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Use of digital photography for analysis of canopy closure

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Abstract

The relationships between trees and understory crops are very important in agroforestry systems. Also, above ground interactions can be related to canopy structure. However, measurements of canopy structural parameters, either destructive or indirect, are time-consuming or prohibitively expensive. The present work explored the use of digital photography as a simple method to characterise the extent of canopy closure (CC), defined as the area of tree canopies projected onto the horizontal ground surface beneath, and expressed as a percentage of the ground covered. Measurements were made in two Eucalyptus (*Eucalyptus nitens*, Deane and Maiden) plantations and a subtropical mixed legume woodland dominated by Albizia (*Albizia* sp), Kidneywood (*Eysenhardtia* sp.) and Desert Fern (*Lysiloma* sp.). Images were captured at dawn to minimise light scattering and the number of sunlit foliage elements. Mean CC estimates provided by analysis of images obtained using digital cameras with contrasting performance, a Kodak DC-120 and a Canon EOS D1, were similar in precision and accuracy both between the two cameras and to those provided by a Li-Cor LAI-2000 canopy analyser. Bias between the estimates provided by the Kodak and Canon cameras was −0.02, between the Kodak and LAI-2000 was −0.07 and between the Canon and LAI-2000 was −0.05. Data from a pruning experiment using alder also demonstrated the repeatability of estimates obtained with a photographic method using the Kodak camera. The number of ring sensors within the LAI-2000 used to estimate CC affected agreement between the photographic method and the LAI-2000.

Introduction

Tree canopy structure is a major factor defining competitive interactions in agroforestry systems. Due to growth, decay or management, the tree canopy structure is constantly changing in time and space. Canopy structure refers to the distribution of positions, orientations, areas and shapes of plant organs (Welles and Norman 1991). Tree canopy structure must be characterised to investigate and explain its effect on biophysical and ecological processes. Relationships between canopy dimensions, sapwood area or basal area are often established from canopy attributes to avoid labour-intensive sampling. Alternatively, canopy attributes such as leaf area or light interception may be measured indirectly using different optical instruments, particularly photography.

Ansley et al. (1992) predicted leaf area using photographs of tree profiles and a planimeter to measure the area of a hand-drawn line delineating the canopy profile. Grace and Fownes (1998) estimated leaf area using film slides and a dot grid to manually count the number of dots intersecting the canopy profile. Both authors found a good relationship between estimates of leaf area obtained by photography as compared to harvesting entire trees. Knowles et al. (1999) estimated canopy closure (CC), defined as the area of the tree canopy projected onto the horizontal ground surface below, using digitised still images taken from 8 mm video film; the canopy area was determined using digital image analysis. They found a good relationship between the extent of CC and stand parameters such as basal area and the ratio of green crown length to mean tree height.

Hemispherical photography combined with digital image analysis is used routinely to estimate canopy attributes such as leaf area or foliage inclination angle (Chen et al. 1991). Photographs are taken from below the canopy looking upwards under conditions where there is high contrast between leaves and the sky. Film-based hemispherical photographs have disadvantages because they cannot be reviewed in the field, and the film needs to be processed before being digitised. Film images lose resolution because they cannot preserve a higher resolution than that provided by the scanner used. Also, few digital cameras have a fisheye lens, and digital reflex cameras that can accommodate a fisheye lens are expensive. Frazer et al. (2001) reported that estimates of canopy closure were 1.4 times greater when obtained using a digital camera than a film-based camera, both using hemispherical lenses.

Comparisons of estimates of CC obtained using film-based or digital hemispherical photographs showed that image resolution, file compression, shutter speed and heterogeneity in sky luminance determine the accuracy of photographic estimates (Chen et al. 1991; Macfarlane et al. 2000; Frazer et al. 2001). Overexposure is the main problem associated with errors in the measurement of CC because this causes excessive light scattering and diffraction along the edges of branches and leaves (Chen et al. 1991; Frazer et al. 2001). The accuracy of digital image analysis depends on the edge definition between the structures, in this case the canopy and sky areas. Edge definition or sharpness is obtained by using the correct shooting speed, adequate contrast and film or sensor sensitivity (ISO speed). The accuracy of the imaging system also depends on tree architecture. The quality of digital images can also be improved by increasing image resolution, and photographs are taken under diffuse sky conditions because the range of brightness of foliage is minimised.

