Sustainable Forest Management

Australian Government
Forest and Wood Products Research and Development Corporation

Evaluation and Validation of Canopy Laser Radar Systems for Native and Plantation Forest Inventory

Summary Report

Project No. PN02.3902

Australian Government
Forest and Wood Products Research and Development Corporation

Publication: Evaluation and Validation of Canopy Laser Radar Systems for Native and Plantation Forest Inventory - Summary Report

Project no: PN02.3902

Researchers:
D. Culvenor
CSIRO Forestry and Forest Products
Private Bag 10, Clayton South, Vic 3169

D.L.B. Jupp, J. Lovell and G. Newnham
CSIRO Earth Observation Centre
GPO Box 3023, Canberra, ACT 2601

Final report received by the FWPRDC in April 2005

Forest and Wood Products Research and Development Corporation
PO Box 69, World Trade Centre, Victoria 8005
Phone: 03 9614 7544 Fax: 03 9614 6822 Email: info@fwprdc.org.au
Web: www.fwprdc.org.au

Evaluation and Validation of Canopy Laser Radar Systems for Native and Plantation Forest Inventory - Summary Report

Prepared for the

Forest & Wood Products Research & Development Corporation

by

D. Culvenor, D.L.B. Jupp, J. Lovell and G. Newnham

The FWPRDC is jointly funded by the Australian forest and wood products industry and the Australian Government.

EXECUTIVE SUMMARY

In recent years, research into the use of Lidar technologies to characterise forest structure has increased rapidly. However, the use of such technologies to assist commercial forest inventory operations has not yet been addressed.
The objectives for this study were to:

- Validate and promote the use of airborne and ground based Lidar technologies as tools in forest inventory programs in Australian plantation and native forests.
- Test the accuracy and value of the data against conventional inventory and other field measurements.

Lidar systems use a short pulse of laser energy to measure the range to solid objects. Airborne Lidar systems are routinely used for mapping terrain and can also be used as a tool for mapping forest structural attributes such as height and foliage cover. A number of innovative processing algorithms for this data were tested in plantation forestry settings using commercially available airborne Lidar data. The study also incorporated a detailed evaluation of the CSIRO's ECHIDNA® ground-based scanning Lidar. The ECHIDNA® was designed by CSIRO specifically for objective plot-scale assessment of forest attributes such as basal area, bole height, canopy height and stocking. The ECHIDNA® was tested at a range of forest sites and the resulting estimates compared to measurements recorded using traditional techniques.

Key outcomes from this study were:

- Simple variables available from airborne Lidar data correlate well with a range of inventory and site quality parameters;
- ECHIDNA® can provide a plot-based assessment of stem characteristics suitable for estimating volume by size class;
- Multi-angular analysis of ECHIDNA® data allows estimates of canopy structural parameters including leaf area index and canopy height;
- ECHIDNA® derived allometric equations can be integrated with broad scale airborne Lidar data to provide plot-equivalent structural mapping over large geographical areas.

The hardware and software validation undertaken in this project has significantly reduced the technology risk associated with the commercial and operational use of Lidar in Australian forestry. Further operational trials are planned as part of a commercialisation of the ECHIDNA® concept.

1 INTRODUCTION

1.1 Project Objectives

The aim of this project was to validate and promote the use of airborne and ground based Lidar technologies in commercial forest inventory activities. The specific objectives were to:

- Validate and characterise new CSIRO methods (Jupp and Lovell, 2005) for forest inventory measurements in Australian plantation and native forests using airborne and ground based Lidar data;
- Demonstrate and validate ECHIDNA® Lidar measurements using available hardware with patented algorithms and methods;
- Test the accuracy and value of data obtained by this technology against conventional forestry and other field measurements; and
- Develop strategies for the widespread adoption of the technology and the methods for use in Australian and international forest inventory.

In the case of the ground-based system, simulations using commercially available systems proved to be inadequate to demonstrate the potential of existing algorithms. Consequently, the objectives were revised to use a prototype ECHIDNA® instrument – the ECHIDNA® Validation Instrument (EVI).

1.2 New Technology Options using Lidar

Light detection and ranging (Lidar) technology involves the transmission of a laser pulse and analysis of the time trace of reflected light; often referred to as a "waveform". The nature of this waveform can be analysed in terms of the:

- Range (distance) to discrete objects from the instrument;
- Intensity with which the pulse is reflected from discrete objects; and
- Structure of spatially distributed targets.

