ON THE RELATIONSHIP BETWEEN CROWN COVER, FOLIAGE PROJECTIVE COVER AND LEAF AREA INDEX

Peter Scarth[1]

John Armston[1]

Tim Danaher[2]

[1]Joint Remote Sensing Research Program
Remote Sensing Centre, Department of Natural Resources and Water, Queensland Government, Climate Building, 80 Meiers Road, Indooroopilly, QLD 4068, Australia
Centre for Remote Sensing and Spatial Information Science, School of Geography, Planning and Architecture, The University of Queensland, Brisbane, QLD 4072, Australia
Ph: +61 7 3896 9627
Email: peter.scarth@qld.gov.au

[2]Information Sciences Branch
Department of Environment and Climate Change
PO Box 664, Alstonville, NSW, Australia, 2477
Ph: +61 2 6627 0108
Email: Tim.Danaher@environment.nsw.gov.au

Abstract

Vegetation crown cover is a popular structural descriptor in both the remote sensing and ecological fields. However, several different definitions of vegetation crown cover are commonly measured and used, and relating one against the other is often difficult. In this study we derive simple expressions relating mature forest crown cover (CC), foliage projective cover (FPC) and leaf area index (LAI) using canopy gap fraction and canopy clumping theory. The relationship between FPC and CC is shown to be related to the ratio of the within canopy to between canopy clumping. A comprehensive field data set collected in forests and woodlands across Queensland is used to demonstrate the validity of the models. The results have widespread application in the modelling and analysis of forest structure.

Introduction

Cover of natural systems is complex to describe and map. In remote sensing, several measurements of vegetation crown cover are commonly used. These are crown cover (CC), foliage projective cover (FPC) and leaf area index (LAI). CC is defined as the percentage of ground area covered by the vertical projection of crowns, which in this case are assumed opaque. FPC is the percentage of ground area covered by the vertical projection of foliage (Walker and Hopkins 1990). LAI is defined here as half the total developed area of leaves per unit ground horizontal surface area (Chen *et al.* 1997).

CC is a primary stand density variable in many forest inventories since it is readily understood by a variety of practitioners. It is relatively easily estimated in the field (Walker and Hopkins 1990) and from aerial photography (Fensham *et al.* 2003). FPC is more complex to measure in the field and is typically measured using a transect based method (Johansson 1985). FPC is more closely related to the photosynthetic and evaporative potential of a plant community than CC due to the low density foliage typical of many Australian woody species (Specht 1981). Herein, FPC refers to the overstorey component only, which includes woody life forms above 2 m (Specht 1983). The LAI is the main variable used to model many processes, such as canopy photosynthesis and evapotranspiration. It determines the size of the plant–atmosphere interface and thus plays a key role in the exchange of energy and mass between the canopy and the atmosphere (Chen *et al.* 1997; Simioni *et al.* 2003).

CC treats the crown as an opaque object, however the FPC of individual crowns for most Australian woody plants is between 40% and 70% depending on crown architecture (Walker and Hopkins 1990). For the same leaf area, variation in foliage clumping and leaf orientation angle determines the FPC of individual crowns (Campbell 1990; Henry *et al.* 2002; Kucharik *et al.* 1999). Indeed, high variation in leaf orientation angle and foliage clumping across Australian woody species has been reported in the literature and shown to function to reduce levels of intercepted light at high sun elevations (Falster and Westoby 2003; King 1997).

Forests are defined as vegetation greater than 2 m in height with a minimum crown cover of 20 %. A CC of 20% is suggested as being equivalent to a FPC approximating of 10 to 12% (Australia National Forest Inventory et al. 2003.). Despite the use of both FPC and CC as indicators of vegetation condition and structure in Australia there is a paucity of work quantifying the relationship across a range of native plant communities in Australia. This research links established models of canopy light interception, and used field data collected from plant communities across Queensland, Australia to fit the parameters in the models, resulting in an improved understanding of the usage, linkage and applicability of these fundamental cover metrics

Methods

Study site and sampling design

In order to collect a sufficient quantity of representative field data, a field program was conducted across Queensland (Figure 1) sampling a wide range of forest and woodland types.

