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Accurate area determination of complex leaves using digital image analysis

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Abstract. A recently described computer image analysis method was modified for quantification of leaf area. These areas were compared to those estimated by a lower resolution method based on planimetry. Leaves of *Eucalyptus nitens* (Deane & Maiden) Maiden, pinnae of *Dicksonia antarctica* Labill. and leaves of *Acacia dealbata* Link were used for analysis, offering surfaces of low, intermediate and high complexity, respectively. Low-resolution planimetry was found to be a suitable method for the calculation of leaf area of simple broadleaves. However, for surfaces of greater complexity, the higher resolution of image analysis gave more accurate estimates of area. Overlapping of primary pinnae in the complex *A. dealbata* leaf proved to be a larger source of error than inadequacy of resolution.

Keywords: leaf area, planimetry, *Acacia dealbata*, *Eucalyptus nitens*, *Dicksonia antarctica.*

Introduction

Accurate determination of crown or canopy leaf area is essential for the scaling up of individual leaf measurements in many hydrological, productivity and physiological studies (Grier and Running 1977; Waring *et al*. 1981; Wang *et al*. 1995). Much attention has been given to the problem of adequately describing the three-dimensional distribution of foliar elements within canopies (e.g. Smith *et al*. 1993) and to the relative merits of sampling protocols that estimate leaf area from subsampling canopy components (e.g. Pinkard and Beadle 1998). However, the accuracy of measurement of individual leaves has received less consideration in the literature (e.g. see Kvet and Marshall 1971; Larsen and Kershaw 1990).

Planimetry is the most commonly used technique when measurement of a one-sided leaf area is required, and a range of commercial devices such as the Delta-T leaf area meter (Delta-T Devices Ltd, Cambridge, England) and the Licor LI-3000 area meter (Licor Inc, Lincoln, NE) is available for this purpose. Such instruments use photographic- or videographic-type lenses to measure the area of light occluded by a leaf based on a surface grid of varying resolution. Assuming frequent calibration of the instrument during measurement, radial distortion of the image and low resolution of the lens are potential sources of error with this method. The former is minimised by placing samples close to the centre of the reading frame. The latter is a function of the relationship between instrument resolution and the size of elements to be distinguished (Biscoe and Jaggard 1985). This error is more likely to be significant when dealing with complex or fine leaves rather than broadleaves.

For measurements of fine and needle-leaved species, simple lens-based planimetry may be inadequate, particularly due to parallax errors, and several alternative methods have been proposed including computer scanning and image analysis (Kershaw and Larsen 1992). Recently, several dedicated image analysis systems have been developed for area measurement of leaves and roots, employing both camera and scanner systems for image capture (e.g. Delta-T DIAS and Delta-T SCAN respectively). Such commercial systems have overcome the problems of resolution stated above, but may be expensive and can be time-consuming to operate when dealing with small foliar elements (Kershaw and Larsen 1992).

For the present study we were interested in partitioning a plantation forest canopy between the two dominant tree species, and thus required a high resolution image analysis technique that was inexpensive, simple and labour-saving. A recently described method using computer image analysis for the quantification of light occlusion through fish-cage netting (Hodson *et al*. 1995) was modified for this purpose. Leaves of *Eucalyptus nitens* (Deane & Maiden) Maiden, pinnae of *Dicksonia antarctica* Labill. and leaves of *Acacia dealbata* Link were used for analysis, offering surfaces of low, intermediate and high complexity, respectively. We tested whether image analysis returned significant gains in accuracy over low-resolution planimetry for these surfaces, and identified sources of measurement error for the highly dissected acacia leaves. The results are discussed in the context of sampling protocols in leaf-to-canopy scaling exercises.