The LAI-2000 canopy analyser (Li-Cor Inc., Lincoln, NE, USA) is an indirect method for describing canopy attributes. This instrument estimates leaf area index (LAI) and the fraction of sky visible from beneath the canopy. The LAI-2000 method is fast, but it is sensitive to illumination conditions and stand boundary effects (Welles and Cohen 1996). These problems are reduced using sensor view- caps, obtaining measurements when the sun is low or protecting the sensor from direct sunlight (Li-Cor 1992). Although the effects of multiple light scattering can be corrected (Leblanc and Chen 2001) actual field LAI measurements are still routinely done under a range of illumination conditions, including direct sunlight.

The estimates of LAI obtained can be up to 40% lower than those provided by direct measurements, especially in canopies with large gaps (Welles and Norman 1991). The protocol recommended by Li-Cor (1992) results in substantial underestimation of direct measurements of LAI in agroforestry tree rows and vineyard canopies (Broadhead et al. 2003; Johnson and Pierce 2004). Estimates of LAI provided by hemispherical photography and the LAI-2000 differed only by 10% in forest canopies, but this relationship is sensitive to sky conditions, exposure and field of view (Welles and Cohen 1996). Larger differences in the estimates of LAI obtained by hemispherical photography and the LAI-2000 have also been found (Frazer et al. 1998). Similarly, Macfarlane et al. (2000) reported that the photographic method underestimated LAI by 16–30% when compared to the LAI-2000 method. However, good agreement between direct methods and estimation of LAI with a LAI-2000 was found in a forest canopy (López-Serrano et al. 2000).

Estimates of CC obtained using digital cameras are a potentially valuable alternative to the LAI-2000 method because they are very economical, and provide a permanent visual record of what was measured. If image analysis of digital photographs can provide reliable estimates of CC with the same precision as the LAI-2000, then canopy management decisions could be made based on this relatively straightforward and economical approach. However, there are many kinds of cameras providing a range of electronic capabilities and lens quality. This would affect the accuracy of estimates of CC and calibration would be necessary. The following study reported here compared estimates of CC obtained with digital photography using various camera settings and those provided by the LAI-2000. Three digital cameras were compared. It was hypothesised that estimates of CC provided by the digital photography approach would have a similar variance to those provided by the LAI-2000. A second hypothesis was that good agreement would be obtained between estimates of CC provided by the tested cameras.

Material and methods

Study locations

Measurements were made at three sites in Mexico. The Queretaro site (1867 m.a.s.l. 20°36′ N, 100°22′ W) had 45-year old Eucalyptus trees (*Eucalyptus nitens* (Deane and Maiden)), which were spaced 10–20 m apart, 25–30 m in height and with heavy branching. The Huimilpan site (2318 m.a.s.l. 20°22′ N, 100°16′ W) consisted of a 12-year-old *E. nitens* plantation initially spaced at 4 × 6 m; the trees were 7–12 m tall. The Amazcala site (1919 m.a.s.l. 20°41′ N, 100°16′ W) comprised a mixed subtropical woodland dominated by Albizia (*Albizia* sp.), Kidneywood (*Eysenhardtia* sp.) and Desert fern (*Lysiloma* sp.); the trees were 6–7 m in height. These sites were chosen to provide low, medium and high values of CC.

Data from a fourth site at the Horticultural Research Centre, Aokautere, New Zealand (30 m a.s.l. 40°22′ S, 175°40′ E) are also presented for comparison; this site was planted with 11-year old alder trees (*Alnus glutinosa* (L.) Gaertn). Three shade treatments were created by pruning trees to heights of 2.5, 5.0 and 7.0 m above ground level. These treatments provided three levels of transmitted photosynthetic active radiation i.e. 17, 27 and 77% of full sunlight as determined from measurements made at noon on three clear sky days using a LI-191 SA quantum sensor (Li-Cor Inc., Lincoln, NE, USA). Plot size was 5 by 7 m for all pruning treatments; CC was determined at the centre of each plot (Devkota et al. 2000).

Instrumentation and calculations

Three digital cameras of contrasting capability were used. A Kodak DC-120 camera with a fixed 39–114 mm *f*/2.5–3.8 lens and 1280×960 pixel image resolution (Eastman Kodak Corp., Rochester, NY, USA). A Mavica FD-7 (Sony Corp., New York, NY, USA) with a fixed 40–400 mm *f*/1.8–2.9 lens and 640×480 pixel image resolution. A Canon EOS D1 with an image resolution of 2464×1648 pixels (Canon Inc., Lake Success, NY, USA). This camera was fitted with an EF 28–70 mm *f*/3.5–5.6 lens.