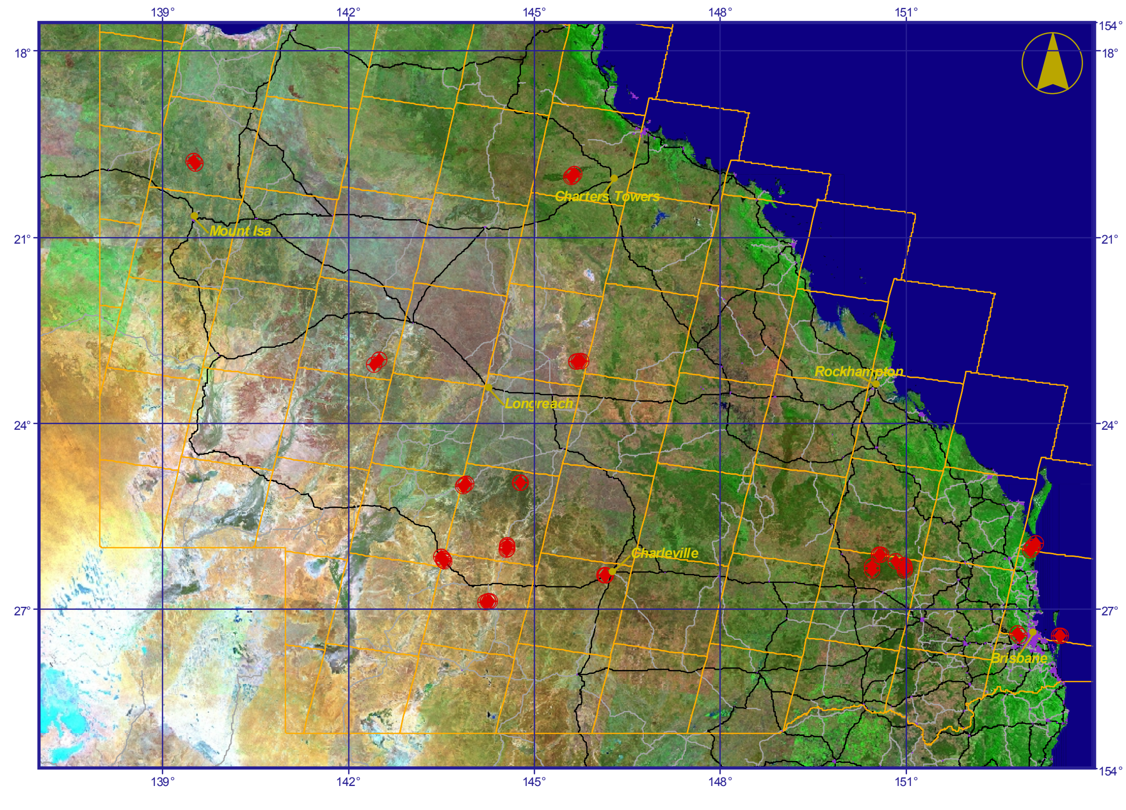

Figure 1 - Map of central and southern Queensland showing the location of transect sites as red crosses and the outlines of Landsat scene extents

This fieldwork was designed to support a LiDAR field campaign for the Statewide Landcover and Trees Survey (SLATS) program and therefore collected a variety of site data including:

- soil type, colour and structure
- ground, mid and upper story species composition and height; and
- live and dead basal area, crown, foliage and ground cover

The 53 sites were each set up as star transects, each 100 metres long, and laid out at 60° intervals (Figure 2). The centre of the star is located using a differential GPS. This is a useful configuration as it is efficient in practice and the area it samples can be readily linked to high and moderate spatial resolution imagery, such as Landsat TM.