Due to both engineering and practical limitations, commercially available airborne Lidar systems record only discrete signals from the Lidar waveform, such as the first and last returns above a given threshold. However, recording the full waveform of returns will have greater potential for the analysis of complex structures. For example, the analysis of full waveforms should increase the information available to characterise mid and under-storey layers.

Airborne Lidar systems recording discrete returns are well established as a tool for measuring terrain elevation. Extension of this work to the measurement and mapping of tree height, canopy and foliage cover has been the subject of much research (e.g. Nelson *et al*., 1984, Nilsson, 1996, Næsset, 1997*a*,*b* and Magnussen *et al.*, 1999). More recently, the measurement of these basic parameters has been used to assess other forest attributes through the use of allometry. These include basal area, wood volume (Gobakken and Næsset, 2004), and biomass in Australian forests through the extension of the foliage profile work of Lee *et al*. (2004).

Since allometry is unstable over different age classes, species and growing conditions, an important aspect of our work is to test the use of ground based technologies that can be used for rapid and repeatable allometric equation development. These could then be used to map critical inventory parameters that are poorly characterised by airborne Lidar sensors with a predominantly vertical perspective. This requires the linking of airborne and ground based data through corresponding measurements of height, cover and vertical foliage profiles (Section 4.4), allowing the scaling up of critical parameters measured at the plot scale (such as stem diameters and stocking) which are required to assess wood volume and biomass.

2 FIELD SITES AND DATA COLLECTED

The location and characteristics of the project's four primary research sites are described in Table 2.1 and Table 2.2. These include both softwood and hardwood plantation and native forests of differing age classes and subjected to vastly differing environmental conditions.

Table 2.1 Primary research site information

Site	Latitude	Longitude	Elevation	Native / Plantation	Field Sampling	Airborne Sampling	Industry Partner
Tumbarumba (NSW)	35°45′	148°00′	700 m	Native / Plantation	Dec 01	Dec 01	SFNSW
Mt Gambier (SA)	37°49′	140°46′	50 m	Plantation	Aug 02 Dec 04	July 02	ForestrySA
Westfield (Tas)	42°40′	146°26′	430 m	Plantation	July 04	Mar 04	CSIRO FFP Forestry Tas
Coffs Harbour (NSW)	30°05′	153°09′	200 m	Native / Plantation	Aug 04	Oct 04	SFNSW

Table 2.2 Conventional inventory measurement data summary

Site	Instrument Station	Species	DBH (m)	Stems per hectare	LAI	Height (m)	Year est.
Tumbarumba	1	*Eucalyptus delegatensis*	0.51±0.23	200		33.96±12.37	Native
	2	*E. pauciflora*	0.26±0.12	330		20.58±8.45	Native
	3	*E. globulus*	0.37±0.32	220		20.99±9.74	Native
	4	*Pinus ponderosa*	0.44±0.05	360		29.85±1.27	1961
Mt Gambier	Patchells TP3	*P. radiata*	0.17	1640	3.13	19.2	1992
	Patchells TP10	*P. radiata*	0.16	1660	3.84	17.6	1992
	Patchells TP18	*P. radiata*	0.12	1520	2.51	13.5	1992
	Penola HQ 1	*P. radiata*	0.16	1480	3.40±0.02	15.7	1996
	Penola HQ 2	*P. radiata*	0.15	1820	3.08±0.03	14.5	1996
	Penola HQ 3	*P. radiata*	0.15	1740	3.36±0.06	15.4	1996
	Penola HQ 4	*P. radiata*	0.14	1940	2.70±0.05	13.9	1996
	Penola HQ 6	*P. radiata*	0.17	1560	3.37±0.04	16.5	1996
	Springs Rd	*P. radiata*	0.35±0.05	350	2.12±0.09	29.23±1.49	1975
Westfield	1	*E. nitens*	0.21±0.05	1170	5.39	23.56±9.32	1993
	2	*E. nitens*	0.18±0.05	1080	6.27	19.06±4.26	1993
	3	*E. nitens*	0.18±0.04	1120	5.25	19.87±2.07	1993
	4	*E. nitens*	0.20±0.03	1620	5.98	24.24±0.97	1993
	5	*E. nitens*	0.15±0.04	1620	6.05	17.87±2.79	1993
Coffs Hbr	1	*E. grandis*	0.29±0.11	270	2.77	33.3±12.76	1953
	2	*E. dunnii*	0.16±0.02	600	2.28	15.1±0.86	1999
	3	*E. pilularis* *E. grandis*	0.40±0.07	80	1.01	40.25±3.07	1973
	4	*E. pilularis (dom)*	0.26±0.11	530	3.11	23.21±9.17	Native
	5	*E. pilularis (dom)*	0.16±0.10	2140	2.91	14.39±8.48	Native

