Calibrating the LI-COR LAI-2000 for estimating leaf area index in eucalypt plantations

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Abstract

A calibration curve relating plant area index (PAI) as measured with the LI-COR LAI-2000 (PCA) to leaf area index was developed for Eucalyptus nitens *plantations in Tasmania. This was done by developing allometric relationships for branch leaf area and branch diameter, and tree leaf area and tree diameter. These were used to estimate leaf area index for six* E. nitens *plantation sites. Leaf area index calculated from the developed allometric relationships* (L^*_1) *was tightly correlated with the PAI measured by the PCA* (L^*_2). *This relationship* ($r^2 = 0.99$) *can be expressed as* $L^*_1 = 1.54 L^*_2 - 0.1$. *The relationship is similar to that reported in studies with other arboreal species and suggests that a common calibration curve may be appropriate for most eucalypt plantation species.*

Introduction

Light interception is a key determinant of forest growth, so that a linear relationship between growth and intercepted light is often observed at a site (e.g. Beadle *et al.* 1995). The amount of incident radiation intercepted by a forest is determined to a large extent by the foliage area per unit ground area, conveniently expressed as leaf area index (*L**). *L** is a primary input to processed based models of forest growth (McMurtrie and Wolf 1983; Battaglia and Sands 1997).

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For many forest canopies, the relationship between light interception and *L** is steep initially and, at an *L** of about 6, there is approximately 95% light interception (Jarvis and Leverenz 1983). As *L** increases above this level, there is little further increase in light intercepted. Vigorously growing eucalypt plantations on good sites (mean annual increment greater than 30 m^3 / ha / yr) usually have *L** of between 4.5 and 6 (Beadle *et al.* 1995). On poor sites *L** may be less than 2.

Direct methods of estimating *L** in plantations and native forests are laborious and time consuming. These methods include destructive sampling of representative branches and trees, and using allometric relationships between leaf area and stem characteristics (Norman and Campbell 1989). Litter-trap methods provide delayed estimates of *L** but rely on measurement of foliage turnover rates which are highly variable, and assume that the stand has reached constant *L**. Indirect methods of determining *L** relate total leaf area to the radiation environment below the canopy and are generally less time consuming as well as non-destructive. Many indirect methods of measuring *L** have been developed and are based on the Beer-Lambert Law (Monsi and Saeki 1953) or gap fraction theory (Miller 1967).

The LAI-2000 Plant Canopy Analyser (PCA, LI-COR Inc, Lincoln, Nebraska, USA) is a portable integrating radiometer which provides a non-destructive means of

Photo 1. Note the sensor mounted on the tripod in the clearing and the data logger recording incident radiation. The second sensor is carried by the operator, as shown, for below canopy measurements.

indirectly estimating L^* using gap fraction theory (Photo 1). The PCA measures the light intercepted not only by the leaves but also by branches, stems and reproductive structures. Such measures estimate plant area index (PAI, Horn 1971; Cermàk 1989). Measures of PAI can provide continuous estimates of L^*, enabling time-series studies not possible with destructive sampling.

The PAI measured using the PCA is generally lower than L^* and this is probably due to deviations from four theoretical assumptions used in calculating PAI (LI-COR 1991). The most critical assumption made is that no radiation is reflected or transmitted by the foliage. Optical filters incorporated in the PCA sensors reject light above 490 nm and, in the portion of the spectrum seen by the sensors, there is relatively little reflection or transmission by the foliage. The second assumption is that the foliage is randomly distributed. The third and fourth assumptions are, respectively, that the foliage elements are small and that the foliage is azimuthally randomly oriented (LI-COR 1991). Forest and plantation canopies do not conform exactly to these assumptions because branches and leaves are clumped and are not optically black, leading to the underestimation of L^*. Because of these deviations from the theoretical assumptions, it is necessary to calibrate the PCA so that measured PAI can be used to predict true L^*.

In this paper, a direct determination of L^* by an allometric technique is used to calibrate the PCA for *Eucalyptus nitens* (Deane and Maiden) Maiden plantations. The relationship is considered in the context of studies on another eucalypt species and canopies of different structure and morphology. Possible uses for the PCA in eucalypt plantations are discussed.