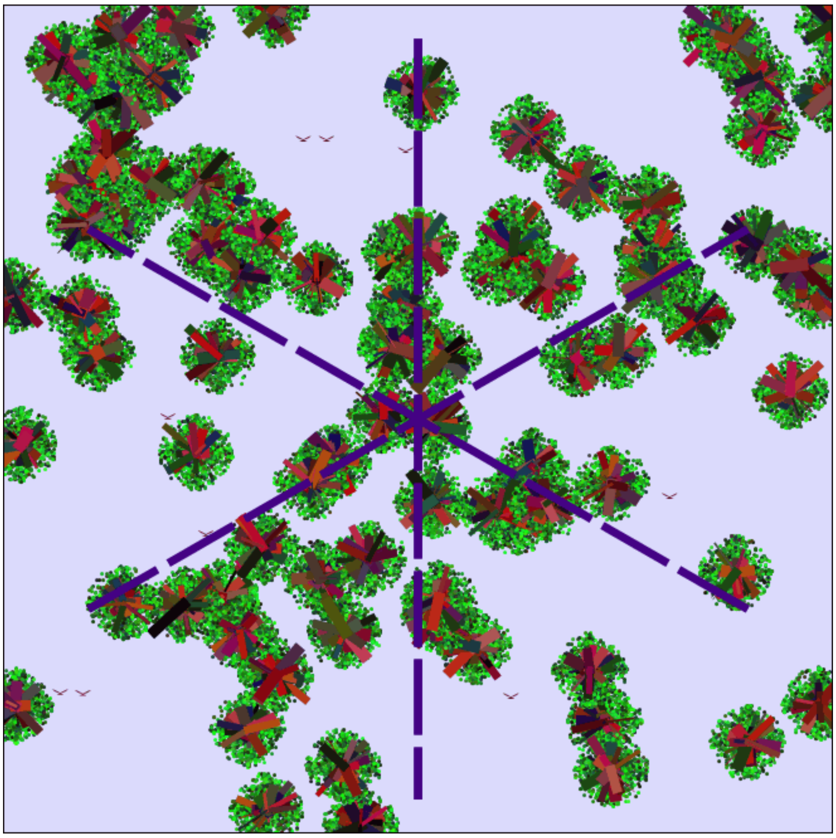

Figure 2 - Hypothetical schematic of a typical field star transect layout showing the location of each of the 100m transects (thick dashed lines) referenced to a central GPS located point.

Each of the three transects were 100 metres long and FPC and CC measurements were made at 1 metre intervals along the length of each transect using a vertical tube method (Specht 1983) with intercepts classified as green leaf, dead leaf, branch or sky by the observer. These measurements were converted to percentage cover for each of the sites. By plotting up the sites in cover vs. height space, it is possible to check that the primary forest and woodland types have been adequately sampled. Figure 3 shows that the field program has achieved a good distribution of sites in all the major structural types encountered across Queensland.

