC.

2000), the 1998 State of the Forest Report (SOFR; NFI, 1998), the National Vegetation Information System (NVIS; NLWRA, 2001) and more recent NFI data (through Montreal Process reporting; Commonwealth of Australia, 2002). Of the existing datasets, the area estimates generated through SLATS and NFI (from the State of the Forests Report, SOFR) suggested a lower proportion of woodland compared to open forest (Table 10). NVIS and the NFI were also similar but suggested that the area of woodland far exceeded that of open forest. In all cases, the area of non-forest was relatively similar. The distribution of FPC within the PSUs/SSUs was most similar to that of SLATs (when based on the LiDAR) and the NFI (SOFR), although some variability between samples was observed. The comparison also suggested a discrepancy in the area of non-forest, with a lower amount estimated using the LiDAR data (Lee et al., 2003).

9. Discussion

The study has shown that LSP and LiDAR can provide estimates of stand level floristics and structure (e.g., canopy cover) which are more comprehensive, precise and of greater number compared to field measurements alone. Through API and the development of empirical relationships with LIDAR data, regional level estimates can be generated through simple extrapolation. This approach provides options for operational mapping of such attributes. These options are discussed in greater detail in the following sections.

9.1. Retrieval of tree and stand level floristics and structure

The identification of tree species and an assessment of their dominance within the community can be achieved through interpretation of LSP, although the skills of an experienced interpreter are required. As the diversity of D1 species is not high compared to D2 and D3 genera and many are spectrally distinct in the visible wavelengths, reasonable identification can be achieved at this scale. This capability was confirmed by the high correspondence between the API assessment of dominant species and the field observations. However, the classification of the community according to the three levels of dominance appears to be more subjective because the composition of the communities is well described but the relative order of dominance is not.

Previous studies within Australia and also overseas have indicated that the estimates of tree height from LiDAR are likely to be more accurate than field-based measurements under most conditions, largely because of the difficulty in locating the highest part of larger, non-uniform crowns in the field (particularly in closed canopies) and the errors associated with the measuring devices (e.g., rangefinders) themselves (Witte et al., 2000). Even so, variations occur between sites (Lovell et al., 2005) as LiDAR estimates of tree height are affected by sensor configurations as well as crown shape (Nelson, 1997). Correction factors may therefore need to be applied, although this requires additional knowledge on tree form or species distributions. Within woodlands and open forests, however, estimates of tree height are likely to be more reliable compared to closed forest situations because of the greater likelihood of retrieving returns from the underlying ground surface.

Strong relationships were obtained between field-based estimates of both FBPC and FPC and LIDAR, regardless of the forest type. Similar outcomes were reported by Riaño et al. (2004), who demonstrated that LiDAR-derived estimates of canopy cover correlated well with ground estimates of covered ground and leaf area index (LAI, $m^2\,m^{-2}$) generated using hemispherical photography, although the study indicated that variation with forest type occurred. The retrieval of both parameters from LIDAR was considered more reliable than from field measurements and (in the case of CC) API estimates, largely because of the capacity to quantitatively encompass the spatial distribution of tree crowns and the variability in crown shapes. Furthermore, the estimates from LIDAR can be re-sampled to support the interpretation of other data (e.g., as acquired by Landsat sensors), thereby avoiding the specific design of field-sampling layouts to suit the resolution of the particular data involved.

9.2. Regional estimates of floristics and structure

Comparison with Queensland Herbarium data suggested that although the area of non-forest was similar, the areas occupied by forest types differed. In particular, the LSP data suggested that Callitris dominated approximately one-third of the forests occurring, whilst the Herbarium data suggested this figure to be less than one-fifth. The Herbarium data also suggested that over 50% of the forests were dominated by Eucalyptus species including Ironbark, whereas the LSP data indicated that Ironbarks were less represented or absent in approximately 15% of the forests observed as containing Eucalyptus. The LSP therefore provided a better indication of the species composition of the forests and a more detailed and permanent record. The areas of Angophora and non-forest were reasonably similar to those mapped by the Queensland Herbarium, although a greater extent of Acacia was noted from the LSP.

Based on the analysis, LSP was considered to be an efficient and reliable sampling tool that also provided a single, consistent source of information on vegetation structure, land use, disturbance regimes and other landscape attributes. The LSP also provided a more robust regional estimate of community composition than existing mapping sources and was also more suited for establishing baselines of community composition and monitoring long-term changes, particularly as a photographic record was provided. In terms of structure, the height (both maximum and range) distributions from LiDAR were considerably more detailed than those available previously (e.g., NFI, 2003) and provided a greater insight into the structure of the forests. For the study area, the greatest heights were typically associated with open forests dominated by Callitris and Angophora. Angophoras are often remnant within the area because of their low commercial value and large individuals with expansive crowns are commonplace. Callitris forests are also managed for commercial purposes (Harris et al., 2003) and large trees are therefore typical. Acacias generally dominated the lower height classes, particularly as many are in the early stages of regeneration as a result of recent clearance and degradation (Scanlan, 1991; Fensham et al., 1998).

The FPC estimated from LiDAR suggested that the majority of the area could be classified as open forest, with woodlands occupying a relatively small amount. The greatest FPC was associated with Callitris and also Eucalypt Ironbark forests. Both CP- and SLI, which are typical to these forests, have a high density of foliage compared to many other species and the density of crowns within CP- is also often large (several thousand per hectare). Although being amongst the largest trees, Angophoras typically support a lower density of foliage (which is generally orientated vertically) and hence there is some representation of Angophoras within the woodland category. Similarly, the Eucalypt/other category was associated more with the woodlands. The lower cover estimates from LSP were attributed to the more qualitative assessment compared to when LiDAR data are used.