The cameras were mounted on a tripod, levelled and oriented to magnetic north. Automatic exposure was used to reduce the possibility of overexposure (Macfarlane et al. 2000). A 10 s self-timer was also used to avoid any movement of the camera associated with the manual release of the shutter button (Frazer et al. 2001). Photographs were taken before sunrise to avoid large variation in brightness across the picture and reflections of direct sunlight from leaves or branches (Hale and Edwards 2002). Digital files were stored as RAW or KDC formats, which are the least compressed file types for the Canon and Kodak cameras, respectively. The Mavica camera stored images as JPG files.

Each measurement with the LAI-2000 was made by recording one reference reading 'above the canopy' and four readings below the canopy. The 'above canopy' values were determined in an open area whose radius was more than four times greater than the adjacent stand height, and using the same view-cap as was used for the below canopy measurements (López-Serrano et al. 2000). A 90° view-cap was used to reduce the bias in the below canopy measurements caused by heterogeneity in gap distribution within the field of view of the sensor (López-Serrano et al. 2000; Nackaerts et al. 2000). All measurements were made using a single LAI-2000 unit. When using this approach, it is essential that sky conditions remain uniform for the above and below canopy measurements (Li-Cor 1992). The readings beneath the canopy were made facing N, S, W and E at approximately 30 cm from the tripod.

The LAI-2000 measures diffuse sunlight by five concentric detector rings associated with the following zenith angles: 0–13°, 16–28°, 32–43°, 47–58° and 61–74°, where zero degrees represents the direct upward-view. These five rings bands are hereafter termed ring numbers 1, 2, 3, 4 and 5, respectively. Because the visual angle of the cameras lens was smaller than that of the LAI-2000, logged records were edited using the C2000 program and then recalculated using rings number 1 and 2, 1–3, 1–4 or 1–5. The diffuse non-interceptance value (DIFN) was used to estimate CC as (1-DIFN).

Measurements

Test 1 Sets of photographs were obtained to investigate the accuracy and precision of estimates of CC obtained using the LAI-2000 and digital photography. The first was collected between 26 and 28 June 2002 from each of the three sites in Mexico. Sampling points were selected using the following criteria: three parallel line transects were laid at each site at least 10 m apart to prevent sampling the same canopy gap. All gaps that were approximately 10 m apart within the transect were identified, at these ground points, the extend of canopy closure was measured using the LAI-2000. Four ground points were randomly selected within the first and fourth quartiles from the median estimates of CC obtained at each site. Similarly, five ground points were randomly selected within the second and third quartiles. Selecting ground points form each quartile ensured that a wider range of canopy closure was included to evaluate the methods of estimation of CC. The 18 selected ground points were surrounded by trees to avoid edge effects. A sample consisted of one photograph obtained using the Kodak camera, one with the Canon camera and corresponding paired LAI-2000 readings. All observations were made during periods of calm weather and clear sky. Collection started at twilight 1100 h Greenwich Mean Time (GMT), and approximately 50 min elapsed between the first and last image taken. Focal length was set to 50 mm for both cameras. For each site, a one-way ANOVA test was used to compare the mean estimates of CC obtained using digital photography and the LAI-2000. Estimates of CC obtained using the LAI-2000 were considered to provide the standard value. To verify if both estimates of CC have the same precision, the Bartlett test was used to compare the variance of the mean estimates of CC. Regression analysis also was used to compare estimates of CC obtained with the different methods. Bias was calculated using the procedures described by Bland and Altman (1986). The difference between each pair of estimates of CC obtained with the methods tested was calculated for each ground point (d). The mean difference ($\bar{d}$) and their standard deviation were used to summarise the lack of agreement between methods. Bias was estimated by $\bar{d}$ and 95% confidence intervals were also calculated.

Test 2 A second set of photographs was collected on 4 September 2002 at the Amazcala site. Two ground points were selected within one standard deviation from the mean estimate of CC determined previously in Test 1 with the LAI-2000. Photographs were taken using the Canon camera at focal lengths of 28, 35 and 50 mm, respectively corresponding to 59°, 49° and 35° vertical angles of view. Three consecutive photographs were taken together with one LAI-2000 measurement. For each ground point, these measurements were repeated four times every 10 min within a 40-min period. Sampling started at twilight (1120 h GMT), weather was calm and sky was cloudy. LAI-2000 measurements were recomputed using the C-2000 software after eliminating data from one ring at a time as described by Li-Cor (1992). This procedure was adopted to examine which group of rings yielded the highest correlation with the photographic estimates of CC. Data were analysed as repeated measures, one factor design, the factor being the vertical angle of view. Replicates were the ground points and the four repeated measures. One degree of freedom contrasts were used to compare mean estimates of CC. Pearson correlation of estimates of CC were obtained excluding different sensor rings of the LAI-2000 and the images obtained with different focal lengths.