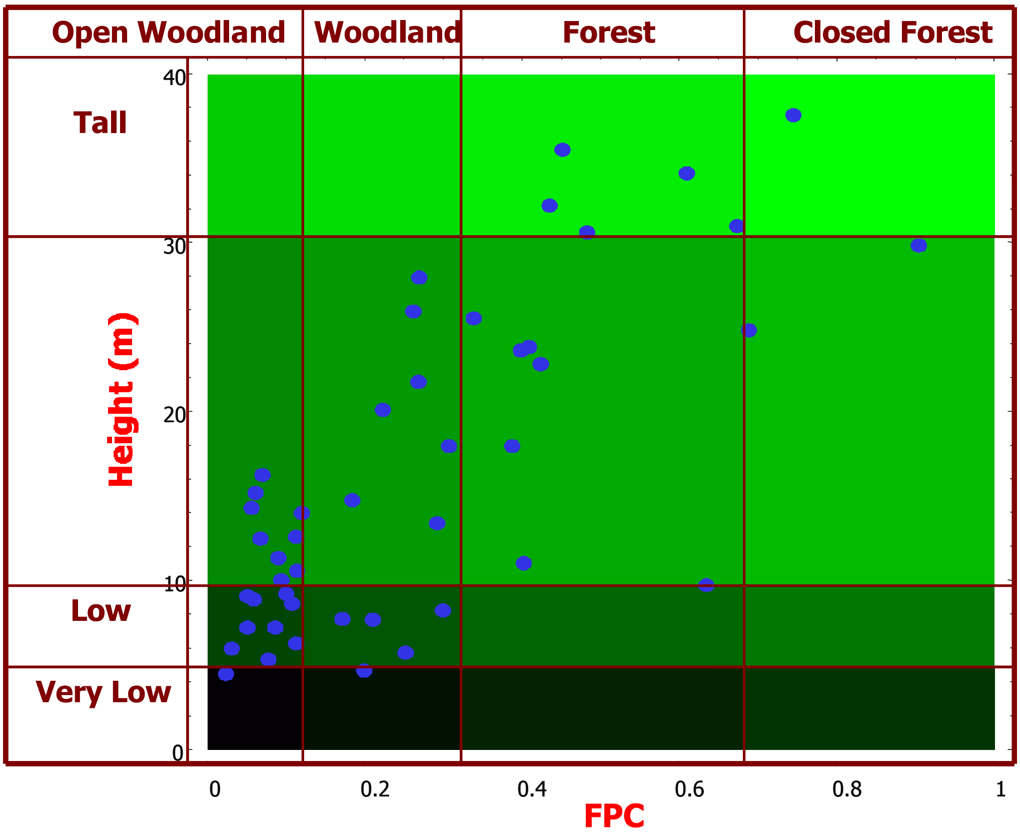

Figure 3 - Study sites (blue dots) plotted against crown height and FPC showing representative spread of sites across the major Queensland forest and woodland types.

Gap probability model linking FPC and CCP in clumped canopies.

The probability ($P_{gapstand}$) of a beam of light travelling at a zenith angle θ passing through a gap in a stand having a LAI of L, a stand clumping factor of $\Omega(\theta)$ and a leaf angle distribution of $G(\theta)$ is given by Chen (1997):

$$P_{\text{gapstand}}(\theta) = e^{-\frac{G(\theta)\Omega(\theta)L}{\cos(\theta)}} \qquad (1)$$

Note that, by definition, FPC is one minus the gap probability at a zenith of zero:

$$P_{\text{gapstand}}(0) = 1 - FPC \qquad (2)$$

Therefore we have

$$FPC = 1 - e^{-\frac{G(0)\Omega(0)L}{\cos(0)}} \qquad (3)$$

This can be inverted to give LAI as a function of FPC:

$$L = \frac{\log(1 - FPC)}{G(0)\Omega(0)} \qquad (4)$$

We note that the probability of intercepting a leaf (FPC) is equal to the probability of intercepting a crown (CC) multiplied by the probability of intercepting a leaf within a crown (1-$P_{gapcrown}$)

$$FPC = CC(1 - P_{gapcrown}) \tag{5}$$

If we define the within crown clumping factor as $\psi(\theta)$ then at a zenith angle of zero degrees:

$$P_{gapcrown} = e^{-\frac{G(0)\Psi(0)L}{\cos(0)}} \tag{6}$$

Thus combining (5) and (6)

$$CC = \frac{FPC}{1 - e^{-G(0)\Psi(0)L}} \tag{7}$$

Substituting in (4) we cancel out L and $G(\theta)$ and get

$$CC = \frac{FPC}{1 - e^{-\frac{\Psi(0)}{\Omega(0)}\log(1-\mathrm{fpc})}} \tag{8}$$

Which can be simplified to:

$$CC = \frac{FPC}{1 - (1 - FPC)^{\frac{\Psi(0)}{\Omega(0)}}} \tag{9}$$

Inverting this gives the ratio of the global to crown clumping as a function of CC and FPC:

$$\frac{\Omega(0)}{\Psi(0)} = \frac{\log(1 - FPC)}{\log\left(1 - \frac{FPC}{CC}\right)} \tag{10}$$

Thus we have the ratio of the stand (Ω) and the within individual crown foliage clumping (ψ) factors as a function of FPC and CC only. We now need to develop a relationship between these clumping factors. To do this, we use Boolean set theory (Strahler and Jupp 1990). In the Boolean model, the objects are assumed to be randomly distributed in a 'Poisson' distribution. Thus, if we assume the individual crowns are randomly located within the stand, the CC can be defined as a function of the mean crown radii (r_c) and the crown density or number of crowns per unit area (λ_c) and is given by:

$$CC = 1 - e^{-\lambda_c \pi r_c^2} \tag{11}$$

However, observation suggests that in natural communities, individual plants may be aggregated due to microsite differences or to competitive interactions resulting in crowns being typically clumped within a stand. In response to this effect, some authors (e.g. Leblanc *et al.* 1999) have proposed a Neyman Type A non-random spatial distribution of crowns to create patches of a forest stand. If we modify (11) to allow the CC to be clumped into "regions" of radii (r_r) and density (λ_r) we get the clumped CC (CC_{clumped}) as:

$$CC_{clumped} = 1 - e^{-\lambda_r \pi r_r^2 (1 - e^{-\lambda_c \pi r_c^2})} \tag{12}$$