Materials and methods

Site description

Six sites in four *E. nitens* plantations were used for the calibration (Table 1). The plantations had been subjected to similar silvicultural treatment, except levels of fertiliser addition. Stocking at Wyena was 1000 stems / ha and at the other sites 1430 stems / ha, with a spacing of 2.5 m and 2.0 m within, and 4.0 m and 3.5 m between rows, respectively. Subsequent losses since planting were not measured. The six sites were chosen from a visual estimation of canopy size to encompass a range of L^*s.

At the time of measurement (winter 1996), the plantations were aged six (Goulds and Lewisham) or seven years (Creekton and Wyena). Canopy closure had occurred within and between rows at all sites except at Wyena where canopy closure was within rows only. All crowns appeared in reasonable health,

Table 1. Characteristics of the sites sampled in winter 1996.

Plantation	Latitude	Longitude	Altitude (m a.s.l.)	Planting density (stems/ha)	Fertiliser (kg/ha N:P:K)	Mean height (m)	Mean diameter[1] (cm)
Creekton 1	43·21' S	146·54' E	110	1430	300:120:0	15.7	15.8
Creekton 2	43·21' S	146· 54' E	110	1430	100:120:0	12.1	11.4
Creekton 3	43·21' S	146·54' E	110	1430	0:120:0	9.0	9.2
Goulds	43·18' S	147·01' E	100	1430	200:120:0	16.5	16.2
Lewisham	42·49' S	147·36' E	20	1430	440:120:0	13.3	16.3
Wyena	41·10' S	147·17' E	150	1000	200:120:0	5.9	7.0

[1] at 1.3 m above ground over-bark

with no evidence of vertebrate or invertebrate browsing. Minimum canopy lift was 2 m. A light understorey was present at all sites and, where this exceeded 1 m in height, it was cleared before measurements commenced.

Harvesting

One plot containing 84 trees (7 rows x 12 trees) was established at the centre of each site. The over-bark diameter at 1.3 m above ground (DBHob) of each tree was measured and the trees ranked into six diameter classes of approximately equal number. Six trees, one representing the average of each size class, were harvested for leaf area determination. The harvested trees were felled at ground level. Tree height and height to the first limb carrying live foliage were measured and the difference, crown length, calculated. The crown was then divided into upper (u), middle (m) and lower (l) zones of equal length. Height above-ground, and diameter over-bark (D) at 4 cm from the base of each first order branch were measured. Five representative branches from each zone were selected, excised at the base of the branch and placed into plastic bags. Stem diameters at the base of the live crown were measured.

The length of harvested branches was measured and the leaves removed from each branch. Ten leaves were randomly selected from each branch for determination of specific leaf area (area:dry weight ratio). The remaining leaves were dried for 72 h (at least) at 40·C and then for 24 h at 80·C. The leaves were cooled in a desiccator and weighed. The area of the 10-leaf sample was measured (Area Measurement System, Delta-T Devices, Cambridge, UK), the leaves dried for 24 h at 80·C and their weight added to the corresponding bulk sample.

Calculations

A group regression procedure (McPherson 1990: p. 549) was used to select the simplest model to describe the relationship between the natural logarithm (ln) of leaf area and ln of branch diameter squared. Initially, a unique equation was fitted to the data for each site in each u, m, and l zone. That is,

$$\ln(L)_{ij} = \mathrm{A}_{ij} + \mathrm{B}_{ij}\ln(D^2)$$

where L_{ij} is the leaf area at the ith site in the jth zone, and D^2 is the branch diameter squared. An analysis of variance procedure was used to simplify the model by progressively testing if the deviance was significantly increased ($P = 0.01$) by generalising the equation parameters, A and B, across sites and zones.