Table 2.3 lists the forest structural attributes estimated using Lidar based methods and the field assessment techniques used to collect validation data.

Table 2.3: Key forest structural attributes and field measurement techniques.

Attribute	Description	Field assessment approach(es)
Stem diameter	mean stem diameter at breast height (DBH)	diameter tape measurement of selected trees*
Stem frequency	tree locations	range and bearing to stems of selected trees*
Canopy height	mean or predominant tree height at plot scale	tree height measurement using Vertex hypsometer*
Bole height	mean bole height at plot scale	bole height measurement using Vertex hypsometer*
LAI	one sided leaf area per unit ground area or projected needle area per unit ground area	hemispherical photography, LICOR LAI meter
Foliage profile	vertical distribution of foliage within the canopy	hemispherical photography with telescopic mast

* Note that trees were selected for measurement using both fixed and variable sized plots.

3 ECHIDNA® VALIDATION INSTRUMENT

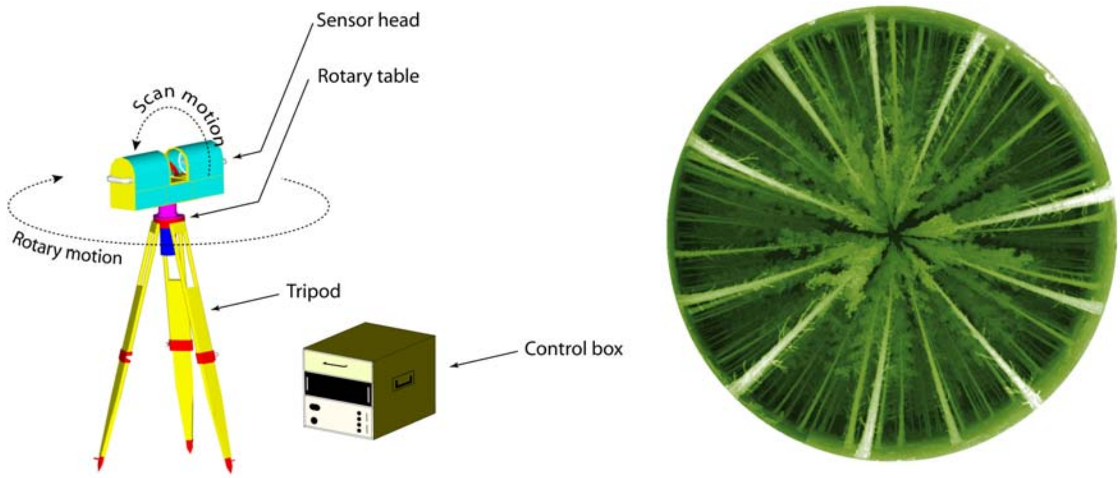
A range of commercially available terrestrial Lidar instruments were considered empirically and theoretically during the initial phase of the project. These investigations showed that the project objectives would not be adequately achieved due to the limitations of existing commercial hardware, which are not optimised for vegetation assessment. This led to the design and construction of the ECHIDNA® Validation Instrument (EVI).

In designing the EVI, a number of specifications were identified to overcome the limitations of commercially-available instruments, these were:

- A minimum and maximum ranging capability from 50 cm to 100 m;
- The recording of all energy reflected from targets as a function of time (full waveform) rather than a single range value;
- The ability to set beam divergence to allow investigation of the effect of cross-sectional beam area on forest structure measurement and the efficiency of operations; and
- Scanning over the full hemisphere above the instrument.