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Materials and methods

Experiment 1 — Optimum scanning resolution

A green broadleaf-shaped paper replica, a green paper rectangle (42.25 cm^2) and three replicates each of an *A. dealbata* leaf and a *D. antarctica* pinna were scanned for image analysis using a computer image analysis protocol modified from Hodson *et al.* (1995). Objects were placed on an Epson GT-6500 scanner and the images were captured as 16 colour grey scale TIFF files on an IBM-pc computer (80486DX2-66) using the software Epson Scan (V. 1.30). The resolution was varied across 22 default resolutions (from 45 dots per inch {dpi} to 600 dpi) for the broadleaf replica and across 9 resolutions (within the same range) for the paper rectangle. The *A. dealbata* and *D. antarctica* foliage was scanned at five resolutions corresponding to those considered suitable for routine measurement (50, 75, 100, 144, 180 dpi). In all cases, a plain white background was used to ensure colour distinction of the object edges. An image analysis package (IDRISI V. 4.1; Clark University, MA, USA) was used to determine the area (cm^2) of the object/s in the scan. The captured TIFF images required conversion to IDRISI format using the IDRISI 'TIFIDRIS' module. The IDRISI 'RECLASS' module was used to assign the value 0 to all colours except the white background and shadows (which were assigned 15) and the IDRISI 'AREA' module was used to measure the object area (i.e. the area covered by pixels with a value of 0). The measured area was automatically saved to a text file at the conclusion of the process. A batch file incorporating the three IDRISI modules was used to process a set of scanned images.

Experiment 2 — Comparison of methods

A Delta-T leaf area meter was used to estimate area by planimetry (A_p) for a set of custom-built black aluminium plates of different shapes. This instrument has a resolution of 1/300 of the scanned width (about 20 cm in this experiment) which equates to approximately 35 dpi and uses a high contrast light occlusion technique. Before experimentation the instrument was calibrated using three rectangular metal standards (100 cm^2, 50 cm^2, 10 cm^2) supplied by the manufacturer. Each aluminium plate was placed in the centre of the reading frame and the area measured three times (one measurement series), with each measurement on a different orientation of the plate. Each plate was then measured once at each of the cardinal radii on the reading frame. Calibration was repeated between each measurement series.

The areas of the plates were then remeasured (A_i) using the image analysis system described above (*Experiment 1*). The resolution was held constant at 300 dpi.

Experiment 3 — Leaf complexity and crown position

Leaves were sampled from four trees in a mixed *E. nitens*/*A. dealbata* canopy; one eucalypt, the dominant of the four, and three acacias which represented co-dominant, subdominant and understorey canopy classes. Tree crowns were divided vertically into thirds for sampling. Twelve replicate leaves were collected from each of the upper, middle and lower thirds of each of the four tree crowns. All leaves were weighed fresh (W_f), measured individually by image analysis (at 75 dpi with the above methods) and subsequently measured by planimetry. The process was completed within 36 h of collection.

Twelve pinnae of *D. antarctica* were excised from a single mature frond. Each was measured in the centre of the planimeter, in three different orientations. The 12 pinnae were then separated into four groups of three. Each group was measured three times in the centre of the planimeter, the pinnae being arbitrarily moved in relation to each other between replicate scans. All pinnae were subsequently measured in the same manner by image analysis.

Experiment 4 — Dissection of A. dealbata

The effect of folding and closing of acacia leaves on measured area (with respect to total area) was assessed on leaves from a subdominant tree (scanning resolution 75 dpi). Three replicates of two representative leaves were sampled from each acacia crown position (18 leaves, 9 samples) and scanned individually (Fig. 1*a*). For each pair of representative leaves, the primary pinnae were detached from the primary rachides, separated across the scanner bed so that none overlapped, and rescanned (Fig. 1*b*). Two primary pinnae sampled from each leaf in the pair (four pinnae per replicate) were then scanned (Fig. 1*c*), prior to detachment and separation of the secondary pinnae and scanning for a fourth time (Fig. 1*d*).