This model was used to calculate the leaf area of each branch. The branch leaf areas were summed for individual trees to give tree leaf area. Regression analysis was used to determine a linear relationship between ln tree leaf area and ln DBHob for the harvested trees at each site. From this model, leaf area

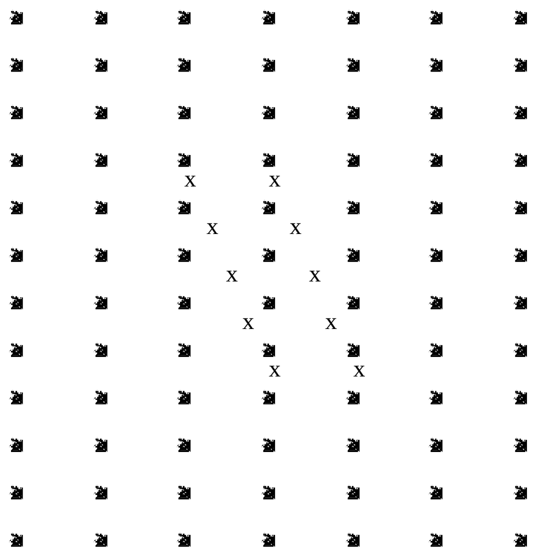

Figure 1. Location of PCA measurement sites (X) in plantation plot rows.

of the plot trees was calculated by expressing the DBHob as *L* for each tree in the plot measured (Figure 1). The sum of the tree leaf areas for each plot and the ground area these trees covered was calculated and expressed as *L**. Linear regression analysis was used to determine the relationship between *L** measured using the PCA and from the above calculations.

LAI-2000 Plant Canopy Analyser (PCA)

All sites were assessed for plant area index (PAI) using the PCA in June and July (winter) 1996. Two PCA consoles and sensors were used in tandem; that is, remote mode (see LI-COR 1991). One sensor was located in the centre of a clearing of at least 40 m diameter, the minimum area necessary at these sites to ensure an uninterrupted view of open sky conditions. The clearing was within 200 m of the edge of the site. Readings were logged at 15 s intervals. Below canopy measurements with a second sensor were taken at 10 stations set diagonally across the rows in the centre of the plots (Figure 1). A minimum of three sets of measurements were taken at each site. All readings were taken on the level at 1.5 m above ground level. All measurements were made in overcast conditions with a consistently high level of cloud cover without using a lens cap (Appendix).

PCA 2000-90 Support Software was used to mask information collected by the 5th ring of the sensor lens from the *L** computations (Appendix).

Results

Branch leaf area

The group regression procedure established that the slope (1.2087) of the relationship between ln L_{ij} and ln (D^2) was common across sites and leaf zones. However, it was necessary to fit a unique intercept to each site by leaf zone combination (Table 2). This model provided a good fit to the data ($r^2 = 0.91$, $P < 0.0001$) and enabled calculation of tree leaf area for the harvested trees at each site.

Tree leaf area

The weighted linear regression analyses of tree leaf area and DBHob provided a unique equation for each site (Table 3). The *L** ranged from 2.24 at the poorest site, Wyena, to 7.43 at Goulds.

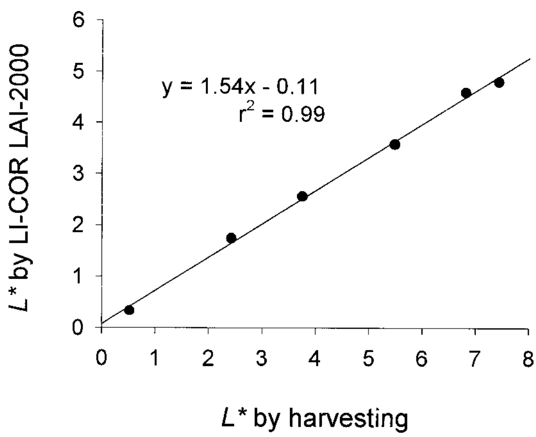

Figure 2. Calibration curve for L* *as calculated by harvesting and* L* *measured using PCA.*

Site leaf area

Regression analysis of the L^* data collected by the PCA and by harvesting was described by a linear model ($r^2 = 0.99$). The slope and intercept were 0.640 and 0.134 respectively (Figure 2).

Discussion

A strong allometric relationship was observed between branch leaf area and branch diameter, enabling the calculation of tree leaf area from the measured diameters of all branches for each sampled tree. A second relationship was developed between the calculated individual tree leaf area and DBHob for each of six eucalypt sites. Leaf area index was calculated for each plot and used to develop a linear model between L^* measured using the PCA and calculated using the developed allometric relationships. This relationship ($r^2 = 0.99$) can be expressed as $L^*_1 = 1.54L^*_2 - 0.1$ (or $L^*_1 = 1.51L^*_2$ if the regression is forced through the origin), where L^*_1 is the leaf area index estimated by destructive sampling and L^*_2 is the PCA reading.