Test 3 A third set of 16 photographs was collected on 16 September 2002 at the Amazcala site to evaluate the relation between estimates of CC obtained using the LAI-2000 and digital photography at different sampling times starting at twilight (1120 h GMT). A total of eight measurements were made every 20 min for each ground point during a 150-min period. Other times of day were not considered because illumination conditions may affect the photographic and LAI-2000 estimates of CC (Chen et al. 1991; Macfarlane et al. 2000; Frazer et al. 2001). Only the Canon camera at a focal length of 50 mm was used in this test. Measurements consisted of paired photographs and LAI-2000 readings. The previously selected ground points in Test 2 were used and considered as replicates. The tripod was repositioned on each occasion at virtually the same position and orientation. The LAI-2000 readings were edited as described previously. Weather was calm and sky conditions were cloudy. Linear regression was used to explore the relationship between time and the estimates of CC provided by both methods.

Test 4 A fourth group of photographs was obtained between 22 October 1998 and 7 May 1999 in a system containing alder at Aokautere, New Zealand. Photographs were taken approximately every 10 days. Eight photographs per pruning level were taken for each date. Photographs were taken at twilight, 30–45 min before dusk, handholding the Kodak camera towards the canopy and manually releasing the shutter. Three sets of digital photographs were obtained using the Mavica camera from 29 January to 21 February 1999.

All models were fitted using MEANS and GLM procedures within SAS (SAS Institute, Cary, NY, USA) to establish differences between means and the significance of regressions. The minimum level for significance was set at $p \leq 0.05$. Residuals were checked for normality and independence using Kolmogorov–Smirnov and Durbin–Watson tests, respectively.

Analysis of digital images

Images were analysed using Photopaint v 9.0 (Corel Corp., Ottawa, ON, Canada). The threshold to classify pixels into 'sky' and 'canopy' was determined for the first image of the set obtained using each camera and date. The threshold was saved in a file and then applied to the rest of the images of the corresponding set. The threshold was estimated again only when it was noticeable that pixels pertaining to the sky were wrongly identified as canopy and *vice versa* and then applied to the remaining images. Classified images were analysed using Sigmascan v 4.0 (SPSS Inc., Chicago IL, USA) to calculate canopy area. The ratio of canopy area to frame area of the image was expressed as a percentage and used as an estimate of CC.

Results

Test 1: comparing cameras

Variance and the mean estimates of CC obtained with the Canon and Kodak cameras set to 50 mm focal length and those provided by the LAI-2000 were similar at all the sites examined in Mexico (Table 1). The estimates of CC obtained using the LAI-2000 presented in Table 1 were calculated using rings 1–3; similar values were obtained when the estimates were based on rings 1–2 or 1–4. Only at the Amazcala site was a significant correlation found between the estimates provided by digital photography and the LAI-2000 ($r^2 = 0.5$ and 0.61

Table 1. Canopy closure (CC) estimated by analysis of digital photographs taken with a zoom lens set to 50 mm focal length or the LAI-2000 canopy analyser using sensor rings number 1–3.

	Basal area $m^2\ ha^{-1}$	Species[b]	CC					
			Kodak DC-120	SE	Canon EOS D1	SE	LAI-2000	SE
Vertical angle of view			46°		35°		38°	
Sites[a]								
Huimilpan	5.5	E	0.20	0.015	0.24	0.019	0.24	0.022
Queretaro	33.9	E	0.45	0.031	0.51	0.035	0.59	0.017
Amazcala	4.9	A, Ey, L	0.61	0.051	0.58	0.047	0.66	0.030

[a]Sites located in Mexico.
[b]E – *Eucalyptus nitens*; A – *Albizia* sp.; Ey – *Eysenhardtia* sp.; L – *Lysiloma* sp.

for the Kodak and Canon cameras, respectively; $p < 0.05$).

At each site, the relationship between estimates of CC provided by the Kodak and Canon cameras was linear ($r^2 = 0.90$, 0.71 and 0.92 for Amazcala, Queretaro and Humilpan, respectively; $p < 0.054$). The relationship between the Kodak (y) and Canon (x) cameras using the data from all sites was also linear ($y = 0.065 + 0.89x$, $r^2 = 0.91$, $p < 0.05$; Figure 1).

