J. Rubb. Res. Inst. Malaysia, **30(2)**, 80 – 90

Characterisation of Leaf Area Index and Canopy Light Penetration of **Hevea brasiliensis** *Muell. Arg. by Hemispherical Photography*

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Hemispherical photography was used to estimate leaf area index (LAI) and canopy light penetration of rubber trees. Three methods to decode the hemispherical pictures were evaluated. They were the electro-optical light intensity scanner, the computerised digitiser and the 'spider web' grid overlay. The three methods gave similar results. The electro-optical light intensity scanner was the preferred method as it was not subjected to inter and intra-observer errors, is less laborious and it takes the shortest time to decode a picture.

Good correlation was obtained between LAI obtained from hemispherical pictures and LAI obtained from in situ *leaf litter collection. The correlation between penetration of diffuse light obtained from hemispherical pictures and actual field measurements was very good. From these results it is suggested that hemispherical photography can be used to estimate LAI and canopy light penetration in a* Hevea *stand.*

In earlier reports[1,2] leaf area index (LAI) of rubber trees *(Hevea brasiliensis* Muell. Arg.*)* was determined by destructive sampling. The determination of LAI by destructive sampling is tedious and requires considerable manpower, it can be determined non-destructively by the inclined point quadrats method developed by Warren Wilson[3]. This method, however, is not suitable for tall crops.

Canopy light penetration in *Hevea* stand has also received limited attention. Mainstone[4] measured the light passing through the canopy with a Megatron photo-electric cell. More detailed measurements of light penetration were reported by Yoon[5]. He developed integrating light sensors to describe the light climate under *Hevea* canopies. In addition, he measured the light transmission by photosensitive papers, anthracene in benzene solution and hemispherical photography.

Hemispherical photography has recently been used in other crops to estimate LAI and radiation microclimate[6–15]. This study assesses its use in rubber, reports the results of evaluation of different systems to decode the hemispherical pictures and of the correlation studies between LAI and canopy light penetration as estimated by hemispherical photography, and LAI/ canopy light penetration obtained from *in situ* field measurements.

MATERIALS AND METHODS

Theoretical Basis

The determination of leaf area from hemispherical pictures was based on the measurement of gap frequency. The light distribution model of Monsi and Saeki[16] showed that light attenuation at any depth for forest and herbaceous communities fits the Lambert-Beer law:

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COMMUNICATION 700

$$I = I_o e^{-uf} \quad \ldots 1$$

where I is the illumination above the canopy, I_o is the illumination on a horizontal surface within a canopy at a depth f which is the cumulative leaf area index at that depth and u is the extinction coefficient.

In the light model, zero P_o of the Poisson distribution gave the relative area of horizontal gaps in a random canopy[17]. This relative horizontal sunlit area is:

$$P_o = e^{-uf} \quad \ldots 2$$

The intensity ratio of the transmitted beam to the incoming beam I/I_o is equal to P_o. This gives the probability of a ray of light passing through the foliage without touching it and is the gap frequency g_β corresponding to a solar evaluation β. Hence the leaf area index (f) can be defined by the equation:

$$f = \frac{1}{u} \ln (g_\beta) \quad \ldots 3$$

where u is the extinction coefficient which depends upon the solar elevation β and leaf inclination α. Knowing u (from tables of Isone[18]) and gap frequency from the hemispherical pictures, f can be calculated.