For controls, square pieces of card (of known dimensions) were measured with the leaf area meter and by image analysis. Three 25-cm^2 squares of card (5 cm × 5 cm) were first measured by the leaf area meter. Each was bisected and remeasured. The process was repeated a further seven times for each replication, yielding 256 elements of an average size of approximately 0.1 cm^2. A subsample of 15 elements was then measured and two further bisections undertaken, yielding the equivalent of 1024 elements of 0.024 cm^2 average area (based on 25 cm^2 original). A single 100-cm^2 square (10 cm × 10 cm) was measured using the image analysis method (above). Prior to dissection of the card, a pixel classification protocol was defined that yielded a value of A_i closest to the geometrically calculated area (length × breadth). The square was subsequently bisected and remeasured 8 times (that is 512 elements, average size of approximately 0.19 cm^2). A subsample of 15 elements was bisected and remeasured a further 4 times yielding elements of the same final size as for the leaf area meter controls (0.024 cm^2, see above). Each image was scanned at 6 resolutions (see Table 3) and all images were adjusted digitally to account for shadow (based on the pixel classification protocol noted above). Where sub-sampling was undertaken (for both the leaf area meter and image analysis), results were expressed as a proportion of the area of original card.

Analysis

Results were analysed using simple descriptive techniques (Experiment 2), *t*-tests (Experiments 1, 3 and 4) and ANOVA (Experiments 3 and 4). All *t*-tests were two-tailed; both single factor and replicated two-factor ANOVAs were used.

Results

Optimum scanning resolution

Area of the broadleaf replica increased in magnitude from 45 dpi (the lowest resolution) to 400 dpi (with a small decrease from 90 dpi to 120 dpi) before declining to a minimum at the highest scanning resolution (600 dpi) (Fig. 2*a*). The paper rectangle returned values closest to the known area (determined geometrically) when scanned at the lowest resolutions (50 and 75 dpi) and again at very high resolution (Fig. 2*a*). The *A. dealbata* series showed decreasing area from 50 dpi to 75 dpi before increasing again to 180 dpi. *D. antarctica* values followed a similar pattern but reached minima at 100 dpi (Fig. 2*b*).

The degree of variation in A_i at different resolutions varied among the surface types measured (from 1% to 5% of the scanned area). These differences were associated with the perimeter/area ratio and the size of the scanned elements, the magnitude of the variation being inversely affected by image area. A comparison of A_i with true area was calculated geometrically for the paper rectangle but at this stage an independent area measure for leaves was not possible (however, see results for Experiment 4 below). The optimum scanning resolution suggested by the standard shape data was 75 dpi. Thus, this resolution was used for subsequent experiments with leaves.