Bias between estimates of CC obtained using the Kodak and Canon cameras was −0.02 with a 95% confidence interval of ±0.019. Bias between the Kodak camera and LAI-2000 estimates of CC was −0.07±0.038. Bias between the Canon camera and the LAI-2000 estimates of CC was −0.05± 0.035. While the Kodak camera had a fixed 160 ISO value, the Canon camera automatically adjusted to the maximum 1600 ISO value and avoided extreme aperture settings. The Canon camera used diaphragm aperture settings higher than 8.4 while the Kodak camera used settings as low as 5.0. Images obtained using the Kodak camera were darker, poorer in sharpness and some fine details were blurred. More effort was required to define the colour threshold in the images from the Kodak camera.

Test 2: focal length

Table 2 summarises the correlations between estimates of CC obtained using the LAI-2000 and the Canon camera set at different focal lengths. A focal length of 50 mm was correlated with LAI-2000 estimates calculated using ring numbers 1–5, 1–4 and 1–3. The photographic method estimated a CC of 0.77 when focal length was set at 50 mm, which was higher than the value of 0.54 provided by the LAI-2000 using ring numbers 1–3 ($p < 0.01$). Similar estimates of CC were obtained for all three focal lengths used with the photographic method (Table 3). However, excluding different ring numbers from the calculations, and thus having different vertical angles of view, yielded different estimates of CC using the LAI-2000 ($p < 0.05$).

Test 3: effect of time on estimates of CC

Over the 150-min time interval examined during the morning, the estimates of CC obtained with the LAI-2000 were not influenced by the time of measurement. However, this was not the case for estimates obtained using the Canon camera because the regression over time was significant ($r^2 = 0.58$ and slope of 0.0003; Figure 2). By

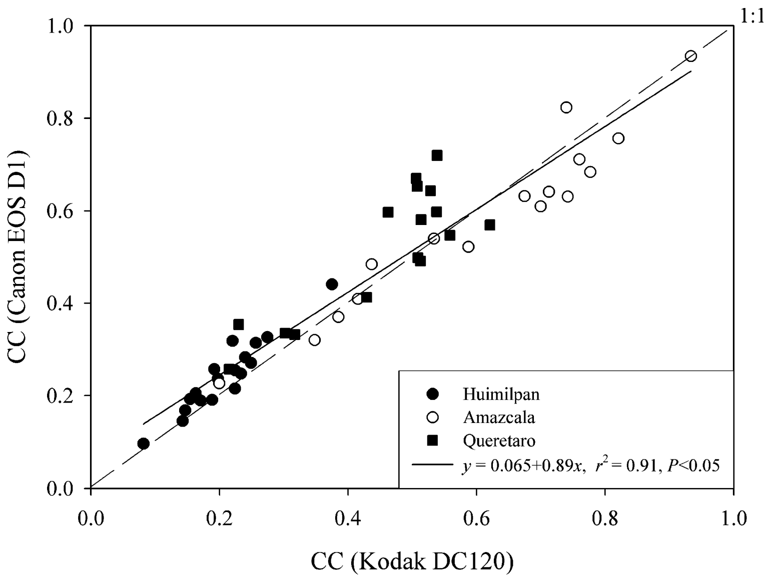

Figure 1. Relationship between CC estimated by analysis of digital photographs taken at three sites in Mexico using two cameras with zoom lenses set to 50 mm focal length.

Table 2. Pearson correlation between estimates of CC within a subtropical mixed legume woodland obtained using different sensor rings of the LAI-2000 canopy analyser and a Canon EOS D1 camera with the lens set at different focal lengths.

LAI-2000 rings used	Vertical angle of view[b]	Focal length (mm)[a]		
		28	35	50
1	7°	0.58	0.45	0.54
1–2	23°	0.58	0.45	0.54
1–3	38°	0.65	0.69	0.82*
1–4	53°	0.77*	0.66	0.74*
1–5	68°	0.80*	0.76*	0.84*

[a]Vertical angle of view was 59°, 49° and 35° for focal lengths of 28, 35 and 50 mm, respectively.
[b]Vertical angle of view corresponds to the mid-angle of the outermost ring.
*$p \leq 0.05$.
Data are for to the Amazcala site, Mexico on 4 September 2002.

contrast, no significant correlation was found between estimates of CC obtained using the photographic method and the LAI-2000. The photographic estimate of CC of 0.73 was higher than that of 0.56 obtained using the LAI-2000 ($p < 0.01$). The photographic estimate of CC was the same in Tests 2 and 3 when focal length was set to 50 mm (0.77 vs. 0.73). The LAI-2000 also provided the same estimates of CC in Tests 2 and 3 (0.54 vs. 0.56).

Test 4: pruning treatments

The time course of CC differed between the pruning treatments (Figure 3, $p < 0.05$). The polled standard error of the mean for the estimates of CC (0.02) was identical for all pruning treatments (17, 27 and 77% of full sunlight) for the growing season.