Based on these key criteria, the EVI was designed and constructed by CSIRO and its contractors: Optical Engineering Associates Pty. Ltd. (OEAPL), and Laser Integrated Technologies (LITE). Design was focussed on meeting or exceeding all data requirements, to ensure that no instrumental limitations were imposed on the success of scientific objectives, irrespective of other practical considerations. It is expected that significant improvements in portability and power requirements could be achieved in any ECHIDNA® instrument built with operational intentions. Figure 3.1

shows a schematic of the EVI instrument and a summary image of the three dimensional dataset it produces. In this image, each waveform (laser shot) is represented by a single point and the brightness at that point is a function of the sum of the intensities received.



(a) (b)

Figure 3.1 Schematic of ECHIDNA® Validation Instrument components (a) and example hemispherically projected EVI data acquired in a mature *P. radiata* plantation (b).

4 RESEARCH OUTCOMES

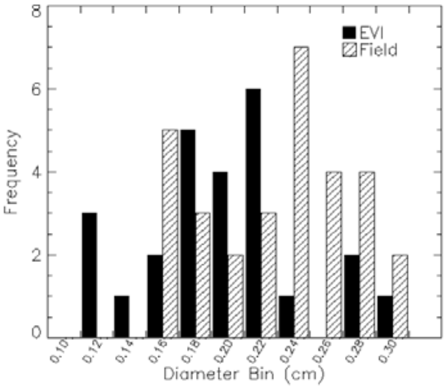
4.1 Trunk Analysis

The characteristically large intensity reflections from hard surfaces mean that trunks can be identified and mapped within the EVI data. The accurate positioning of the Lidar beam enables angular sizes to be determined from which diameters may be calculated. Operation of the instrument in this "spatial" mode is similar to the use of a Relaskop. Examples of the EVI results compared with field data collected using a Relaskop and diameter tapes are shown in Table 4.1. The base parameters shown are basal area (BA), mean stem diameter (Mean D) and the coefficient of variation of stem diameters (CV D) of the sample of "in trees". Two additional lines of data provide the mean diameter (Hist D) and number density (Hist N) calculated from histograms of the diameter distributions.

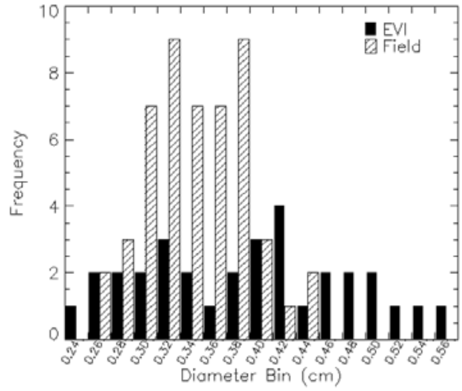
Table 4.1 Comparison of stem parameters from EVI processing with field data.

	Westfield		Coffs Harbour 2		Coffs Harbour 3		Springs Rd	
	EVI	Field	EVI	Field	EVI	Field	EVI	Field
BA	34.3	39.4	15.5	11.9	11.8	10.7	26.2	36.9
Mean D (cm)	16.2	20.0	16.4	15.6	36.1	39.7	37.0	32.7
CV D (%)	13.1	10.6	12.7	5.7	11.0	11.2	18.9	8.3
Hist D (cm)	19.8	22.8	19.9	17.3	42.3	41.6	34.7	34.3
Hist N	30	25	14	15	14	14	36	36

The basal area results show good agreement between the EVI data and the field data, but there is greater discrepancy among the stem diameters. There is also a greater variation (coefficient of variation) in the EVI based estimates. The histogram means and number densities show good agreement, however the examples shown in Figure 4.1 illustrate higher variance in the EVI estimates.



(a)



(b)

Figure 4.1 Comparison of EVI and field stem diameters at the Westfield *E. nitens* plantation (a) and Springs Rd mature *P. radiata* plantation (b).

The results presented here suggest that under conditions where stems are not obscured by large amounts of foliage and understorey vegetation, the EVI data can be used to provide estimates of basal area, mean diameter and stem diameter distributions. Further enhancement of the processing will seek to overcome terrain effects and reduce the impact of minor obscuration, such as foliage and twigs, in the near field.