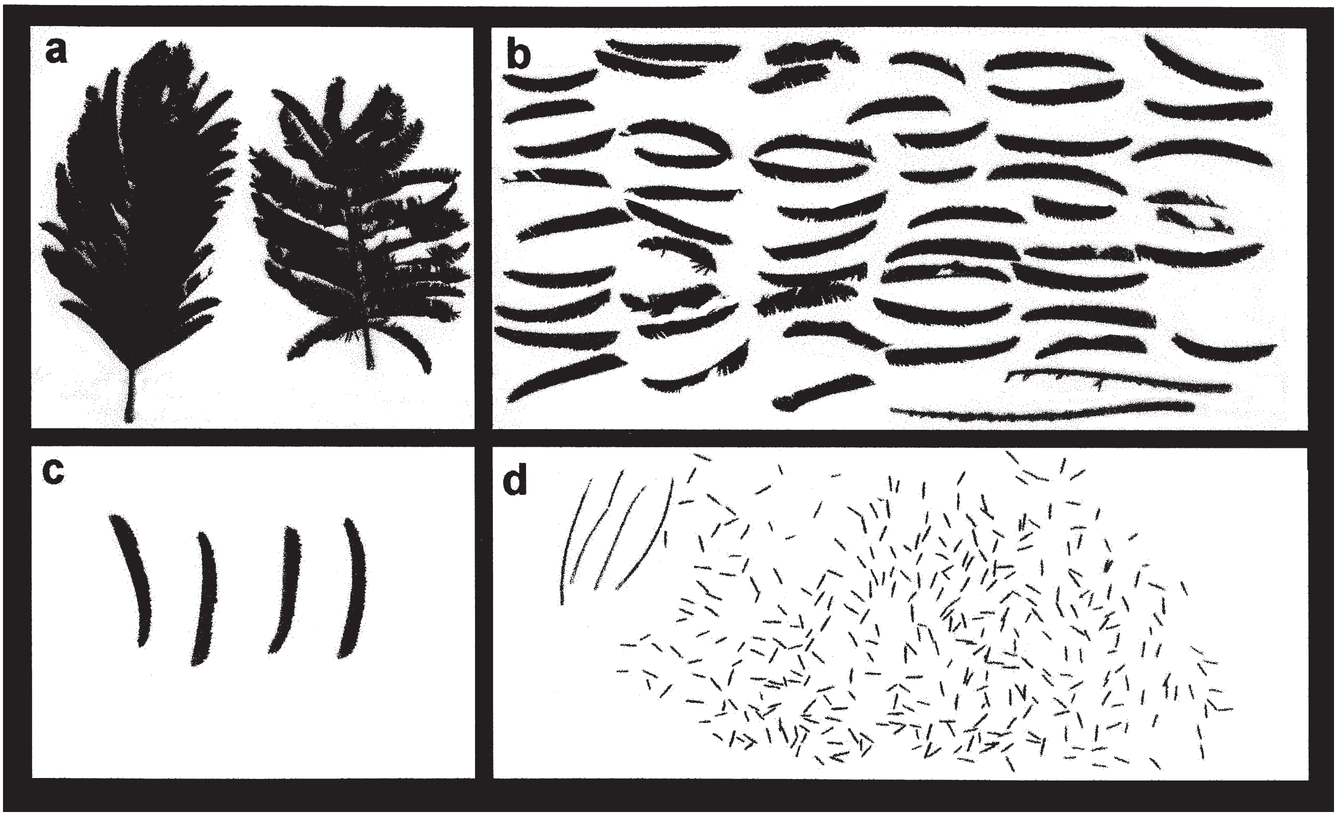

Fig. 1. Progressive dissection of the *Acacia dealbata* leaf, from intact leaf (*a*) to component primary pinnae (*b*), primary pinnae subsample (*c*) and dissection to component secondary pinnae and rachides (*d*).

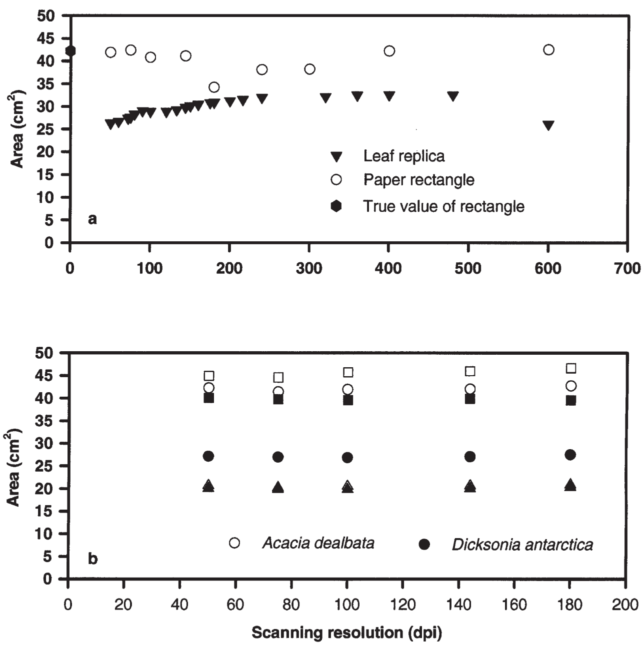

Fig. 2. Variation in measured area with changes in scanner resolution of (upper) a paper broadleaf replica and a paper rectangle of known area, and (lower) three replicates each of a *Dicksonia antarctica* pinna (closed symbols) and an *Acacia dealbata* leaf (open symbols).

