Agricultural and Forest Meteorology, 56 (1991) 129–143
Elsevier Science Publishers B V Amsterdam

Evaluation of hemispherical photography for determining plant area index and geometry of a forest stand

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(Received 20 July 1990, revision accepted 21 December 1991)

ABSTRACT

Chen, J M, Black T A and Adams, R S, 1991 Evaluation of hemispherical photography for determining plant area index and geometry of a forest stand Agric For Meteorol, 56 129–143

Hemispherical photographs were taken beneath an 80-years-old Douglas-fir (*Pseudotsuga menziesii*) forest stand under clear and overcast sky conditions, and under clear sky with the canopy partially covered with snow The photographs were digitized using an optical scanner The 'effective plant area index' (L_e) and the distribution of the inclination angle of plant elements were obtained with Norman and Campbell's linear least-square inversion technique Photographic exposure was determined by matching the L_e values obtained from the photographs with those measured using the Plant Canopy Analyzer (PCA) (Li-Cor LAI-2000) Agreement between the inverted and measured values was found when the photographs were underexposed by 4–5 stops compared with readings of a light meter facing vertically upward under the canopy These values of L_e were about half the plant area index calculated from the measurements of tree diameter at breast height (D_{bh}) using published relationships for Douglas-fir trees The distribution of sky radiance under clear and overcast conditions had a considerable effect on the determination of the angular distribution of plant elements Pronounced differences were found between inclination angle distributions calculated from the PCA gap fraction measurements and the digitized photographs taken with and without a blue filter (Wratten 80B) These differences may have resulted from the effect of the scattering and possibly diffraction of the visible radiation by the foliage The scattering and diffraction caused more leaves to blend into the sky at small than at large zenith angles

INTRODUCTION

Hemispherical or fisheye photography is a useful technique to obtain indirectly information on foliation and architecture of plant canopies This technique has often been used for determining plant canopy cover and canopy radiation regime (Brown, 1962, Anderson, 1964, Jones and Campbell, 1979, Lakso, 1980, Miller, 1981, Olsson et al, 1982, Kellihher, 1985, Chan et al, 1986) Using assumptions of leaf angle distribution, fisheye photographs have also been used to invert the leaf area index of plant canopies (Bonhomme

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and Chartier, 1972, Lemeur, 1973, Bonhomme et al , 1974, Anderson, 1981, Leong et al , 1982) Wang and Miller (1987) improved the inversion technique by employing measured distributions of leaf angles in a red maple forest Neumann et al (1989) compared several inversion methods, including the Poisson, negative binomial and Markov models, to obtain the plant area index (including leaves and woody materials) as well as a clumping index due to the grouping of plant elements However, owing to the unknown distribution of the element inclination angle, their analysis was confined to a narrow annulus about a zenith angle of 57°, where the extinction coefficient is relatively independent of the element inclination In this paper, we report results of using Norman and Campbell's inversion technique (Norman and Campbell, 1989, hereinafter referred to as NC) to calculate plant area index and inclination angle distribution simultaneously from measured gap fractions at several zenith angles in a forest stand Difficulties in determining photographic exposure and in obtaining the correct geometry (inclination angle distribution) of the stand elements are discussed

INVERSION THEORY

The NC linear least-square inversion theory is outlined here Under the assumption of a random distribution of the azimuthal angle of plant elements, the gap fraction ($P(\theta)$) of a plant canopy, which can be obtained photographically, is taken to be dependent on the light incident angle (θ) and element inclination angle (α, 0 for horizontal and $\pi/2$ for vertical elements) If all elements in the canopy are inclined at the same angle α, the expression for $P(\theta)$ is

$$P(\theta)=\exp[-G(\theta,\alpha)\Omega L/\cos\theta] \quad (1)$$

where L is the plant area index, Ω is a clumping index resulting from the non-random distribution of element spatial positions, $G(\theta,\alpha)$ is the mean projection of unit element area on a plane normal to the direction of incident light and is defined by