4.2 Waveform Analysis

Forest structural analysis using hemispherical photography employs estimates of gap probability (Pgap) within given zenith angle ranges to compute leaf area index (LAI) and mean leaf inclination angle. The computed LAI index is more accurately described as a plant area index, as different plant components (leaf, stem, and branch) cannot be adequately separated in the analysis.

Using the same basic principles, EVI data has been analysed to calculate mean gap probability within specified zenith and azimuth sectors as a function of range. This enables not only true LAI to be determined (independent of stems and branches) but also allows the calculation of the foliage density as a function of height above the canopy floor.

In general, this approach did not show a strong relationship with field estimates of LAI. This was particularly true for the Westfield site, where field records showed unusually high LAI values relative to observed conditions. This disappointing result might be expected given the uncertainty in conventional LAI measurement techniques and the disparate sources of the validation data used. Removal of the Westfield data improved the estimation accuracy to some extent and this is presented in Figure **4.2**.

Comparisons between field and EVI canopy height data (Figure 4.2) showed a smaller relative bias and higher correlation with the standard inventory measurements. This more predictable relationship may in part be explained by the relative standardisation and repeatability of height measurements recorded in the field.

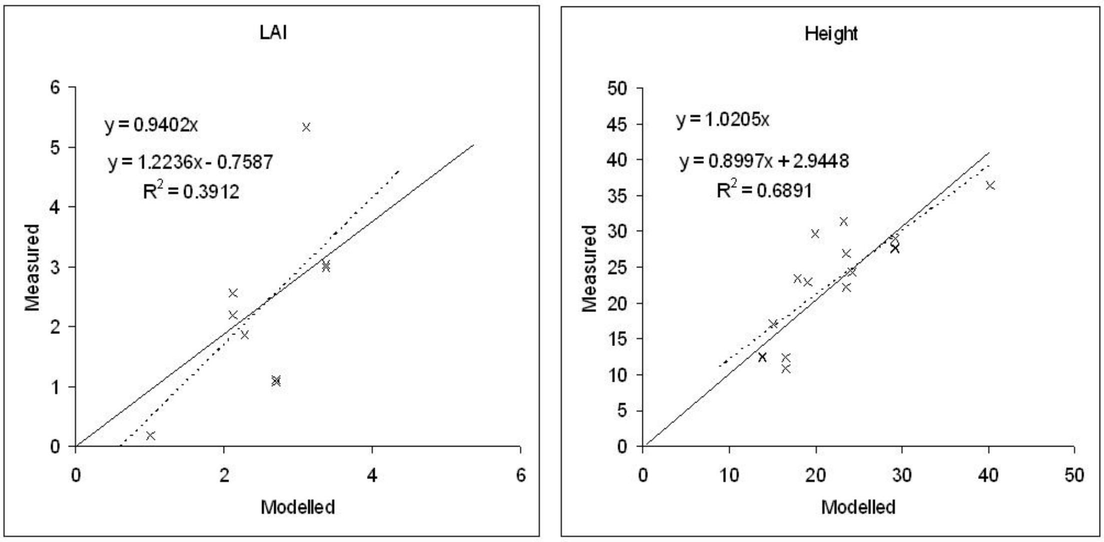


Figure 4.2: Relationship between LAI and canopy height (in metres) measured in the field and those derived from inversion of Pgap profiles from EVI. The Westfield LAI field data have been excluded due to their unusually high values.

The ECHIDNA® Validation Instrument records return intensity waveforms. In a second approach to LAI and canopy height estimation, these waveforms are averaged within specific zenith and azimuth ranges and analysed using a multi-angular full waveform canopy model, which is parameterised in terms of basic structural characteristics of the canopy. LAI values were retrieved for all sites through inversion of this model. These showed an improved relationship with field measurements (see Figure 4.3) except for the Westfield site, where very high field measured values need further investigation. Height estimates from the model inversion also showed an improved relationship to field measured values.