In this study, eight solar elevations β of 5°, 15°, 25°, 35°, 45°, 55°, 65° and 75° were used and:

$$\bar{f} = \frac{\sum_{\beta=1}^{8} -\frac{1}{u} \ln (g_\beta)}{8} \quad \ldots 4$$

Warren Wilson[3] has shown that at the solar elevation of 32.5°, the extinction coefficient u was virtually independent of leaf inclination. Hence, f was also determined at the solar elevation of 32.5° and the equation was:

$$f_{32.5} = -\frac{1}{u} \ln (g_{32.5}) \quad \ldots 5$$

where $g_{32.5}$ is the gap frequency determined at the solar elevation of 32.5°

For the determination of light penetration of diffuse radiation, it is assumed that isotropic radiation is generated by a hemispherical source of uniform brightness. Further, in the calculation of light penetration function, sky zones following those of Lemeur[19] were used. The hemisphere was divided into a number of parallel sky zones j at different elevations β^j. β^j is the midparallel elevation of a sky zone j *(Figure 1)*. After integration and

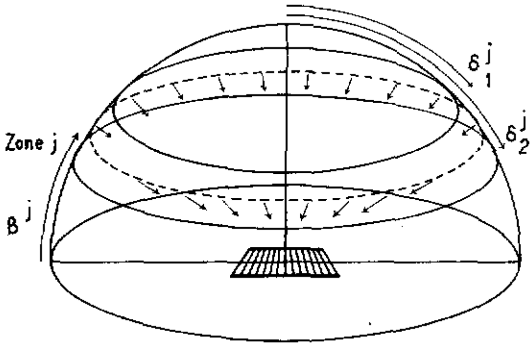

Figure 1. Schematical representation of incoming isotropic radiation from a parallel sky zone β^j on a leaf segment. δ_1^j and δ_2^j denote the zenith distances of the upper and lower zone boundaries respectively (After Lemeur, 1971).

normalisation, the expression for the light penetration function *(P)* becomes:

$$P = \sum_{j=1}^{n} \exp [-u(\alpha, \beta^j) f], E^j(O) \quad \ldots 6$$

where $u(\alpha, \beta^j)$ is the extinction coefficient for leaf inclination α and solar elevation β^j, f is the leaf area index and $E^j(O)$ is the weight factor corresponding to the relative contribution of zone j to the irradiance on horizontal plane. The weight factor E^j (O) is calculated from:

$$E^j(O) = \sin^2 \delta \frac{j}{2} - \sin^2 \delta \frac{j}{1} \quad \ldots 7$$

where $\delta \frac{j}{1}$ and $\delta \frac{j}{2}$ are the zenith distances of the upper and lower zone boundaries respectively.

The factor exp $[u\ (\alpha, \beta^j)\ f]$ is the gap frequency ($g_\beta\ j$) at solar elevation β^j. Knowing $g_\beta\ j$ and $E^j\ (O)$, the light penetration function (P) can be calculated:

$$P = g_\beta\ j.\ E^j\ (O) \quad \ldots 8$$

An alternative approach to determine light penetration is based on an expression, for the total illuminance on a horizontal surface (I) from a standard overcast sky[20]:

$$I = \frac{1}{3} \sin^2 \beta + \frac{4}{9} \sin^3 \beta \quad \ldots 9$$

A plot of this expression as a function of altitude β gives in effect a graph of the percentage of the total illuminance from a standard overcast sky received at the centre of circular obstruction of angular height.

Hemispherical Pictures

The hemispherical pictures were taken with a Nikon camera fitted with a fish-eye lens (Fisheye-Nikkor 10 mm f 5.6 180° – OP). Kodak plus X film was used and was developed in Kodak D76 for 6 min with continuous agitation. Generally, the pictures were taken at 1/2 s with f/11 to f/8 aperture with an orange filter in the early morning or overcast sky. A preliminary experiment with these original pictures showed that they did not have sufficient contrast for the image decoder, the electro-optical light intensity scanner, to scan correctly. To enhance the contrast, the original negatives were duplicated with high contrast Agfaortho 25 film and developed in Agfa Neutol NE for 3 min with continuous agitation.

Image Decoding Systems

Electro-optical intensity scanner. The electro-optical light intensity scanner used in the decoding of the hemispherical pictures is shown in *Figure 2.* It was developed in the Laboratory of Plant Ecology, State University of Ghent based on the design of Bonhomme and Chartier[6]. The final test calibration of the instrument was done in an ealier study[13]. The pictures were projected on the screen in such a manner that the centre of the picture coincided with the axis of the motor driven arm placed in front of the screen. The arm had ten phototransistors and described one revolution in 4 minutes. A reversing device permitted the arm to change direction to avoid the twisting of the wire.