$$G(\theta,\alpha)=\begin{cases}\cos\alpha\cos\theta & \theta\leq\pi/2-\alpha \\ \cos\alpha\cos\theta\left(1+\frac{2(\tan x-x)}{\pi}\right) & \theta>\pi/2-\alpha\end{cases} \quad (2)$$

where

$$x=\cos^{-1}(\cot\alpha\cot\theta) \quad (3)$$

When a canopy is clumped, Ω is less than unity As Ω is generally unknown, it is convenient to use the parameter of 'effective plant area index' (L_e) which is the product of L and Ω (Black et al , 1991), i e

$$L_e=\Omega L \quad (4)$$

After defining the following expressions

$$T(\theta) = -\ln P(\theta) \qquad (5)$$

and

$$K(\theta,\alpha) = G(\theta,\alpha)/\cos\theta \qquad (6)$$

as a transmission function and as a kernel, respectively, eqn (1) becomes

$$T(\theta) = K(\theta,\alpha)L_e \qquad (7)$$

If the value of α is known, obtaining L_e by inverting eqn (7) is straightforward and requires only the measurements of light transmission at a single zenith angle However, if L_e is distributed at several inclination angles as is generally the case, i e having $L_{e1}, L_{e2}, \ldots, L_{en}$ at $\alpha_1, \alpha_2, \ldots, \alpha_n$, respectively, it is easy to write from eqn (1) that

$$T(\theta) = K(\theta,\alpha_1)L_{e1} + K(\theta,\alpha_2)L_{e2} + \ldots + K(\theta,\alpha_n)L_{en} \qquad (8)$$

where

$$L_e = L_{e1} + L_{e2} + \ldots + L_{en} \qquad (9)$$

In this case, obtaining L_e requires the determination of all unknown L_{ej}, $j = 1,2, \ldots, n$ This inversion can be achieved provided $T(\theta)$ is obtained at n or more incident angles, i e measuring $T_1, T_2, \ldots, T_m$ at $\theta_1, \theta_2, \ldots, \theta_m$ respectively, where $m \geq n$ In this way m linear equations are available for solving n unknowns using least squares If we denote K_{ij} for $K(\theta_i, \alpha_j)$ and T_i for $T(\theta_i)$, the equations are expressed as follows

$$T_i = \sum_{j=1}^{n} K_{ij} L_{ej} \qquad (10)$$

where $i = 1,2, \ldots, m$ and $j = 1,2, \ldots, n$ In a matrix form, the expression becomes

$$\boldsymbol{T} = \boldsymbol{K}\boldsymbol{L} \qquad (11)$$

where $\boldsymbol{T}$ is a matrix with elements T_i and dimension $m \times 1$, $\boldsymbol{K}$ is the kernel matrix with elements K_{ij} and dimension $m \times n$, and $\boldsymbol{L}$ is a matrix with elements L_{ej} and dimension $n \times 1$ As m may be greater than n, the generalized equation for the calculation of L_{ej} is

$$\boldsymbol{L} = (\boldsymbol{K}^{\mathrm{T}}\boldsymbol{K})^{-1}(\boldsymbol{K}^{\mathrm{T}}\boldsymbol{T}) \qquad (12)$$

where $\boldsymbol{K}^{\mathrm{T}}$ is the transpose of matrix $\boldsymbol{K}$ In this equation, the inverted L_{ej} are sensitive to the noise in the gap fraction measurements and very often, one or two unrealistic negative values of L_{ej} are calculated To avoid this problem, a constraint matrix has been introduced, which provides a constraint towards a uniform angle distribution of plant elements The constraint matrix, given as $\boldsymbol{H}$, is an $n \times n$ tridiagonal matrix with off-diagonal values of -1 and diagonal values of 2 except for the upper left and lower right corners which are 1 The rest are all zero For $n=5$, the constraint matrix is

$$H=\begin{pmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 \\ 0 & -1 & 2 & -1 & 0 \\ 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & -1 & 1 \end{pmatrix} \quad (13)$$

With this constraint, eqn (12) becomes

$$L=(K^{T}K+\gamma H)^{-1}(K^{T}T) \quad (14)$$

where γ is a parameter determining the strength of the constraint and is generally between 0 and 0 5