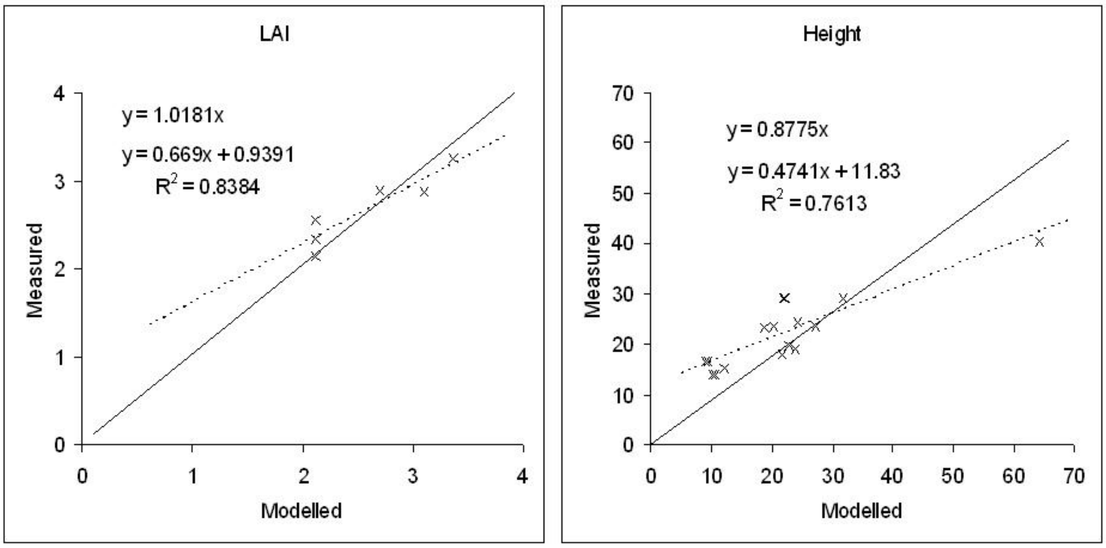


Figure 4.3: Relationship between LAI and canopy height (in metres) derived from inversion of the waveform model and those measured in the field.

Overall, the Pgap analysis method showed low estimation accuracy for LAI and a slight over estimation of height, while the waveform model inversion showed an increased LAI estimation accuracy with some bias introduced in the estimation of height. The more predictable relationship between measured and estimated values of

LAI produced using the waveform model (R^2 of 0.84) supports the notion that fully utilising the waveform recording capability of the EVI provides advantages in characterising soft targets like foliage. Both techniques have the potential to be developed further for accurate retrieval of other parameters such as the angle distribution of foliage and parameters related to basal area.

4.3 Comparisons between ground and airborne data

Comparisons were made between field measured predominant height and similar measures derived from the airborne Lidar data. Figure 4.4 shows this comparison in the form of a linear regression. The presence of a non-zero intercept indicates some bias in the relationship. However, given the narrow beam divergence and limited sampling frequency of the instrument this is an expected result due to the low probability of the laser light interacting with the peaks of tree canopies.

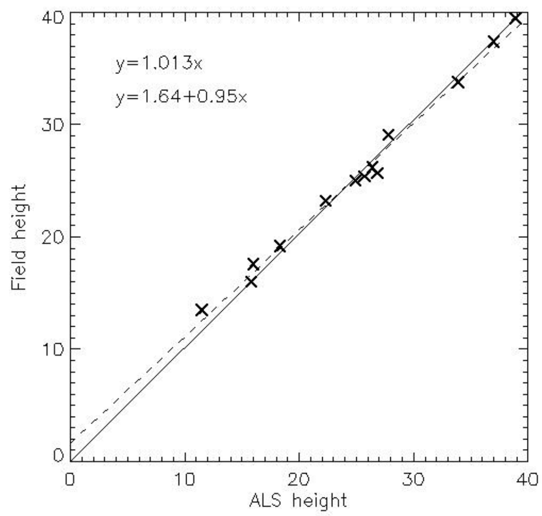


Figure 4.4. Linear regression between airborne Lidar derived predominant heights and field data at the plot scale measured in metres.

The results displayed in Figure 4.4 represent a number of different forest types. Interpretation of results from individual sites highlighted the following factors influencing the level of agreement:

- Canopy density affects the accuracy of canopy height measures from airborne Lidar;
- Steep terrain affects the accuracy of height measurements from both manual and Lidar methods; and
- Accurate location of field plots has a large effect in heterogeneous stands.