As has been observed in previous studies (e.g. Chason *et al.* 1991; Chen *et al.* 1991; Smith *et al.* 1991), plant area index assessed with the PCA was consistently less than leaf area index but this bias was easily corrected. It has been suggested that underestimation of L^* at high L^* is due to clumping of the foliage. Overestimation can occur at lower values of L^* than were measured in this study, or when the bias due to clumping is removed, because of the effects of branch and stem area index on the estimation of L^* (Chen *et al.* 1991; Deblonde *et al.* 1994; Sampson and Allen 1995).

The calibration curve derived for *E. nitens* here was identical to that developed for *E. globulus* plantations in south-western Western Australia ($L^*_1 = 1.51L^*_2$, Hingston *et al.* 1994). Site fertility varied markedly between stands in the Tasmanian calibration set. Site water-supply and stocking varied markedly between stands used in the Western Australian calibration set. For the normal range of L^* (2–8) for eucalypt plantations, this suggests that the calibration curve for the PCA may be applicable in temperate Australia providing horizontal heterogeneity in leaf area distribution is low (that is, large, between-tree gaps are not frequent). Concerns about the effects of site quality, management practices and stand structure on canopy architecture (Sampson and Allen 1995) may not apply to the use of calibration curves relating PCA readings to actual values of L^* for these eucalypt species, though

Table 2. Intercepts of the linear relationships between the natural logarithm of D^2 *and the natural logarithm of branch leaf area in the upper* (u), *middle* (m) *and lower* (l) *canopy zones. The common slope was 1.2087.*

Site	Leaf zone	Intercept
Creekton 1	*l*	2.5647
Creekton 1	*m*	2.7709
Creekton 1	*u*	1.9764
Creekton 2	*l*	2.7111
Creekton 2	*m*	2.9173
Creekton 2	*u*	2.1228
Creekton 3	*l*	2.2359
Creekton 3	*m*	2.4421
Creekton 3	*u*	1.6476
Gould's	*l*	2.5573
Gould's	*m*	2.7635
Gould's	*u*	1.9690
Lewisham	*l*	2.5979
Lewisham	*m*	2.8041
Lewisham	*u*	2.0096
Wyena	*l*	2.0164
Wyena	*m*	2.2226
Wyena	*u*	1.4281

Table 3. Parameters describing the linear relationship between the natural logarithm of the over-bark diameter at 1.3 m above ground (DBHob) and the natural logarithm of tree leaf area.

Plantation	Intercept	Slope	r^2
Creekton 1	-2.4721	2.2581	0.93
Creekton 2	-2.3926	2.1867	0.92
Creekton 3	-3.1583	2.5362	0.97
Goulds	-4.2721	2.9180	0.96
Lewisham	-1.6499	2.0415	0.93
Wyena	-4.1234	2.8821	0.88

clearly caution is required if measuring L^* in stands subject to silvicultural interventions such as thinning or pruning that will affect the structure of canopies and the frequency of canopy gaps.

For the range of L^*, 2–8, the relationship for *E. nitens* (and *E. globulus*) was also similar to that developed for predominantly coniferous plantations in the USA ($L^*_1 = 1.88L^*_2 - 1.88$, Gower and Norman 1991) and to that for *Pinus sylvestris* L. ($L^*_1 = 1.4L^*_2 - 0.6$), if the non-linearity is disregarded (Smölander and Stenberg 1996). For example, at a true L^*_1 of 2, the equation from this work, from the coniferous plantations of Gower and Norman (1991) and the *Pinus sylvestris* plantation of Smölander and Stenberg (1996) indicate that the PCA reading will be 1.36, 2.06 and 1.86 respectively and, at a true L^*_1 of 8, the readings will be 5.26, 5.26 and 6.14 respectively. The relationship does not appear to differ markedly except in cases of extreme foliar clumping, such as for *Picea mariana* (Paul Jarvis, pers comm.).