Only in the 17% of full sunlight treatment was a close relationship found for estimates of CC obtained using the Mavica and Kodak cameras ($r^2 = 0.73$, $p < 0.05$). When all three pruning treatments were considered, a non-linear relationship was obtained between estimates of CC obtained using the Mavica (y) and Kodak (x) cameras ($y = 0.86 \cdot x^{0.03}$, $r^2 = 0.86$, $p < 0.05$). However, photographic estimates of CC differed between cameras for the 27% of full sunlight treatment and were more similar for the other pruning treatments (Table 4, $p < 0.05$). Also, the polled standard error of the mean for the estimates of CC was similar for both cameras (0.02). The bias between estimates of CC obtained with the photographic method using the Kodak and the Mavica cameras was −0.07 with a 95% confidence interval of ± 0.018.

Discussion and conclusions

Camera comparison

Images obtained using the Kodak and Canon cameras were equally useful in estimating CC at the three sites examined. Considering the technical differences between these cameras, it was expected that the estimates of CC at Queretaro would be

Table 3. Estimates of CC within a subtropical mixed legume woodland obtained using different sensor rings of the Licor LAI-2000 canopy analyser and a Canon EOS D1 camera with the lens set at different focal lengths.

	LAI-2000 rings used[a]					Focal length (mm)		
	1	1–2	1–3	1–4	1–5	28	35	50
Vertical angle of view	7°	23°	38°	53°	68°	59°	49°	35°
CC	0.72 a[b]	0.72 a	0.54 b	0.52 b	0.52 b	0.77 a	0.78 a	0.78 a
SE	0.007	0.007	0.017	0.020	0.018	0.011	0.010	0.007

[a]Vertical angle of view correspond to the mean angle of the outermost ring.
[b]Means with same letter were not significantly different ($p < 0.05$).
Data are for to the Amazcala site, Mexico on 4 September 2002.

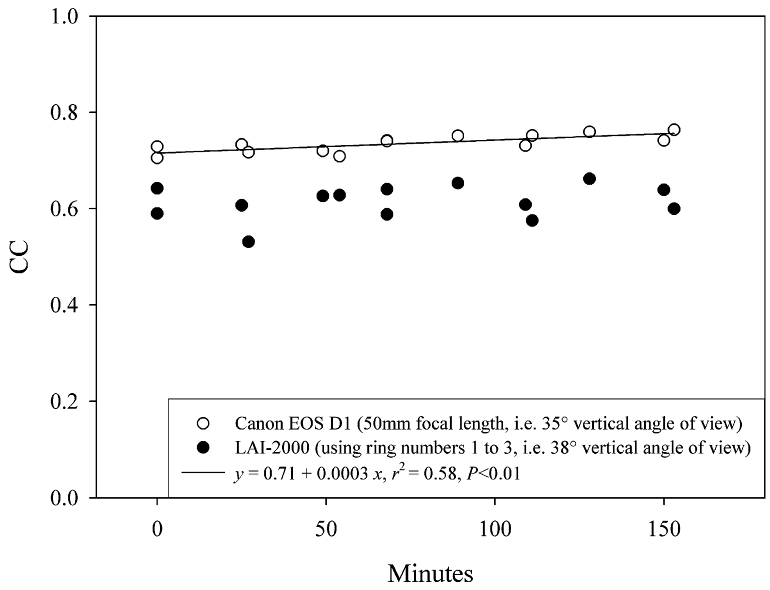

Figure 2. Time trend of estimates of CC within a subtropical mixed legume woodland obtained during the morning (11:20 GMT) on 16 September 2002 at Amazcala, Mexico.