The oscillator generated 750 impulses per minute and these impulses were registered on a reference counter. In the course of one complete revolution each phototransistor received 3000 impulses and they were transmitted to the counter if they were not blocked when the irradiance on the screen was low (*i.e.* when phototransistor encountered the leaves*). The transmission of the impulses was blocked when the irradiance on the screen was high (*i.e.* when phototransistor encountered the sky) and less impulses were transmitted to the corresponding counter. The blockage of the transmission of impulses was dependent on the level of amplification which was regulated by a variable resistance. The amplification was adjusted to adapt the threshold of counting to the characteristics of the pictures.

The location of the phototransistors corresponded to the elevation β of 5°, 15°,

*Since positive slides was used, leaves were dark and the sky was clear.

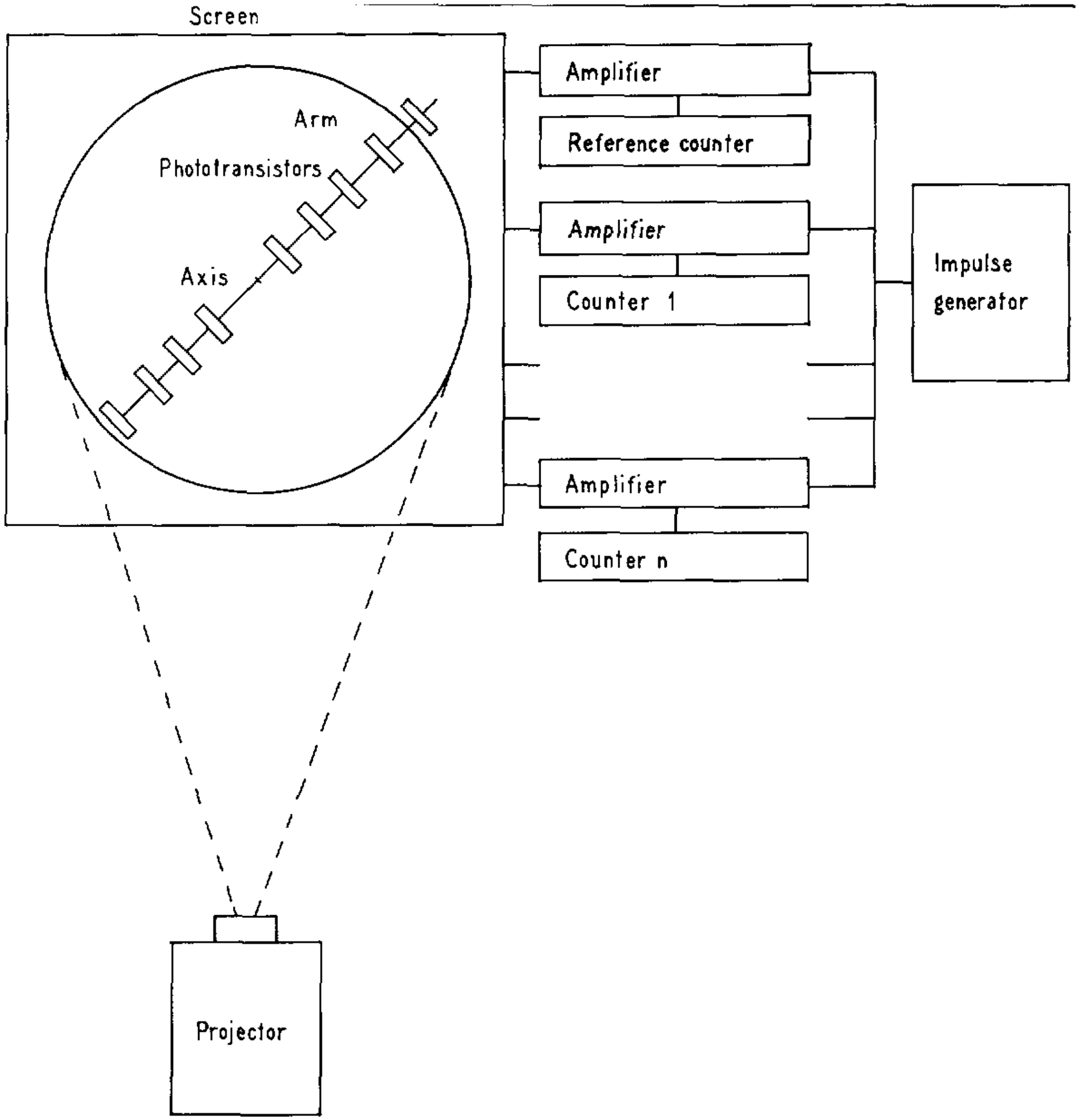

Figure 2. Schematic diagram of the electro-optical light intensity scanner.

25°, 32.5°, 35°, 45°, 55°, 65°, and 75°. For example, in the course of a complete revolution, when the phototransistors corresponding to the elevation β of 45° gave n impulses the reference counter gave N impulses, then the gap frequency for elevation β was

$$g_{45°} = 1 - \frac{n}{N}$$

Computerised digitiser. The frequency of gaps in the hemispherical picture was determined with a digitiser by measuring the lengths of gaps in each circle corresponding to various elevations, β. The picture was projected on a vertical board of a Summagraphics Digitizer which was connected to a Hewlett Packard mini computer (HP 9815A). A series of special soft ware programmes were developed in the Laboratory of Plant Ecology, State University of Ghent to read gap lengths on the digitiser and to calculate the gap frequency as explained below.

A grid of 40 cm diameter with concentric circles corresponding to elevation β of 5°, 15°, 25°, 32.5°, 45°, 55°, 65° and 75° was fixed on the vertical board. The enlargement of the picture on the board was of the same diameter as the grid and with its centre coinciding with the grid's centre. The length of the gap along each concentric circle was measured by tracing the length with a digitising stylus connected to the digitiser and computer. The tracing was converted into sets of X-Y co-ordinates in a process called digitisation and these were interpreted by the computer to give the length. The frequency of gap per circle was calculated as:

$$\frac{\Sigma g_\beta}{c_\beta}$$

where g_β was the length of each gap within the circle at elevation β whose circumference was C_β:

'Spider Web' grid overlay. This system follows the method described by Anderson[20]. A 'spider web' grid overlay was constructed based on the equation, $I = \frac{1}{3}\sin^2\beta + \frac{4}{9}\sin^3\beta$, so that each of the 1000 segments cover an area contributing 0.001 of the radiation from a standard overcast sky. The grid overlay was superimposed on the hemispherical picture of similar diameter as the grid. Working round each annulus in turn from the horizontal to zenith, the percentage of observed sky was scored and this was summed to give the list penetration.

In situ *Field Measurements*

Leaf area was calculated from leaf fall collected in cages measuring 2 × 2 metres. The leaves in the cages were collected every third day and their areas determined using the dry weight/leaf area conversion factor determined from a sub sample of the leaves.

Light penetration was measured with a quantum metre and sensor (Lambda L1 185A).

A transact was placed diagonally across the plot. Sticks were erected at the centre of the plot along the transact at 0.5 metre interval to give fifty measurement points. As it was impossible to take each reading simultaneously under the canopy and in the open, readings were taken under the canopy and in the open within a scan period of 5 min where seventy to one hundred readings were obtained. Means of these readings were calculated and these were expressed as percentages of the measurements in full light for the same period.

Regression

Linear regression was carried out in the comparison of decoding systems. Linear and non-linear curve fittings were carried out in the correlation studies. High coefficients of correlation were obtained from linear regressions. The non-linear models which included parabolic, power, exponential and hyperbolic did not improve the coefficient substantially *(Table 1)* and for simplicity the linear model was selected.