The total effective plant area index (L_e) is the sum of L_{ej} (eqn (9)), and the plant element angle distribution function ($g(\alpha)$) is calculated from

$$g(\alpha_j)=\frac{L_{ej}}{L_e \Delta\alpha_j} \quad (15)$$

where $\Delta\alpha_j$ is the range of the element inclination angle (in radians) in which L_{ej} is obtained Eqn. (15) satisfies the condition that

$$\sum_{j=1}^{n} g(\alpha_j)\Delta\alpha_j=1 \quad (16)$$

MATERIALS AND METHODS

The research site was an 80-year-old Douglas fir forest stand located in Pacific Spirit Park adjacent to the University of British Columbia The forest floor was horizontal and the canopy was homogeneous in terms of tree height and spacing. The stand was about 30 m in height and had a minimum width of approximately 200 m The plant area index (L) of the stand, defined as half the total area of leaves and woody materials per unit ground area, was estimated from measurements of tree diameter at breast height (1 3 m) (D_{bh}) and stand density (stems ha^{-1}) The diameter of all trees was measured within a 33 3 m×33 3 m plot in the middle of the stand The values of D_{bh} varied from 24 to 95 cm with an average of 50 cm The stem density was 340 stems ha^{-1} Half the total leaf area (A,m^2) of each tree was calculated using the following empirical formula derived from relationships for old growth Douglas fir trees given by Gholz et al (1976)

$$A=8\ 5 \exp(-3.89+1\ 89 \ln D_{bh}) \quad (17)$$

where D_{bh} is in centimeters In deriving this formula, the ratio of half the total leaf area to leaf dry weight was taken to be the average for 0- to 3-year old needles, being 85 $cm^2\ g^{-1}$, and the projected area was multiplied by a factor of 1 18 to obtain half the total area The leaf area index, which was calculated as half the total leaf area of all trees within the plot divided by the area of the plot, was 9 8 As the area index of the woody materials was estimated to be 0 9, the plant area index was 10 7 Our measurements of the ratio of half the total leaf area to dry weight in a 28 year old Douglas fir stand was 73 $cm^2\ g^{-1}$ If this value were used, the plant area index would have been 9 3

Hemispherical photographs were taken in the middle of the stand using a vertically mounted camera (Olympus OM-1) equipped with a 180° fisheye conversion lens (Soligor) mounted on a 35 mm primary lens The distortion of the hemispherical image was tested to be within ±2 5° (Kelliher, 1985) Low contrast black and white photographs of an overcast sky taken with the lens exhibited very little variation in the tonality across the radius of the image, indicating uniform angular transmissivity of the lens As the canopy was tall and uniform, little difference was found between the photographs taken at two different spots 5 m apart In order to study the effect of photographic exposure on the determination of the effective plant area index, the photographs were taken at six exposures with a fixed shutter speed (0 5 s) and varying apertures (from f number 4–16) as the aperture adjustment in a camera is generally more accurate than the speed adjustment Following several preliminary measurements made in February and March 1990, experiments were undertaken under clear sky (8 April 1990) and overcast (9 April 1990) conditions to investigate the influence of the angular distribution of sky visible radiance on the photographed gap fractions and the resultant inclination angle distribution of the plant elements On another overcast day (6 June 1990), a blue filter (Wratten 80B) was used to reduce the effect of the green and red portions of the visible light scattered by the foliage elements The shutter speed was changed to 2 s when photographs were taken with the filter, which decreased the light intensity by a factor of 2 7 (about 1 5 stops) High contrast black and white (B/W) film (Kodalith Ortho Film 6556, type 3, ASA = 6) was the principle film used in this study Lower contrast B/W film (T-Max, ASA = 100) was used as a comparison