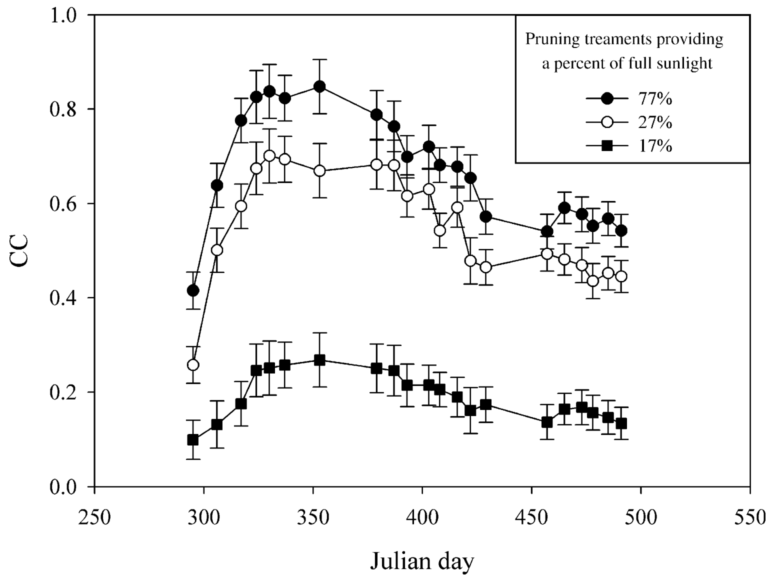

Figure 3. Development of CC for *Alnus glutinosa* at Aokautere, New Zealand, estimated by analysis of digital photographs captured with a Kodak DC-120 camera. Vertical bars represent a 95% confidence intervals for the mean estimate of CC. Julian day 1 was on 1 January 1998.

statistically different. The data for the Queretaro site shown in Figure 1 showed more scatter because the canopy was the tallest at this site and some small foliage objects were lost during image processing of the Kodak images, as their chromatic values were very similar to those of the sky. Images from the Canon camera registered a higher canopy area because the definition of small branches and leaves at the top of the canopy was better than in the images provided by the Kodak camera.

Table 4. Canopy closure (CC) of pruned alder (*Alnus glutinosa*) estimated by analysis of digital images captured using Kodak DC-120 or Mavica FD-7 cameras. The pruning treatments correspond to levels of 17, 27 and 77% of full sunlight.

Julian day[a]	CC						SE[b]
	17%		27%		77%		
	Mavica	Kodak	Mavica	Kodak	Mavica	Kodak	
402	0.68 a[c]	0.74 b	0.39 a	0.21 b	0.68 a	0.54 b	0.020
408	0.71 a	0.68 a	0.35 a	0.19 b	0.59 a	0.59 a	0.019
416	0.70 a	0.68 a	0.34 a	0.19 b	0.60 a	0.59 a	0.024

[a]Julian day 1 was on 1 January 1998.
[b]Pooled standard error.
[c]Within pruning treatments, means in the same row were not significantly different ($p < 0.05$).
Measurements were made during February 1999 at Aokautere, New Zealand.

This also explained the lower regression coefficient between these cameras at Queretaro ($r^2 = 0.71$) when compared to Humilpan and Amazcala ($r^2 = 0.90$ and 0.92, respectively), where the canopies were much lower. Images from the Queretaro site were processed again using the additive threshold mode and the magic wand mask tool (Corel Corp.) to manually select all foliage elements in the Kodak images and using the Canon images as a reference. The resulting mean estimate of canopy closure obtained using images from the Kodak camera was 0.50. However, selecting foliage elements manually took 2 h per image, whereas each image could be processed in under 3 min using the colour threshold file definition.

The Kodak camera consistently selected a higher diaphragm aperture to compensate for the low illumination environment, but this also reduced the depth of field and increased the possibility of blurred foliage borders because some objects were not in focus. Chen et al. (1991) showed that variation in shutter speed for the same image taken at the same time causes large variation in estimates of CC. Good definition of foliage was also important at Amazcala because the canopy was denser and closer to the camera than at the other sites; the shorter distance to the focused object decreased the depth of field. The particularly small and pinnate leaf form of the leguminous tree species present at the Amazcala site imposed a further requirement for clear definition of the foliage border of the most distant canopy stratum, which the Kodak camera could not define adequately. The difference between estimates of CC provided by the Kodak and Canon cameras probably was smaller at Amazcala because the problem of foliage definition was less pronounced at this site (Table 1). However, the quality of Canon images could be improved if the ISO speed was set to its lower limit (200) rather than the 1600 ISO automatically selected. Although higher ISO speeds are needed to take photographs under poor light, they also increase the amount of noise in the image.

Data from all tests indicate that the repeatability of the photographic method was adequate for the description of tree canopies. Agreement between repeated measurements using the Kodak camera was similar for all three pruning treatments in the alder canopy in New Zealand (0.02 standard error of the mean), and also similar to that observed at the three sites in Mexico (0.015, 0.031 and 0.051; Table 1). The consistent variability of the estimates of CC obtained using the Kodak camera indicates that the repeatability of the method was unaffected by canopy development during the growing season or differences in canopy structure; this is clearly shown by the similarity of the 95% confidence intervals for the estimates of CC for the various pruning treatments (Figure 4). Repeatability of the photographic method was also unaffected by selection of camera or selected sites because the standard error of the mean of estimates of CC was similar in magnitude for the Kodak, Canon and Mavica cameras in all tests (0.01–0.03). Nonetheless, using the Canon would be preferable to the Kodak camera because the magnitude of the bias was smaller with respect to the LAI-2000 (−0.05 vs. −0.07, respectively). Similarly, using the Kodak camera would be preferable to the Mavica because the bias between the Kodak and Canon cameras was smaller than between the Kodak and Mavica cameras (−0.02 vs. −0.07, respectively).