We let $b = \lambda_r \pi r_r^2$ in (12) and with some manipulation, simplify the relationship to:

$$\frac{CC_{clumped}}{CC} = e^{b(CC-1)} \tag{13}$$

The term $e^{b(\text{ccp}-1)}$ represents an estimate of the crown clumping parameter (χ) at a zenith of zero, and the relationship linking it to the stand clumping parameter (Ω) and the within crown clumping parameter (ψ) is given by:

$$\Omega(\theta) = \chi(\theta)\psi(\theta) \tag{14}$$

Then, by combining (14) and (13) we can also express the ratio of the stand and the within individual crown foliage clumping factors as a function of CC with two parameters, ***a*** and ***b***:

$$\frac{\Omega(0)}{\Psi(0)} = a \quad e^{b(CC-1)} \tag{15}$$

Note that we introduce the parameter ***a*** to account for the ratio in (15) never reaching 1. ***a*** can be thought of as a parameter describing the dispersion of point patterns in spatial statistics. We would expect ***a*** to be less than one for a clumped point pattern, equal to one for random pattern, and greater than one for uniform pattern (Batista and Maguire 1998; Moeur 1997).

Thus, from (9) and (15) we have the final relationship between CC and FPC as:

$$CC = \frac{FPC}{1 - (1 - FPC)^{a \; e^{-b(CC-1)}}} \tag{16}$$

Results

To recover the parameters ***a*** and ***b*** we fit the results of (10) to the field estimates of CC using nonlinear regression (Figure 4). Here the fit is reasonably good across all our field data with the nominal value of ***a*** as 0.968±0.007 and ***b*** as 0.347±0.023.

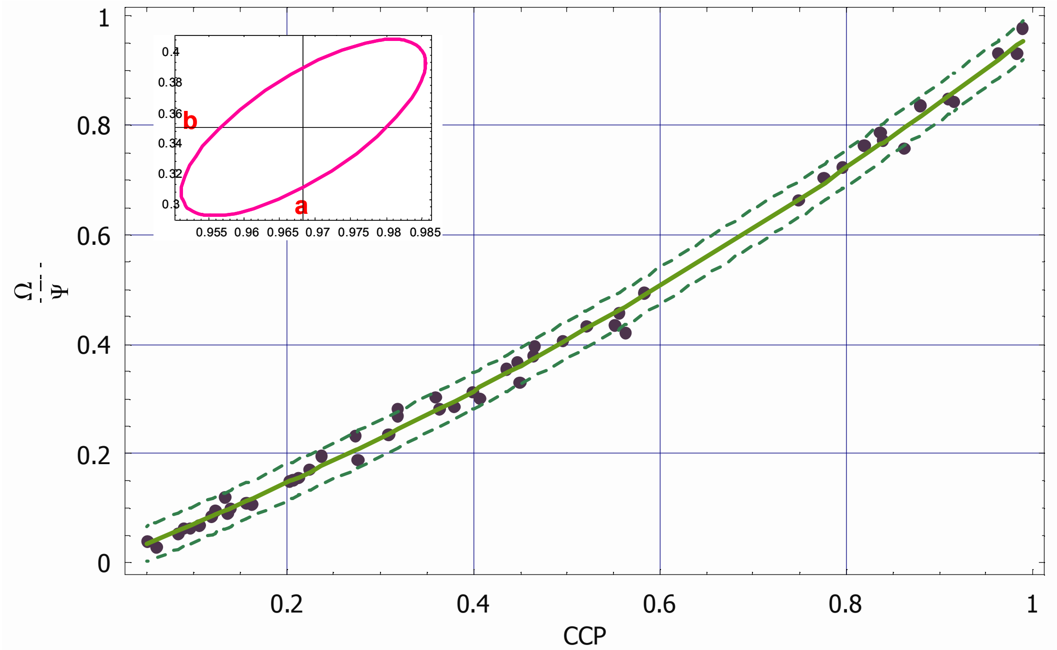

Figure 4 - Plot of field determined $\frac{\Omega(0)}{\Psi(0)}$ from (10) vs. CC and result of fitting (15)with 95% confidence limits. Inset is the confidence ellipse for the fitted parameters ***a*** and ***b***.