The exposures indicated by the camera light meter were compared to those determined from the illuminance measured with a photometer (Model Li 185, Li-Cor Inc , Lincoln, NE) The comparison was made in an open field under an overcast sky when there is little variation in luminance with zenith angle This minimizes the effect of the difference in field of view (FOV) between the photometer (180°) and the camera light meter (70°, centre weighted) on the indicated exposure It was not possible to use the camera light meter with the fisheye conversion lens in place because of its vignetting property Measured illuminance was converted to photographic exposure using the expression of Unwin (1980) which is rearranged to include the film speed,

$$I = \frac{244}{F}\frac{n^2}{t} \tag{18}$$

where I is the illuminance in lux, F is the ASA rating of the film, n is the lens aperture (f number) and t is the exposure time in seconds The exposure indicated by the camera light meter was found to be 2 stops smaller than that calculated from the photometer readings The same comparisons made for a hand-held light meter and another camera indicated 1 and 4 stops of underexposure, respectively This large variation between cameras is not unusual (Shaw, 1987) Following this comparison all exposures indicated by the camera light meter were increased by 2 stops All exposures reported in this paper were taken to be relative to the readings of the calibrated camera light meter pointing vertically upwards The exposure calculated from eqn (18) assumes the light comes from a mid-gray surface (18% visible reflectivity) In order to make the sky appear white, it is required to overexpose the photograph by 3 stops as compared with the calculated value

The high contrast negative film was developed with Kodalith Super RT A and B for 3 min at 20°C The final image was printed on Ilford Multigrade Resin-coated paper with a No 2 filter The printing time was adjusted to allow dark segments to appear black The developing time is much more critical than printing time for high contrast films (e g 20% overdevelopment results in 2 stops overexposure)

The photographic image was enlarged to a size of 8 6 cm × 8 6 cm and was digitized with an optical scanner (Scanman Plus, Logitech, Inc , Fremont, CA) which provided a resolution of 79 pixels per centimetre when a 200 dpi (dots per inch) option was chosen The uncompacted Scanman data file was decoded Pixels were stored as bits with a line width of 816 bits and a header of 1392 bits in the TIF file format Computer programs were written to count the gap fractions in 9 annuli representing incident angles from 0 to 90° with 10° separation and to compute the effective plant area index as well as the distribution of the inclination angle of the plant elements With an existing microcomputer, the system was inexpensive as the scanner was commercially available for only Can $ 300 00

In each of the experiments, measurements of L_e of the stand were made with the Plant Canopy Analyzer (PCA) (Li-Cor LAI 2000, Lincoln, NE), which calculates L_e from the fraction of skylight transmitted through the canopy in five 15°-wide angles extending from a zenith angle of 0–75° The instrument measures the light level above and below the canopy in the 400–490 nm waveband (blue light) in which leaf reflectivity and transmissivity are small On clear days, a 90° view restrictor was used to eliminate the effect of direct sunlight The reference measurements outside the stand were made on an open playing field 500 m from the stand The measured fractions of light transmission were taken as the gap fractions and used as inputs to our computer program to calculate the values of L_e and the inclination angle distribution for comparison with those derived from the photographs The values of L_e calculated from the PCA Gap fractions were within 4% of the direct readings of the PCA

RESULTS AND DISCUSSION

Effective plant area index (L_e)

Figure 1 shows the values of L_e calculated from the digitized photographs as affected by photographic exposure under clear and overcast conditions On the clear day, the light meter reading under the canopy was $n=2$ 8 (f number) and $t=0$ 5 s for ASA=6, and the photometer reading was 270 lux According to eqn 18, the calculated exposure was $n=2$ 8 and $t=0$ 85 s for the same film speed This calculated exposure is about 1 stop greater than the light meter reading The radiance of the skylight would decrease with increasing zenith angle because of the corresponding increase in the path length through the canopy The camera light meter indicated this variation by showing increasing exposure as it was tilted towards the horizontal On the overcast day, the reading from the light meter in the same position was $n=2$ 8 and $t=1$ s for the same film speed, while the photometer reading was 180 lux The calculated exposure in this case was $n=2$ 8 and $t=1$ 77 s, again indicating approximately 1 stop greater than the light meter reading