The FPC estimates from LiDAR for the PSUs corresponded well with those generated by SLATS and to a certain extent with the NFI SOFR. However, the estimates of the proportion of the area allocated to woodland and open forest differed substantially from the NVIS and NFI (Montreal Process reporting) which was attributed largely to differences in mapping techniques and issues of scale.

9.3. Operational implications

The study has confirmed that LSP and LIDAR, both singularly or in combination, can provide stand-based and landscape estimates of floristics and structural attributes (e.g., height, FPC) for structurally complex forests that are typical to large areas of Australia. At the stand level, such estimates are probably at least as accurate as and potentially more precise than ground-based sampling methods and can be implemented at the same cost once initial calibrations with field data are undertaken. As illustration, 4500 0.25 ha estimates of stand height and cover were produced across the 37 km $\times$ 60 km area for approximately AU $120,000 including labour. The same 4500 ‘‘plots’’ would take more than 20 person years to complete and are estimated to cost between AU $4–6 million using traditional field-based methods. Such methods would also be difficult to implement across the area due to problems of access. Additional analyses are required to estimate how these savings and benefits may translate into national and regional inventory and monitoring programs. However, it is realistic to expect cost savings well in excess of 90% over traditional field-based methods when surveying large areas.

Whilst the potential savings through integration of LSP and LiDAR have been indicated, further savings would be realized through their combined use within an integrated monitoring framework. For baseline surveys of very mixed and heterogeneous forests, LSP is crucial for identifying, for example, land cover, floristics and disturbance, and for assisting with the calibration and validation of LiDAR information. Under many circumstances, LSP alone may seem a ‘‘cheaper’’ option compared to flying both LSP and LiDAR, particularly considering LSP offers the ability to record more than structural attributes. However, the labour costs associated with LSP are effectively fixed, so each subsequent survey will cost approximately the same as the first. LiDAR is significantly different in that the majority of the cost in terms of labour occurs in the early stages of the first survey and automated procedures decrease labour costs as the areas flown and the requirement for monitoring increase. LiDAR also offers the ability to automatically monitor structural attributes (e.g., canopy density or defoliation) relating to, for example, forest condition at a more precise level than LSP. For these reasons, the use of both LSP and LiDAR in an initial baseline survey and the acquisition of LiDAR in subsequent survey would be the most cost-effective option for sample-based inventories. Fully automated procedures could also be used to identify significant areas of change using the LiDAR data.

10. Conclusions and recommendations

The research has demonstrated that sampling using LSP and/or LIDAR can provide quantitative assessments of floristics and key structural attributes (height, cover) which can be extrapolated across the landscape. These estimates are comparable to those generated using traditional wall-to-wall mapping approaches although absolute comparison is limited because of the coarser level of detail associated with many existing datasets. This feature highlights then the additional information that can be obtained using the fine spatial resolution datasets. Furthermore, the assessments are based largely on statistical relationships established between remote sensing data and field-based measurements and the procedures are consistent, reproducible and are also cost-effective.

Although the level of detail is greater and the sampling appears to represent the distribution of floristic and structural attributes across the landscape, wall-to-wall mapping is still regarded as essential for certain purposes (e.g., to evaluate the loss of communities associated with land clearing). However, such mapping is actually enhanced considerably by the provision of an extensive fine spatial resolution dataset as acquired during this research.

The study therefore recommends the establishment of an integrated mapping and monitoring framework which has, at its base, sampled acquisition of fine spatial resolution data (namely LIDAR, LSP, videography or even hyperspectral data) supported by a comprehensive and targeted field campaign and same-date acquisition of airborne or spaceborne remote sensing data for scaling purposes. Once established, repeated overflights of all datasets can be used to determine change in floristics and structure and better inform and/or support regional forest and woodland management, obligations to international agreements (e.g., the Montreal Process, International Biodiversity Treaty and the UNFCCC) and national and international opinions on, for example, greenhouse gas emissions and conservation of biodiversity.

Within Australia, a Continental Forest Monitoring Framework (CFMF) has been initiated to provide an integrated, nationally consistent inventory and monitoring program for meeting assessment and reporting requirements (BRS, 2003). For the CFMF, new data integration and analysis techniques are being investigated and evaluated on the basis of cost-effectiveness, ease of application, repeatability, transparency and verification. The outcomes from the CFMF are intended to provide a scientifically robust analysis of status and trends in the extent and condition of forest ecosystems (including the environmental services they provide) in a timely and consistent manner across all tenures. The information will be used to inform and evaluate national policy and regional decisions on trans-boundary issues and to support sub-regional monitoring activities aimed at evaluating management actions (BRS, 2003). The CFMF will be designed with consideration to political, economic and scientific requirements and constraints. This design will take advantage of opportunities presented by recent developments in remote sensing at a range of scales, whist at the same time retaining the maximum extent of coverage and incorporating new and more efficient data collection techniques as these become available. The design features three interrelated tiers of data collection and is being evaluated in north–east Victoria where a wide range of forest types and environments exist (Lee et al., 2003). The techniques developed in this research are contributing to this CFMF pilot project and it anticipated will form the basis for wider application across Australia.

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