We can substitute these fitted parameters into (16) to recover the final equation relating CC and FPC for Queensland. Note however, that (16) cannot be solved directly since CC occurs on both sides of the equation. Therefore, we use a numerical root-finding algorithm to produce the plot of CC vs. FPC (Figure 5). Tables created from (16) for selected FPC and CC values can be found in Appendix 1 - Tables of fitted values.

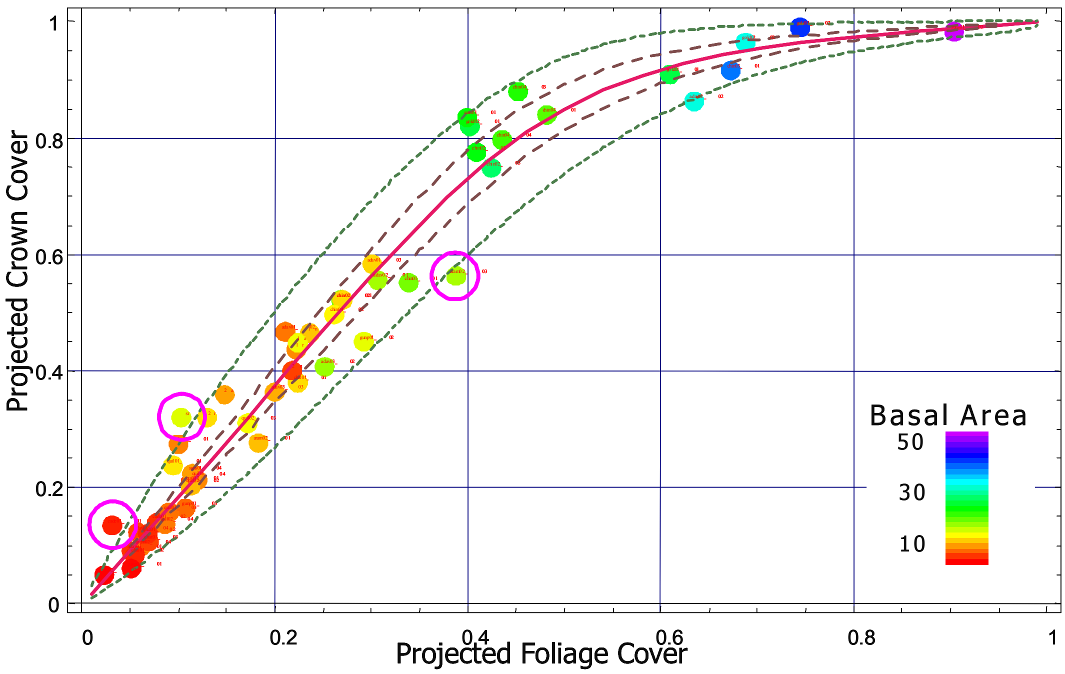

Figure 5 - Field determined FPC vs. CC. The colour scale represents field measured stand basal area (m ha^{-1}). Red line indicates fitted values of a and b applied to (16). Coarse dashed line indicates 95% confidence interval. Fine dashed line indicates 95% prediction interval. Pink circles highlight outlying field sites in the fitted result.

Discussion and conclusions

Simple established models of crown light interception and spatial clumping can be readily combined to develop a semi analytical model relating FPC to CC where the parameters can be easily retrieved from transect based field survey data. Of the 53 sites measured in the field, only three sites (highlighted with pink circles in Figure 5) could be considered as outliers in the final relationship. The two low cover sites have lower than expected FPC given the site CC and basal area. This is due to these sites being sampled while they were severely drought stressed resulting in fewer leaves and a steeper mean leaf angle. The single site with higher than expected FPC was a site along a creek line that was recovering from storm disturbance. The storm had removed many branches from the trees with epicormic growth increasing the FPC quickly on the remaining branches, resulting in a relative reduction of CC.

One important point to note is that FPC has a higher dynamic range than CC which saturates once FPC reached about 75% (see Appendix 1 - Tables of fitted values). This saturation has been noted before in analysis of geometrical optical models (Scarth and Phinn 2000). Given the diversity of sites sampled in this field campaign, it is likely that the relationship observed between CC and FPC would be similar across large parts of Australia. Further analysis of this data is in progress which will demonstrate how the three clumping factors (Ω, ψ and χ) can be retrieved from the field data set, allowing a comprehensive linkage of FPC, CC, LAI and stand basal area. This work has important implications for Australian vegetation monitoring frameworks as it demonstrates that vegetation clumping at multiple scales is an important attribute to measure, reiterating previous work in measuring and modelling heterogeneous plant canopies (e.g. Ni-Meister *et al.* 2001; Privette *et al.* 2004).