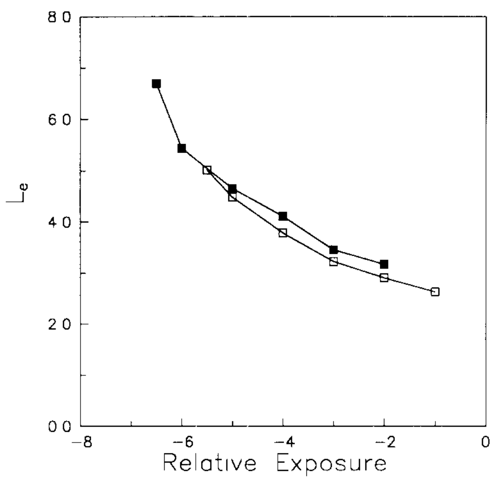

Fig 1 The effective leaf area index (L_e) calculated from digitized hemispherical photographs taken at different exposures in an 80-year-old Douglas fir stand adjacent to the University of British Columbia under clear (□) (6 April 1990) and overcast (■) (9 April 1990) conditions The exposure shown here is relative to the exposure measured with a camera light meter with a 35 mm lens facing vertically upward under the forest canopy

The values of L_e measured with the PCA in these two experiments were 4 43 and 4 51, respectively These values of L_e are much smaller than the estimated value of actual plant area index (L), which is 10 7 or 9 3 as mentioned earlier This large difference between L and L_e is an indication of a strong foliage clumping effect The clumping index Ω defined by eqn (4) is 0 42 or 0 48 These values agree fairly well with the value of 0 36 obtained for the 28-year-old stand referred to earlier, which was thinned and pruned This value was calculated from destructive and non-destructive (radiation tram) measurements of plant area index The estimation of L based on measurements of trunk diameter in this study is crude and may be in error by 25% The measurements of the PCA may also be subject to an error resulting from the effect of scattered blue light on the gap fraction (transmission) measurement Our calculation with Norman's multilayered model (Norman, 1979) shows that, when the reflectivity and transmissivity of Douglas fir needles for blue light are taken to be 6% and 2%, respectively (Jarvis et al , 1976), the scattering increases the below-canopy blue irradiance by 36% at $L_e = 4$ 5 under clear sky conditions This increase results in a decrease in the calculated value of L_e by 9% Under overcast conditions, the decrease is less than 4%

Fisheye photography is an independent technique for measuring the effective plant area index, but more precautions must be taken before successful measurements can be made We therefore tentatively used the commercially available PCA as a standard for comparison Figure 1 shows that the values of L_e were close to those determined by the PCA when the photographs were underexposed by approximately 4 5 stops The reason for the required underexposure is likely that the exposure calculated from the illuminance is the exposure required to photograph the combination of the canopy and the sky as a mid-gray body, but the correct photography for our purpose is to show the leaves as black objects The extent to which the photographs should be underexposed depends on the relative contribution of the sky and the canopy to the total solid angle of the hemisphere Fewer stops of underexposure are expected for a canopy which is more open than the stand studied in this report Our experience suggests that under overcast conditions, the exposure under the canopy can be determined from the measurements of illuminance outside the canopy and is probably independent of the canopy openness as the same exposure should make the sky appear white whether or not the photograph is taken outside or inside the forest stand As 'a rule of thumb', an exposure which is 1–2 stops greater than the value calculated from the measurements of illuminance on a horizontal surface outside the canopy under overcast conditions would be approximately correct for obtaining effective plant area index The reason that only 1–2 stops rather than 3 stops of overexposure appeared to be suitable under the canopy will be discussed in the next section

The effect of photographic exposure on the gap fraction measurements can be easily seen from Fig 2, which shows that the photographed gap fraction became smaller as the exposure decreased The decrease in the gap fraction results in the increase in L_e as shown in Fig 1 (the open symbol line) Similar patterns of the variation of L_e with the film exposure were also found in the preliminary experiments and the supplementary measurements with the blue filter Table 1 shows all the experimental results under various weather conditions In one of the cases, 3 to 4-day-old snow partially covered the tree crowns and completely covered the forest floor All of the photographic results were obtained at the exposure 4 5 stops less than that calculated using