RESULT

Comparison of Decoding Systems

Leaf area index was determined from the hemispherical pictures with the

TABLE 1. REGRESSION EQUATIONS AND THEIR COEFFICIENTS OF CORRELATION

Model	Equation	
	Regression of F^{11} on F	
Linear	$y = 0.122 + 1.332x$	0.951
Parabolic	$y = 0.551 + 0.728x + 0.155x^2$	0.959
Power	$y = 1.619x^{0.704}$	0.943
Exponential	$y = 0.779e^{0.564x}$	0.946
Logarithmic	$y = 1.915 + 1.406 \ln x$	0.803
Hyperbolic	$y = 2.675 - \frac{0.340}{x}$	0.455
	Regression of $F^{11}_{32.5}$ on F	
Linear	$y = 0.232 + 1.324x$	0.902
Parabolic	$y = 1.035 - 0.074x + 0.421x^2$	0.934
Power	$y = 1.721x^{0.391}$	0.828
Exponential	$y = 0.788e^{0.584x}$	0.933
Logarithmic	$y = 2.026 + 0.815 \ln x$	0.737
Hyperbolic	$y = 2.541 - \frac{0.172}{x}$	0.399
	Regression of F^{1} on F	
Linear	$y = 0.485 + 1.148x$	0.955
Parabolic	$y = 0.587 + 1.001x + 0.035x^2$	0.956
Power	$y = 1.771x^{0.629}$	0.954
Exponential	$y = 0.931e^{0.471x}$	0.919
Logarithmic	$y = 2.089 + 1.285 \ln x$	0.831
Hyperbolic	$y = 2.659 - \frac{0.268}{x}$	0.463

digitiser (F^{11}) and the electro-optical light intensity scanner (F^{1}). Leaf area index values determined by the digitiser were higher than those determined at low LAI by the scanner. At higher LAI the reverse trend was observed (*Figure 3*). The regression was highly significant ($P < 0.1\%$) and yielded r value of 0.975. There was significant difference between the intercepts ($P < 1\%$) and slopes ($P < 5\%$) of the regression line and the 1 : 1 line. The LAI determined by both decoding systems were not statistically ($P < 5\%$) different.

Light penetration was measured by the 'spider web' grid overlay and compared with light penetration determined by the electro-optical light intensity scanner (*Figure 4*). The regression was highly significant ($P < 0.1\%$) and yielded r value of 0.989. The values obtained from the 'spider web' grid overlay method were generally higher than those obtained with the scanner. There was significant

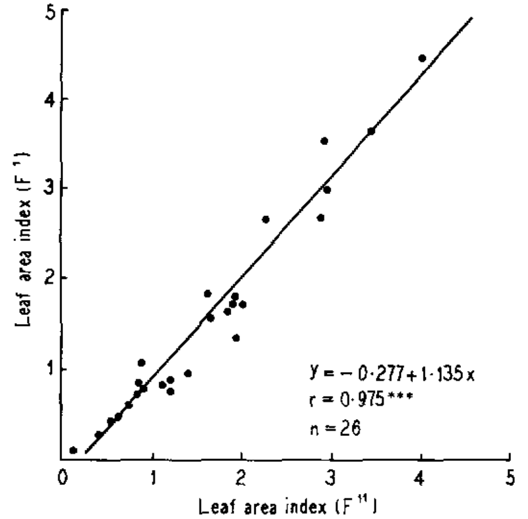

Figure 3. Relationship between leaf area index determined from hemispherical pictures with digitiser (F^{11}) *and with electro-optical light intensity scanner* (F^1).