Future work will build on the LiDAR data captured at each of the sites sampled in this work. The LiDAR data has provided a far denser data set than the transect surveys and has allowed the retrieval of some vegetation structural parameters over a much larger area than is possible with transect based approaches. Many of the vegetation sites used in this work will be remeasured over the coming years, providing information on the variation in these structural attributes over time. Capturing data on vegetation state and condition is a fundamental monitoring task, and it is hoped that this work will provide guidance and impetus to those planning similar field campaigns to support forest and carbon inventory and help facilitate valid comparison of FPC and CC image products derived from remote sensing.

Acknowledgments

The authors would like to thank Rob Hassett and Sel Counter for their assistance in planning and executing the field data collection for this project.

References

Australia National Forest Inventory, Australia Dept of Agriculture Fisheries and Forestry, & Sciences., A.B.o.R. (2003.). *Australia's state of the forests report 2003*. Canberra: Dept. of Agriculture, Fisheries and Forestry; Bureau of Rural Sciences

Batista, J.L.F., & Maguire, D.A. (1998). Modeling the spatial structure of topical forests. *Forest Ecology and Management, 110*, 293-314

Campbell, G.S. (1990). Derivation of an angle density function for canopies with ellipsoidal leaf angle distributions. *Agricultural and Forest Meteorology, 49*, 173-176

Chen, J.M., Rich, P.M., Gower, S.T., Norman, J.M., & Plummer, S. (1997). Leaf area index of boreal forests: theory, techniques, and measurements. *Journal of Geophysical Research D, 102*, 29429-29443

Falster, D.S., & Westoby, M. (2003). Leaf size and angle vary widely across species: What consequences for light interception? *New Phytologist, 158*, 509-525

Fensham, R.J., Fairfax, R.J., Choy, S.J.L., & Cavallaro, P.C. (2003). Modelling trends in woody vegetation structure in semi-arid Australia as determined from aerial photography. *Journal of Environmental Management, 68*, 421-436

Henry, B., Danaher, T., McKeon, G., & Burrows, W. (2002). A review of the potential role of greenhouse gas abatement in native vegetation management in Queensland's rangelands. *The Rangeland Journal 42*, 112-132

Johansson, T. (1985). Estimating canopy density by the vertical tube method. *Forest Ecology and Management, 11*, 139-144

King, D.A. (1997). The functional significance of leaf angle in Eucalyptus. *Australian Journal of Botany, 45*, 619-639

Kucharik, C.J., Norman, J.M., & Gower, S.T. (1999). Characterization of radiation regimes in nonrandom forest canopies: Theory, measurements, and a simplified modeling approach. *Tree Physiology, 19*, 695-706

Leblanc, S.G., Bicheron, P., Chen, J.M., Leroy, M., & Cihlar, J. (1999). Investigation of directional reflectance in boreal forests with an improved four-scale model and airborne POLDER data. *IEEE Transactions on Geoscience and Remote Sensing, 37*, 1396-1414

Moeur, M. (1997). Spatial models of competition and gap dynamics in old-growth Tsuga heterophylla/Thuja plicata forests. *Forest Ecology and Management, 94*, 175-186

Ni-Meister, W., Jupp, D.L.B., & Dubayah, R. (2001). Modeling lidar waveforms in heterogeneous and discrete canopies. *IEEE Transactions on Geoscience and Remote Sensing, 39*, 1943-1958

Privette, J.L., Tian, Y., Roberts, G., Scholes, R.J., Wang, Y., Caylor, K.K., Frost, P., & Mukelabai, M. (2004). Vegetation structure characteristics and relationships of Kalahari woodlands and savannas. *Global Change Biology, 10*, 281-291

Scarth, P., & Phinn, S. (2000). Determining forest structural attributes using an inverted geometric-optical model in mixed eucalypt forests, Southeast Queensland, Australia. *Remote Sensing of Environment, 71*, 141-157