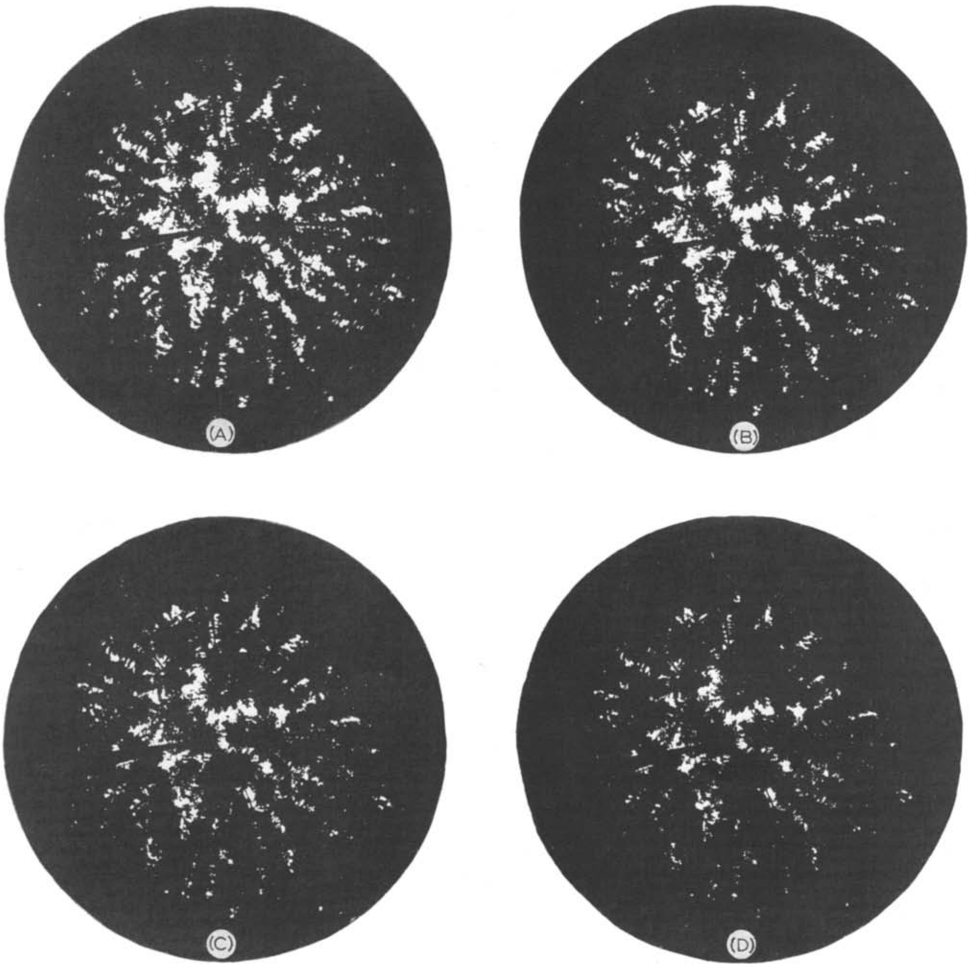

Fig 2 Hemispherical photographs taken beneath a Douglas fir stand under overcast conditions (9 April, 1990) (A) 2 stops underexposure, (B) 3 stops underexposure, (C) 4 stops underexposure, (D) 5 stops underexposure

TABLE 1

Comparison of the values of the effective leaf area index L_e measured with the Plant Canopy Analyzer (Li-Cor LAI 2000) and those inverted from digitized hemispherical photographs taken in an 80-year-old Douglas fir stand adjacent to the University of British Columbia High contrast B/W Kodalith film (ASA = 6) and low contrast B/W T-Max film (ASA = 100) were used

Date (1990)	Time (PST)	L_e			Sky condition
		Li-cor LAI 2000	Photographs		
			Kodalith	T-Max	
16 Feb	15 16	4 13	4 15		Clear with snow on trees
	16 09	3 83			
22 Feb	15 44	4 41	4 52		Clear
	16 29	4 24			
15 Mar	15 27	4 12	3 75	3 86	Overcast
	16 22	4 04			
6 Apr	15 54	4 43	4 14		Clear
9 Apr	16 18	4 51	4 37		Overcast
8 Jun	15 42	4 55	4 34		Overcast

the reading of the light meter pointed upward to the zenith The PCA results were slightly more consistent than the photographic results The difference in the consistency may be attributed to the following (1) the results from photographs are subject to errors in the film developing and printing as well as an error in the light meter reading, (2) in the case of the PCA measurements, radiances of the skylight transmitted through the canopy at different zenith angles are referenced to those outside the canopy so that the effect of the uneven distribution of the sky radiance are taken into account, (3) the measurements of the PCA are confined to blue light in which the scattering of light by the foliage elements is minimized However, our results indicate that good estimates of L_e can be obtained using fisheye photography when film exposure is carefully selected