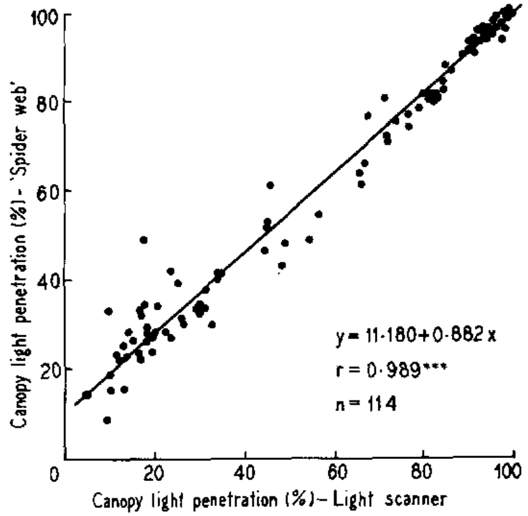

Figure 4. Relationship between canopy light penetration determined from hemispherical pictures by electro-optical light intensity scanner and by 'spider web' grid overlay.

difference between the intercepts and slopes (P < 0.1%) of the regression line and the 1 : 1 line.

Correlation Studies

Correlation between leaf area index obtained from in situ *field measurement and leaf area index from hemispherical photography.* Leaf area index obtained from *in situ* leaf litter collection and that obtained from hemispherical pictures decoded by different systems are plotted in *Figures 5, 6* and *7.*

The linear regression in *Figure 5* shows that there was statistically significant

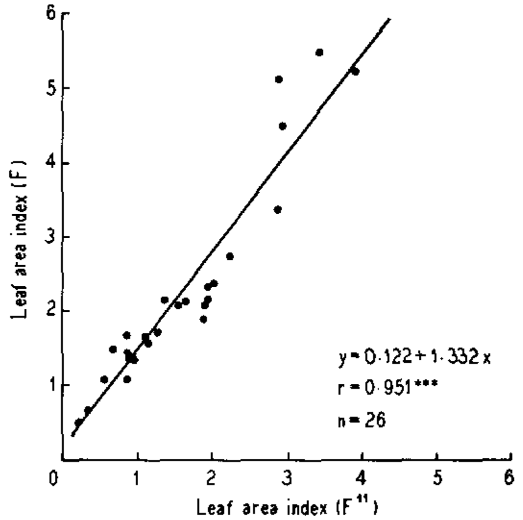

Figure 5. Relationship between leaf area index determined from hemispherical pictures with digitiser (F^{11}) *and leaf area index determined from* in situ *leaf litter collection* (F).

(P < 0.1%) correlation between LAI, determined from *in situ* leaf litter collection cages *(F)* and LAI determined from hemispherical pictures using the digitiser and *Equation 4* (F^{11}). The coefficient of correlation *r* was 0.951. There were no significant (P < 5%)

differences between the intercepts of the regression line and the 1 : 1 line. There was *significant* (P < 0.1%) *difference* between the slopes of the two lines.

The relationship between *F* and LAI determined from hemispherical pictures using the digitiser and *Equation 5* ($F^{11}_{32.5}$) was significant (P < 0.1%) and has a coefficient of correlation *r* of 0.902 (*Figure 6*). The coefficient of correlation was lower than that obtained with *F* against F^{11}. There was no statistically significant (P < 5%) difference between the intercepts of the regression line and the 1 : 1 line. There was statistically significant (P < 5%) difference between the slopes of the two lines.

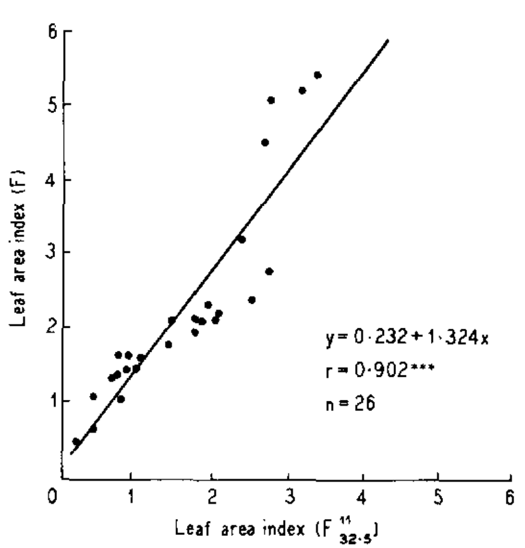

Figure 6. Relationship between leaf area index determined from hemispherical pictures with digitiser ($F^{11}_{32.5}$) *and leaf area index determined from* in situ *leaf litter collection (F).*