Simioni, G., Gignoux, J., & Le Roux, X. (2003). Tree layer spatial structure can affect savanna production and water budget: Results of a 3-D model. *Ecology, 84*, 1879-1894

Specht, R.L. (1981). Foliage projective cover and standing biomass., *Vegetation classification in Australia* (pp. 10-21). Canberra: CSIRO Division of Land Use Research

Specht, R.L. (1983). Foliage projective covers of overstorey and understorey strata of mature vegetation in Australia. *Austral Ecology, 8*, 433-439

Strahler, A.H., & Jupp, D.L.B. (1990). Modeling bidirectional reflectance of forests and woodlands using Boolean models and geometric optics. *Remote Sensing of Environment, 34*, 153-166

Walker, J., & Hopkins, M.S. (1990). Australian soil and land survey : field handbook. In R.C. McDonald, R.F., Isbell, J.G.,Speight, J. Walker, and M.S. Hopkins. (Ed.), *Australian soil and land survey : field handbook* (p. 190). Canberra: CSIRO

Appendix 1 - Tables of fitted values

CC	FPC	CC	FPC	CC	FPC	CC	FPC
0%	0%	25%	14%	50%	27%	75%	41%
1%	1%	26%	14%	51%	27%	76%	42%
2%	1%	27%	15%	52%	28%	77%	43%
3%	2%	28%	15%	53%	28%	78%	44%
4%	2%	29%	16%	54%	29%	79%	44%
5%	3%	30%	16%	55%	29%	80%	45%
6%	3%	31%	17%	56%	30%	81%	46%
7%	4%	32%	17%	57%	30%	82%	47%
8%	4%	33%	18%	58%	31%	83%	48%
9%	5%	34%	18%	59%	32%	84%	49%
10%	6%	35%	19%	60%	32%	85%	50%
11%	6%	36%	19%	61%	33%	86%	51%
12%	7%	37%	20%	62%	33%	87%	52%
13%	7%	38%	20%	63%	34%	88%	54%
14%	8%	39%	21%	64%	34%	89%	55%
15%	8%	40%	21%	65%	35%	90%	57%
16%	9%	41%	22%	66%	36%	91%	59%
17%	9%	42%	22%	67%	36%	92%	61%
18%	10%	43%	23%	68%	37%	93%	63%
19%	10%	44%	24%	69%	37%	94%	66%
20%	11%	45%	24%	70%	38%	95%	69%
21%	11%	46%	25%	71%	39%	96%	73%
22%	12%	47%	25%	72%	39%	97%	78%
23%	12%	48%	26%	73%	40%	98%	84%
24%	13%	49%	26%	74%	41%	99%	92%

FPC	CC	FPC	CC	FPC	CC	FPC	CC
0%	0%	29%	54%	58%	91%	87%	98%
1%	2%	30%	56%	59%	91%	88%	99%
2%	4%	31%	58%	60%	92%	89%	99%
3%	5%	32%	60%	61%	92%	90%	99%
4%	7%	33%	62%	62%	93%	91%	99%
5%	9%	34%	63%	63%	93%	92%	99%
6%	11%	35%	65%	64%	93%	93%	99%
7%	13%	36%	67%	65%	94%	94%	99%
8%	15%	37%	68%	66%	94%	95%	99%
9%	16%	38%	70%	67%	94%	96%	100%
10%	18%	39%	72%	68%	95%	97%	100%
11%	20%	40%	73%	69%	95%	98%	100%
12%	22%	41%	75%	70%	95%	99%	100%
13%	24%	42%	76%	71%	96%		
14%	26%	43%	77%	72%	96%		
15%	28%	44%	79%	73%	96%		
16%	30%	45%	80%	74%	96%		
17%	32%	46%	81%	75%	96%		
18%	33%	47%	82%	76%	97%		
19%	35%	48%	83%	77%	97%		
20%	37%	49%	84%	78%	97%		
21%	39%	50%	85%	79%	97%		
22%	41%	51%	86%	80%	97%		
23%	43%	52%	87%	81%	98%		
24%	45%	53%	88%	82%	98%		
25%	47%	54%	88%	83%	98%		
26%	49%	55%	89%	84%	98%		
27%	51%	56%	90%	85%	98%		
28%	53%	57%	90%	86%	98%		