The results from low contrast photographs (T-Max, ASA = 100) showed the same variation of L_e with photographic exposure The values of L_e were almost identical to those obtained from the corresponding high contrast photographs when a suitable contrast setting of the scanner was chosen (it was +2 in our case) The value of L_e inverted from the low contrast photographs increased linearly with increasing contrast, but the effect of the contrast setting on the results from the high contrast photographs was small The printing time is less critical for high contrast film, for which standardized procedures may be more easily established However, the high contrast film may suffer from the constraint of low film speed which limits the useful camera shutter speed The effect of the motion of the canopy owing to wind remains undetermined in our investigation From the comparison of the results from the films of different speeds, this effect was found to be insignificant Our results do not justify the use of the more sophisticated 'pushing' procedure in film exposure and development or the use of high contrast filters in printing processes in order to produce high contrast photographs from high speed films

Inclination angle distribution of plant elements

The inversion technique of NC allows simultaneous determination of plant area index and the distribution of plant surface area in the various angle classes from which the distribution of the inclination angle of plant elements can be calculated (eqn (15)) Figure 3 shows the angular distributions calculated using the gap fractions derived from three photographs and from the measurements of the Plant Canopy Analyzer (PCA) under clear and overcast conditions The photographs used in Fig 3 are those having the values of L_e closest to the measurements of the PCA

Figure 3 shows that the distributions of the inclination angle of plant elements obtained from the photographs were different from those from the PCA measurements The largest difference appeared to be at small inclination angles The PCA results indicated an extremophile distribution of foliage elements in the canopy, elements being distributed near two extremes horizontal and vertical (Ross, 1981) The angle distribution of the foliage elements

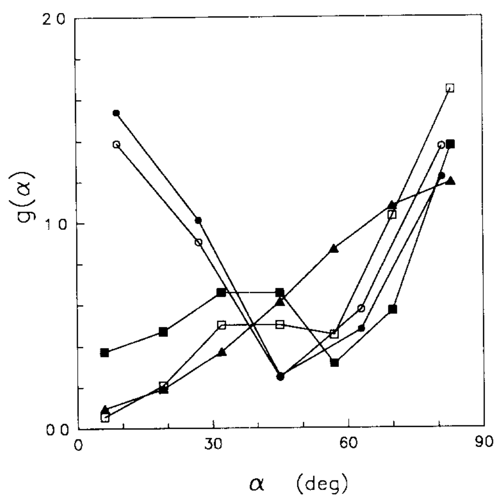

Fig 3 Comparison of the distributions of the inclination angle of plant elements (α) in the same stand as in Fig 1 obtained from digitized hemispherical photographs under clear (■) (6 April 1990) and overcast (□) (9 April, 1990) conditions with those calculated from the measurements made with the Plant Canopy Analyzer under clear (●) and overcast (○) conditions Also shown is the distribution obtained from a photograph taken with a blue filter under overcast conditions (▲) (8 June, 1990)