At Queretaro and Amazcala, where the foliage was further from the camera or smaller, image resolution was important. This problem was discussed by Yamamoto (2000), who examined canopy gap size, and concluded that higher resolution images would estimate the gap size more precisely than low resolution images. The use of higher resolution also was advocated by Takenaka (1987). Frazer et al. (2001) concluded that estimates of CC derived from low image resolutions (1024×768 or 640×480 pixels) combined with 1:4 file compression were lower than those obtained from 1600×1200 uncompressed images provided by a Nikon Coolpix 950 digital camera. Using the same camera (Coolpix 950), Englund et al. (2000) found that differences in digital image quality did not affect estimates of CC. Nevertheless, the relationship between estimates of CC provided by the Kodak and Canon cameras in the present study (slope = 0.89, $r^2 = 0.91$) was close to that found by Hale and Edwards (2002) for CC when comparing hemispherical pictures from a film-based Nikon FM2 and Nikon Coolpix 950 cameras over a range of canopy densities (slope = 0.905, $r^2 = 0.92$). A bias value of −0.003 to −0.04 could be added to the CC estimates obtained using the Kodak camera as correction factor with respect to the Canon camera. This would be appropriate as the measurement errors of both methods were comparable, and also because the correlation between the difference of the two estimates of CC (d) and their average was small ($r = 0.2$, Bland and Altman (1986)).

Comparison between the LAI-2000 and cameras

Results from three field tests showed that the digital photography and LAI-2000 approaches provided estimates of CC with similar precision because the variance within the results was similar. Although the standard errors of the mean were similar in Test 1 (Table 1), they were one order of magnitude greater than in Tests 2 and 3 (Table 3 and Figure 2). This difference was attributed to the sampling procedure used to obtain representative ground points. Ground points used in Test 1 were selected within each quartile of the median distribution of canopy closure estimated with the LAI-2000, whereas those used in Test 2 and 3 were selected to be within one standard deviation of the mean estimate of CC, with the result that variation between the ground points was smaller.

The photographic and LAI-2000 methods provided similar estimates of CC except in Tests 2 and 3, when LAI-2000 rings 3, 4 and 5 were included in the calculations. It is possible that the photographic and LAI-2000 methods spatially assess CC differently. This possibility is supported by the non-significant regressions between CC estimates from either, the Canon or Kodak cameras, and the LAI-2000. In fact, the high correlation at 68° vertical angle of view between the LAI-2000 and the camera was considered an artifact because the camera was not able to capture light between 60° vertical angle of view and the horizon, when focal length was set to 28 mm (Table 2). Correlations of estimates of CC also were low between hemispherical photography and LAI-2000 methods in a deeply shaded conifer-dominated forest or tropical forest, even when the outermost zenithal rings were disregarded (Machado and Reich 1999; Ferment et al. 2001). Nonetheless, analyses based on hemispherical photography and LAI-2000 measurements revealed similar developmental trends in CC and stand leaf area, despite significant quantitative differences in their estimates (Frazer et al. 1998; Paula and Lemos-Filho 2001). Also, Peper and McPherson (2003) reported that estimates based on digital analysis of photographs obtained with a Kodak DC-50 camera and the LAI-2000, showed good correlation with total leaf area of isolated trees ($r^2 > 0.71$).

The regression shown in Figure 2 suggests that the sensor of the Canon EOS D1 was more responsive to changes in illumination than the sensors within the LAI-2000 and, hence, would also require measurements to be made under overcast conditions or low solar angles (Li-Cor 1992). Obtaining canopy images at other times of day is not advisable, because foliage elements may be sunlit and reflected light in images is difficult to distinguish from the sky. Images containing lateral chromatic aberration (halos) also have unpredictable effects on estimates of CC (Frazer et al. 2001).

It was concluded that digital photography is suitable for characterising CC within agroforestry systems, and that the estimates obtained exhibit similar variability to those provided by the LAI-2000 canopy analyser. Estimates of CC obtained using the photographic method and a focal length of 50 mm were comparable to those provided by the LAI-2000 when considering rings 1 and 2 or 1–3 were used in the calculations. The reasons why the estimates disagreed at lower angles of view require further exploration. Estimates of canopy closure obtained by analysis of images from different cameras could be calibrated by including a correction factor within the calculation. However, cameras with higher resolution should preferably be used.

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