The ability to rapidly assess L^* using the PCA provides a means of establishing a correlation between L^* and site factors. For example, it may be possible to predict improved growth returns from silvicultural practices such as fertilisation or irrigation by predicting the extent to which L^* can be increased (Battaglia *et al.* 1997). L^* estimated by the PCA also is useful for examining seasonal changes in L^* and differences between treatments imposed on eucalypt plantations. The instrument also offers the opportunity of time-series measurements for following impacts of defoliation on production by either vertebrate or invertebrate browsing, the effectiveness of pesticides or other measures in controlling defoliation, and defoliation from environmental causes such as drought. Several factors, for example plot size, tree height and the distribution of canopy gaps should be considered prior to measurement which must be undertaken under diffuse light conditions. These factors are considered in the Appendix.

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References

Battaglia, M., Cherry, M.L., Beadle, C.L. and Hingston, A. (1997). Leaf area index prediction in eucalypt plantations: accommodating the effects of water stress and temperature. *Tree Physiology* 18: 521–528.

Battaglia, M. and Sands, P.J. (1997). Modelling site productivity of *Eucalyptus globulus* in response to climate and site factors. *Australian Journal Plant Physiology* 24: 831–850.

Beadle, C.L., Honeysett, J.L., Turnbull, C.R.A. and White, D.A. (1995). Site limits to achieving genetic potential. In: *Eucalypt Plantations: Improving Fibre Yield and Quality* (eds B.M. Potts, N.M.G. Borralho, J.B. Reid, R.N. Cromer, W.N. Tibbits and C.A. Raymond), pp. 325–331. CRC Temperate Hardwood Forestry, Hobart.

Cermàk, J. (1989). Solar equivalent leaf area: an efficient biometrical parameter of individual leaves, trees and stands. *Tree Physiology* 5: 269–289.

Chason, J.W., Baldocchi, D.D. and Huston, M.A. (1991). A comparison of direct and indirect methods for estimating forest canopy leaf area. *Agricultural and Forest Meteorology* 57: 107–128.

Chen, J.M., Black, T.A. and Adams, R.S. (1991). Measuring leaf area index of plant canopies with branch architecture. *Agricultural and Forest Meteorology* 55: 129–143.

Deblonde, G., Penner, M. and Royer, A. (1994). Measuring leaf area index with the Li-cor LAI-2000 in pine stands. *Ecology* 75(5): 1507–1511.

Gower, S.T. and Norman, J.M. (1991). Rapid estimation of leaf area index in conifer and broad-leaf plantations. *Ecology*. 72(5): 1896–1900.

Hingston, F.J., Galbraith, J.H and Dimmock, G.M. (1994). Evaluating the effect of soils and climate on productivity of *Eucalyptus globulus* plantations on contrasting sites in south west of Western Australia. *Rural Industries Research and Development Corporation Final Report. No. CSF-41A*, Rural Industries Research and Development Corporation, Perth, Western Australia.

Horn, H.S. (1971). *The Adaptive Geometry of Trees.* Princeton University Press, Princeton, N.J.

Jarvis, P.G. and Leverenz, J.W. (1983). Productivity of temperate and evergreen forests. In: *Physiological Plant Ecology. IV. Ecosystem Processes, Mineral Cycling, Productivity and Man's Influence* (eds O.L. Lange, P.S. Noble, C.B. Osmond and H. Ziegler), pp. 233–280. Springer-Verlag, New York.

LI-COR (1991). *Plant Canopy Analyser Instruction Manual.* LI-COR Inc., Lincoln, Nebraska, USA.

McMurtrie, R.E. and Wolf, L. (1983). Above- and below-ground growth of forest stands: a carbon budget model. *Annals of Botany* 52: 437–448.

McPherson, G. (1990). *Statistics in Scientific Investigation. Its Basis, Application and Interpretation.* Springer-Verlag, London.

Miller, J.B. (1967). A formula for average foliage density. *Australian Journal of Botany* 15: 141–144.

Monsi, M. and Saeki, T. (1953). Über den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung für die Stoffproduktion. *Japanese Journal of Botany* 14: 22–52.