Comparison of methods

A_p was marginally higher (<1%) at the frame edges than at the centre of the reading frame of the Delta-T planimeter ($P < 0.05$). The magnitude of this variation was small compared to the measured differences in area between planimeter and image analysis where the mean ratio A_p/A_i was 0.97 ($P < 0.05$, SD = 0.01).

Leaf complexity and crown position

Data for each crown position for the four trees are summarised in Table 1. A_p was significantly different to A_i for each of the 12 data sets ($P < 0.001$ in all cases). A_p was consistently 97% of A_i for the eucalypt with no significant difference ($P > 0.05$) among crown positions. For acacias, A_p varied between 8% and 65% of A_i for individual leaves and the ratio (A_p/A_i) was significantly different among acacia crown positions and canopy classes ($P < 0.001$). In each of the three acacia crowns sampled, A_i decreased from the upper crown to the lower crown (Table 1). The coefficient of variation did not differ significantly between A_p and A_i among eucalypt crown positions ($P > 0.05$). However, significant differences in the coefficient of variation were observed among acacias and crown positions within acacias between

Table 1. Variation in leaf area between planimetry (A_p)

Tree ID	Crown third	A_p (cm^2)	A_i (cm^2)	A_p/A_i
E. nitens	Top	66.61	69.05	0.97
	Middle	77.07	80.60	0.96
	Lower	83.89	86.95	0.97
A. dealbata	Top	27.64	50.41	0.55
co-dominant	Middle	24.68	73.88	0.35
	Lower	18.17	70.57	0.25
A. dealbata	Top	22.03	55.61	0.39
sub-domininant	Middle	28.68	75.96	0.37
	Lower	14.52	67.07	0.22
A. dealbata	Top	22.82	68.21	0.33
understorey	Middle	23.96	62.67	0.37
	Lower	14.63	69.03	0.21
D. antarctica	–	22.80	23.90	0.93

A_p and A_i ($P < 0.001$). The coefficient of A_i was less than 20% in eight of the nine acacia crown thirds sampled.

The mean value of A_p/A_i for *D. antarctica* was 0.93 (standard deviation 0.05) for both the 12 individual pinnae and the four pinna groups. There was no significant difference in A_p/A_i between the pinna groups and the sums of the corresponding individual pinna measurements.

Dissection of A. dealbata

Dissection of *A. dealbata* leaves to primary pinnae resulted in increases of A_i between 26% and 83% (ratio primary pinnae / intact leaf) with significant differences among crown positions (P<0.01) (Table 2). Hence, the overlapping of primary pinnae is a large source of error in estimation of true area. Further reduction of primary pinnae to composite secondary pinnae (ratio secondary pinnae/ primary pinnae subsample) resulted in significant increases of A_i of up to 10% for upper and middle crown and 43% for the lower crown ($P < 0.01$) (Table 2).

Measured area of the controls increased with decreasing element size for the leaf area meter down to 0.1 cm^2 element size (Table 3*a*). The measured area subsequently decreased markedly with decreasing element size. For image analysis, a similar trend was evident (Table 3*b*). However, the coefficients of variation were markedly smaller for image analysis compared with the leaf area meter. No significant improvement in the coefficient of variation was achieved by using a scanner resolution of greater than 75 dpi (Table 3*b*).

Discussion

Significant increases in measured leaf area were obtained by using image analysis compared to planimetry. Greater leaf complexity resulted in larger errors using planimetry or low resolution image analysis. Inadequate instrument resolution was a particularly important source of error when estimating leaf area of *A. dealbata* and was exacerbated by the presence of overlapping pinnae.