may have been distorted if the distribution of the measured gap fraction was affected by the anisotropy of the scattered blue light However, this distortion was estimated to be small as the scattered blue irradiance was small compared with the transmitted irradiance (see previous section) Studies by Black et al (1991) in a younger Douglas fir stand (26 years old) suggested that the leaf angle distribution was essentially planophile The extremophile distribution found in the present study may have been a result of the considerable contribution of the area of the vertical tree trunks which dominated a large portion of the lower part of the stand and was estimated to account for about 12% of the L_e However, the characteristics of the planophile or extremophile distribution were not shown in the photographic results, which indicate that there was comparatively much less foliage area in the first 30° inclination angle range This difference in the PCA and photographic results was due to a difference in the measured gap fraction distributions The gap fraction measured by the PCA was smaller at small zenith angles and larger at large zenith angles than that obtained from the digitized photographic images, suggesting that the photographs were overexposed in the near vertical direction and underexposed in the near horizontal direction All photographically obtained gap fraction distributions were found to have the same bias compared with the PCA measurements and this may be an inherent problem with this application of fisheye photography From careful visual examination of the low contrast photographs, we found that the edges of leaves and tree branches were blurred by the light scattered from and diffracted around them Blurring was more apparent near the centre of the images Even in the photographs which were underexposed by 6 and 7 stops, the effect of the blurring could still be identified This loss of leaf area owing to light blurring may explain the requirement of the necessary 1–2 stops rather than 3 stops of overexposure, compared with the measurements outside the canopy, to obtain the correct plant area index discussed in the previous section

Figure 3 also shows that the calculated distributions of plant element inclination angle were different between the clear and overcast conditions The difference was more pronounced in the photographic results than in the PCA results The measurements of the PCA outside the stand indicated that the sky radiance at the smallest zenith angle (7°) on the overcast day was approximately twice as high as that on the clear day, while at the largest angle (68°) the overcast sky radiance was two-thirds of the clear sky value Corresponding to the comparatively low radiance at the small zenith angle under clear conditions, the gap fraction obtained from the photographs was also comparatively small, resulting in more leaf area calculated in the lower inclination angle range as compared to the overcast case The same tendency of underestimating the gap fraction at the lower angle range was evident in the PCA results, but it was much smaller This effect of the uneven distribution of the sky radiance provides further support to the argument that the scattering and possibly the diffraction of incident light by the foliage may have substantially distorted the distribution of the gap fraction measured with the photographic method resulting in an unrealistic calculated angle distribution of foliage elements

The use of the blue filter would have considerably reduced the effect of the visible light scattered by leaves The fact that the inclination angle distributions derived from the photographs taken with and without the filter are effectively the same (Fig 3) indicates that the scattering of light by the foliage is not the only underlying problem It is possible that light diffraction around the edge of leaves, which was not reduced with the filter, was also responsible for the loss of leaf area at the top of the canopy As the probability of seeing the leaves at the top from the forest floor is greater at small than at large zenith angle, the loss of leaf area is proportionally large in the near vertical direction This uneven loss of area with respect to the zenith angle could have caused the distortion of the angle distribution of plant elements

CONCLUSIONS

(1) The effective plant area index (L_e) calculated from the digitized fisheye photographs was significantly affected by the exposure of the photographs It was found that agreement between photographic and Plant Canopy Analyzer (PCA) measurements of L_e could be obtained when the photographs were underexposed by 4–5 stops as compared with the exposure determined with a camera light meter using a 35 mm lens facing vertically upward under the forest canopy Under overcast conditions, the correct exposure was found to be 1–2 stops greater than the value measured outside the stand with the meter pointed to the zenith of the sky The exposure determined this way is probably independent of the leaf area index of the stand

(2) Measurements of L_e made by both optical methods were about one half the plant area index estimated from the measurements of tree diameter at breast height This strongly suggests a marked clumping effect in the Douglas fir forest stand and the need to determine the clumping index as part of plant area index measurements using optical or radiation methods

(3) The distributions of the inclination angle of plant elements obtained from digitized photographic images were substantially different from those calculated using the measurements by the Plant Canopy Analyzer The foliage area at small inclination angles was considerably underestimated using the photographic technique This may be a result of the scattering and possibly diffraction of the incident light by the foliage elements, which caused considerable loss of the photographed plant area at small zenith angles The photographic results were not much improved by the use of a blue filter to reduce the effect of the scattered light

ACKNOWLEDGMENTS

This research was supported by University–Industry and Operating Natural Science and Engineering Research Council research grants The assistance of Bob Sagar and David Loh in taking and developing the photographs respectively is greatly appreciated We would like to thank Dr G S Campbell for his constructive comments on the manuscript

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