4.4 Foliage profiles from airborne Lidar, EVI and field data

A direct comparison between airborne Lidar data, hemispherical photography profiles and EVI data is possible by using computed apparent foliage area density profiles. Comparison of the EVI and airborne Lidar profiles provides the opportunity to build relationships between the two datasets and thus enhance the broad-area coverage of the airborne Lidar data with other information available from the EVI data (through allometry). The foliage profiles shown in Figure 4.5 have been modelled with a Weibull distribution representing the cumulative foliage area density as a function of height.

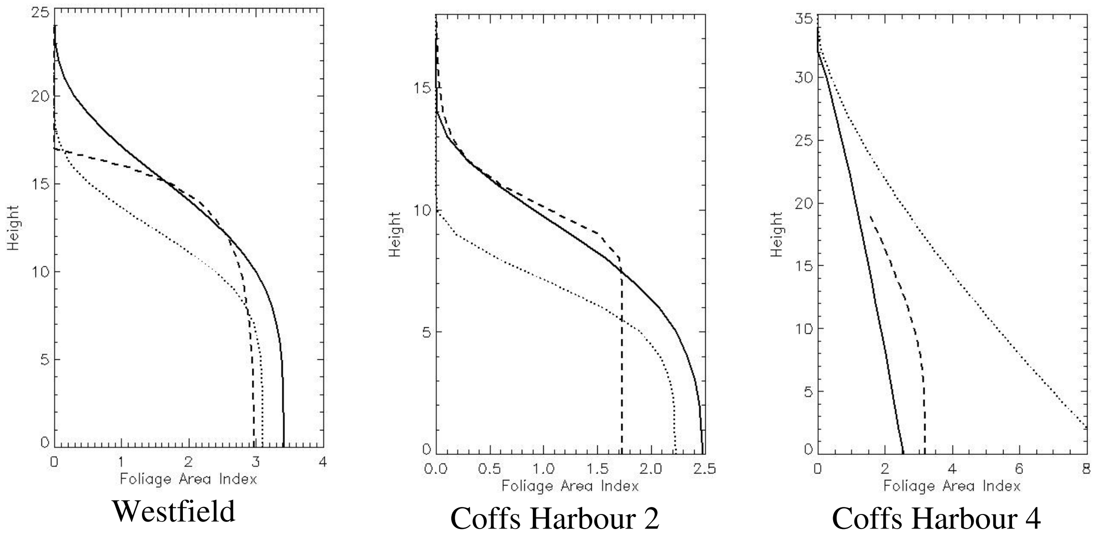


Figure 4.5 Examples of comparison of cumulative foliage area density profiles from airborne Lidar (———), hemispherical photographs (-------) and EVI data (············).

The profiles from the Westfield and Coffs Harbour 2 sites show a concentration of foliage at the top of the canopy and display similar shapes with some variation in magnitude. The shape of the Coffs Harbour 4 foliage profiles is consistent with mixed native eucalypt forest, displaying contributions from all levels within the canopy rather than a single dominant layer. There is a significant magnitude discrepancy between the three profiles shown here. This may be due to the specific location of the ground-based data collection which was in an enclosed part of the site, while the airborne Lidar profile is an average over a larger area that includes both this dense region and other more open areas.

In general, the canopy height shown in the EVI and hemispherical photography profiles is lower than that in the airborne Lidar profiles. This is due to the difference between bottom-up and top-down sensing. The data used here have been processed simply to find the first target in a given direction, so when a canopy volume contains gaps smaller than the spot size of the sensing instrument, a top-down sensor will detect the top of the volume while a bottom-up sensor will detect the lower envelope. Differences in magnitudes can largely be explained by the effects of different beam sizes and averaging footprints, and the ways in which threshold levels are selected.

5 CONCLUSIONS

This report outlines the way in which data from airborne Lidar and the ground-based EVI can be processed to provide forest information of value in both commercial forestry and environmental assessment. Critical parameters measured using these technologies include foliage cover, foliage density profiles, LAI and canopy height. Further development of the ECHIDNA® concept will continue to demonstrate the accuracy and efficiency gains that such instruments offer to the forest industry.