Although image analysis can avoid potential sources of error in planimetry, it is complex due to the interaction of pixel classification and resolution issues. For each set of similar images scanned, subjective decisions must be made as to which pixels are to be classified as true image, shadow and background. Increasing complexity of image (particularly with surface depth) leads to increasing difficulty in classification of the shadow / image boundary (Hodson *et al.* 1995). In addition, increasing resolution does not indefinitely improve the accuracy of the measurement. Beyond an optimum resolution, overestimates and underestimates of true surface area may be observed depending on a number of surface properties. In the present study, the subjectivity of

Table 2. The effect on measured area of progressively dissecting *A. dealbata* leaves to component primary and secondary pinnae. Leaves were sampled from three crown positions on a sub-dominant tree

Crown position		Area (cm^2)					
		Intact leaf	Primary pinnae	Primary pinnae subsample	Secondary pinnae	Primary pinnae/ leaf	Secondary pinnae/ primary pinnae
Upper crown	Rep1	33.56	56.72	3.24	3.52	1.69	1.09
	Rep2	31.00	54.08	4.70	5.06	1.74	1.08
	Rep3	33.75	53.21	3.99	4.40	1.58	1.10
	Mean					1.67	1.09
	C.V. (%)					5.13	1.21
Mid crown	Rep1	35.90	52.50	4.73	5.16	1.46	1.09
	Rep2	27.61	34.71	3.36	3.64	1.26	1.08
	Rep3	31.69	44.78	6.03	6.18	1.41	1.02
	Mean					1.38	1.07
	C.V. (%)					7.78	3.39
Lower crown	Rep1	35.51	58.69	5.38	7.61	1.65	1.41
	Rep2	29.46	51.99	4.88	7.38	1.76	1.51
	Rep3	38.97	71.38	4.90	6.64	1.83	1.36
	Mean					1.75	1.43
	C.V. (%)					5.17	5.56

Table 3. Control bisection of paper square to elements

Bisection number	Number of elements	Mean size of element (cm^2)	Area (cm^2)				
			(a) Leaf area meter				
			Rep 1	Rep 2	Rep 3	Mean	
0	1	25.0	25.0	25.0	25.0	25.0	
1	2	12.5	25.1	25.0	25.0	25.0	
2	4	6.25	25.0	25.1	25.1	25.1	
3	8	3.125	25.2	25.1	25.1	25.1	
4	16	1.563	25.4	25.3	25.2	25.3	
5	32	0.78	25.6	25.5	25.4	25.5	
6	64	0.39	26.0	25.6	25.7	25.8	
7	128	0.19	26.2	25.6	25.7	25.8	
8	256	0.1	26.0	25.8	25.8	25.9	
9	512	0.05[A]	12.5	20.0	17.5	16.7	
10	1024	0.024[A]	2.5	7.5	7.5	5.8	
C.V. (%)			34.3	23.5	24.6	27.3	
			(b) Image analysis				
			50 dpi	75 dpi	100 dpi	150 dpi	200 dpi
0	1	100.0	97.4	101.5	102.5	101.8	101.5
1	2	50.0	101.6	101.6	102.5	102.9	103.1
2	4	25.0	101.7	101.8	101.9	101.9	101.4
3	8	12.5	101.6	101.2	101.8	101.9	101.9
4	16	6.25	101.8	101.5	101.6	101.7	101.7
5	32	3.125	100.6	101.1	101.4	101.5	101.6
6	64	1.563	100.3	100.9	101.4	101.7	101.6
7	128	0.78	99.7	100.5	101.5	101.8	101.7
8	256	0.39	97.8	99.6	100.6	101.4	101.3
9	512	0.19	96.1	98.8	100.6	101.6	101.5
10	1024	0.1	99.1	101.0	102.8	104.1	103.7
11	2048	0.05[A]	96.7	96.7	106.7	107.0	106.6
12	4096	0.024[A]	91.8	97.8	100.2	102.4	102.0
C.V. (%)			3.0	1.6	1.6	1.5	1.4

[A]Subsample calculated back to the area of the original square.

these decisions (pixel classification and optimum resolution) was partly overcome by consideration of a synthetic surface of known area and of the same colour as the leaves later measured (paper rectangle).