Norman, J.M. and Campbell, G.S. (1989). Canopy structure. In: *Plant Physiological Ecology: Field Methods and Instrumentation* (eds R.W. Pearcy, J. Ehleringer, H.A. Mooney and P.W. Rundel), pp. 301–325. Chapman and Hall, London and New York.

Sampson, D.A. and Allen, H.L. (1995). Direct and indirect estimates of leaf area index (LAI) for lodgepole and loblolly pine stands. *Trees* 9: 119–122.

Smith, F.W., Sampson, D.A. and Long, J.N. (1991). Comparison of leaf area index estimates from tree allometrics and measured light interception. *Forest Science* 37(6): 1682–1688.

Smölander, H. and Stenberg, P. (1996). Response of LAI-2000 estimates to changes in plant surface area index in a Scots pine stand. *Tree Physiology* 16: 345–349.

Appendix. Considerations in the use of PCA in eucalypt plantations.

Plot size

The PCA measures the attenuation of light at five zenith angles simultaneously. The optical sensor projects the image onto five detectors arranged in concentric rings. Detector 1 measures the brightness overhead (0–13· from vertical) while detector 5 measures brightness of a ring between 61· and 74· from vertical. Therefore, as plot height increases, the distance seen horizontally by the sensor increases. The fifth ring views the light closest to the horizon. Therefore, with fifth ring data removed, what remains represents a smaller plot area. Fifth ring data were removed routinely in this experiment and, in a plantation with mean tree heights of 5, 10, 15 and 20 m, the plot sizes required would be approximately 7 x 7, 12 x 12, 34 x 34 and 48 x 48 m, respectively. The larger plot sizes needed for the taller trees can be handled through use of view caps and removal of the data taken by more of the outer rings of the sensor. The view caps can be used so that readings can be taken on the edge of a plot where the view cap blocks light seen by the sensor in the direction of the plot edge. For example, measurements can be taken at the four corners of a plot using the view cap that covers 270· of the sensor rings such that the sensor views into the centre of the plot.

Raising the sensor also allows measurement of taller canopies with smaller plot sizes by decreasing the horizontal area seen by the sensor.

Plot characteristics

Canopy size and density vary seasonally. In comparative or time-series studies, it is recommended that measurements using the PCA be completed at a similar time of year or level of canopy development. The period of slow growth and low rates of litterfall during winter provide an ideal period for measurement as canopy size tends to be stable.

Plots with heavy understorey above the sensor height chosen by the operator and below the eucalypt canopy to be measured need to be cleared. This can be both costly and time consuming. If the total forest canopy is to be assessed, for example in mixed forest, the sensor height can be set at ground level. The PCA has a requirement for a minimum foliage distance from the sensor (see LI-COR 1991: appendix F).

Measurement plots of small dimensions, with narrow buffer zones or on the edge of forests or plantations, can be subjected to light entering horizontally beneath the canopy. This leads to the below canopy sensor seeing a higher amount of light than would be indicative of the canopy density and consequently causes an even greater underestimation of L^* by the PCA. Data from the fifth ring can be removed and / or readings taken with the sensor positioned at the edges of the plot and using a view cap to exclude any view of the surrounding vegetation.

A spirit level attached to the sensor arm is used to level the PCA. On sites with extreme slopes, the view seen by the sensor can be interrupted by the surrounding hillslope. View caps can be used to block sight of the surrounding landscape.

Sky conditions

The PCA must be used under diffuse light conditions which can be achieved under clear skies by the use of view caps. In this work, the PCA calibration was done on days with a consistently high level of cloud cover, when the view cap is not required to obscure the solar disc. Our experience indicates that L^* is underestimated more severely when view caps are used under clear sky conditions. Shading the canopy can alleviate this problem but, in a mature plantation or forest with a tall canopy, this is impractical. The PCA can be used successfully at dawn and dusk when the surrounding landscape effectively shades the canopy being studied but a limited period only is available for measurements.

Light intensity must also be considered before measurements are taken. A minimum level of around 22 lux (the level of light required for comfortable reading) is required for successful PCA measurements. Our experience indicates that at lower light levels L^* values are severely underestimated. This is particularly important when using the PCA at dawn and dusk.