Outcomes from the airborne Lidar surveys undertaken during this project have demonstrated the relevance of simple variables available from airborne Lidar data that correlate well with inventory or site quality parameters. Currently, barriers to the operational uptake of airborne Lidar for forest inventory include both the cost of data acquisition and difficulties with processing. It is expected that data costs will be reduced in the coming years as the demand for airborne Lidar data increases and more commercial instrument operators emerge. We have provided a beta-version of CSIRO processing software to the partners involved in this project and are pursuing commercial avenues for its widespread distribution.

The combined results arising from the realisation of the EVI instrument and the validation of associated algorithms have been to illustrate the potential benefits of synergistic use of ground based and airborne Lidar technologies. The EVI provides high quality data that allows estimation of forest information of direct value in commercial forest inventory. A major benefit of the instrument is its ability to provide this information in an objective, quantitative and repeatable manner.

CSIRO has an active plan for ECHIDNA® commercialisation that involves:

- Disseminating the outcomes of this project to FWPRDC partners and the wider industry;
- Engaging in pilot projects using EVI in an operation environment to demonstrate and quantify industry value;
- Establishing specifications for future commercial instruments;
- Finding industry partners and sufficient investment to develop a commercial prototype; and
- Establishing a business model to develop the market and provide access for users to the technology through a commercial framework.

There are limitations in the apparent precision of Lidar based estimates of forest structural parameters in this document with respect to field measured values. This is not unexpected since the sampling methods are so markedly different and restricting Lidar based estimation to the measurement of all trees within conventional plot boundaries is often difficult. As such, fair assessment of the worth of these technologies should be based on whether estimates fall within the range of values expected within the forest being sampled. We believe this to be the case and that the accuracy shown by overall results is comparable with other more labour intensive techniques. Differences between the ground-based and airborne Lidar results can be interpreted in terms of sensing direction, beam size and spatial sampling, therefore allometry that accounts for these effects has great potential.

The validation results made possible through the support of this project by the FWPRDC have significantly reduced the inherent risk in the adoption of a new technological approach to current manual inventory methods. Ultimately, adoption of Lidar technology by the forestry industry will be based on cost benefit and ability to integrate with current forest measurement and management systems. In the case of the ECHIDNA®, this is being pursued through extension projects designed to apply the instrument in an operational setting.

ACKNOWLEDGEMENTS

We would like to thank the FWPRDC and our industry partners; ForestrySA and Forests NSW for their interest, support and guidance during the course of this project. We also acknowledge the work of David Parkin, George Poropat, Phil Connor and Stuart Young that helped establish the technical basis for the ECHIDNA® development and to Barrie May and Maria Ottenschlaeger for providing field data. Credit is also given to the private engineering companies, Optical Engineering and Associates Pty. Ltd. (OEAPL) and Laser Integrated Technologies (LITE), who played critical roles in the design and construction of the EVI.

REFERENCES

Gobakken, T.and Naesset, E. (2004). Estimation of diameter and basal area distributions in coniferous forest by means of airborne laser scanner data. *Scandinavian Journal of Forest Research*, **19**(6), 529-542.

Jupp, D.L.B. and Lovell, J.L. (2005). *Airborne and Ground-Based Lidar Systems for Forest measurement: Background and Principles*. EOC Technical Report 2005/03

Lee, A., Lucas, R. and Brack, C. (2004). Quantifying vertical forest stand structure using small footprint Lidar to assess potential stand dynamics. Proceedings of the ISPRS working group VIII/2 Laser-Scanners for Forest and Landscape Assessment conference. Freiburg, Germany. www.isprs.org/commission8/workshop_laser_forest/LEE.pdf

Magnussen, S., Eggermont P., and LaRiccia, V. (1999). Recovering tree heights from airborne laser scanner data. *Forest Science*, **45**, 407-422.

Næsset, E. (1997*a*). Estimating timber volume of forest stands using airborne laser scanner data. *Remote Sensing of Environment*, **61**, 246-253.

Næsset, E. (1997*b*). Determination of mean tree height of forest stands using airborne laser scanner data. *ISPRS Journal of Photogrammetry and Remote Sensing*, **52**, 49-56.

Nelson, R.L., Krabil, W.B. and MacLean, G.A. (1984). Determining forest canopy characteristics using airborne laser data. *Remote Sensing of Environment*, **15**, 210.

Nilsson M. (1996). Estimation of tree heights and stand volume using an airborne Lidar system. *Remote Sensing of Environment*, **56**, 1-7.