A resolution of 75 dpi was suitable for measurement of leaves of low, intermediate and high complexity in the current study. The accuracy of this resolution was shown for surfaces of low complexity (Fig. 2*a*) and the acacia resolution series (Fig. 2*b*) shows that increases beyond 75 dpi have little effect with surfaces of high complexity. Analysis of control surfaces further showed that resolutions above 75 dpi do not reduce coefficients of variation between the measurement of elements the size of secondary acacia pinnae (Table 3). In a similar study with small leaf elements, Kershaw and Larsen (1992) showed that a resolution of 100 dpi is suitable for measurement of conifer needles. The use of resolutions well above 100 dpi is thus unnecessary, and moreover, should be avoided as they incur increased costs in processing time and computing resources.

Variation in measured area across a planimeter reading frame has been well established and is routinely accounted for in experimental work of this nature (Wolf 1983). However, the magnitude of this variation in the present study (<1%) was small compared to other errors identified. Resolution was of increasing importance with increasing surface complexity. Hence, mean values of A_p (at 35 dpi) were 97%, 93% and less than 40% of A_i (at 75 dpi) for eucalypt leaves, fern pinnae and acacia leaves respectively.

In addition to potential errors associated with resolution, measurement of acacia leaves is further complicated by their habit of closing around the rachides in response to diurnal rhythms, moisture conditions and mechanical disturbance (Daubenmire and Charter 1942; Robbertse 1972). For these reasons, accurate measurement is logistically very difficult with planimetry (Vertessy *et al*. 1995). The leaf area of intact acacia leaves was underestimated by almost half due to overlapping and folding of primary pinnae, and significant differences in this underestimation were identified among crown positions. Between-tree variation was not considered here but is likely to be important (Kvet and Marshall 1971). If present, it may preclude the establishment of relationships sufficiently robust to apply one correction factor across a sample of trees. Hence, acacia leaves must be reduced to their component pinnae for area analysis. Further division to secondary pinnae increased measured area, particularly in the lower canopy foliage, but it is difficult to attribute these increases in A_i to greater accuracy. The secondary pinnae are elements at the limit of the scanning resolution. Thus an underestimate of A_i is inherently probable (based on control data in Experiment 4) though opposite to the result obtained. Inadequate identification of shadows from the secondary pinnae during image analysis probably contributed to the larger area measured. The equivocal nature of these results and the costs in time and resources associated with reduction to component secondary pinnae prior to measurement suggest that it is not warranted.

Results from the present study have implications for directing sampling effort during canopy studies. Differences within crown positions in *A. dealbata* emphasise morphological variation in response to light environment, the importance of which has also been identified for both broadleaves and conifers (Niinimets and Kull 1995; Sprugel *et al*. 1996). The data from Experiments 3 and 4 in this study were used elsewhere for the calculation of specific leaf area (SLA) in the sample trees (Hunt 1998). SLA is the scaling variable normally used to estimate total crown or canopy leaf area from a foliar sub-sample (e.g. Pinkard and Beadle 1998). Within-crown variation in SLA was found to be small (less than 20% in all but one of nine acacia crowns) compared to the SLA variations resulting from resolution changes in the measurement of leaf area (50–1200%) and leaf to pinnae dissection (average 60%). Therefore emphasis must be placed on obtaining accurate leaf measurements during a scaling exercise, rather than the number of leaves included in a canopy sub-sample, the latter being the traditional approach due to the inherent within-crown variability of SLA (Kvet and Marshall 1971).

Low-resolution planimetry is not a suitable method for determining the area of fine complex leaves such as those of *A. dealbata*. The data indicate that a scanning resolution of at least 75 dpi is necessary for resolution of elements of the necessary size. However, higher resolution does not overcome the largest errors in the measurement of *A. dealbata* leaves which are associated with the overlapping of primary pinnae, particularly in upper canopy foliage. Reduction of leaves to their component primary pinnae is essential for accurate measurement.

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