The regression of *F* on F^1 and LAI determined by the electro-optical light intensity scanner, were statistically significant (P < 0.1%) and the *r* value was 0.955 (*Figure 7*). There was statistically significant (P < 1%) difference between the intercepts of the regression line and the 1 : 1 line. There was no statistically significant (P < 5%) difference between the slopes of the two lines.

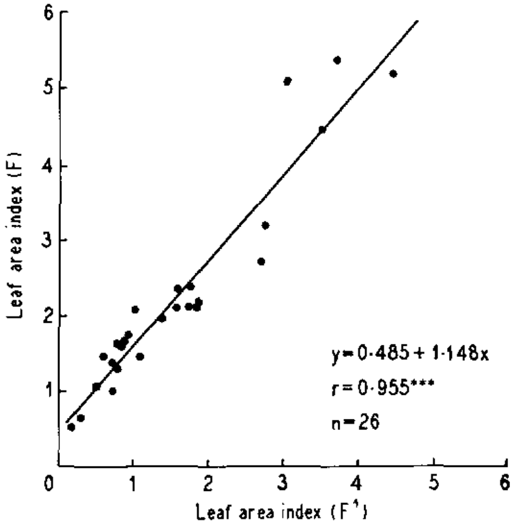

Figure 7. Relationship between leaf area index determined from hemispherical pictures with electro-optical light intensity scanner (F^1) *and leaf area index determined from* in situ *leaf litter collection (F).*

Correlation between light penetration from hemispherical photography and light penetration obtained from in situ *field measurement.* Light penetration was determined from hemispherical pictures decoded with the electro-optical light intensity scanner and compared with light penetration measured in the same fields where the pictures were taken with quantum sensors. The results are plotted in *Figure 8*. The regression of the light penetration from the hemispherical pictures on actual field measurements was statistically significant (P < 0.1%) and yielded *r* value of 0.995. There was no statistically significant (P < 5%) difference between the intercepts and slopes of the

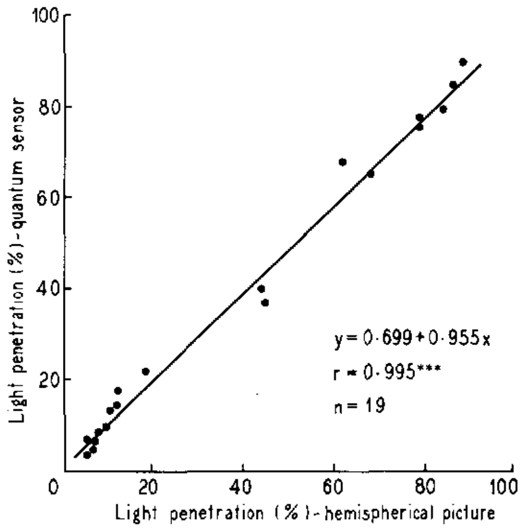

Figure 8. Relationship between canopy light penetration determined from hemispherical pictures with electro-optical light intensity scanner and canopy light penetration measured in the field.

regression line and the 1 : 1 line. The *t*-test of the means showed no statistically significant (P < 5%) difference in light penetration obtained from the hemispherical pictures and from field measurements.

DISCUSSION

The study on the comparison of different image decoding systems showed no significant differences in the results obtained from the hemispherical pictures decoded by the digitiser, electro-optical light intensity scanner and the 'spider web' grid overlay. The digitiser and the 'spider web' grid overlay, however, are visual methods and subjective to inter and intra-observer errors.

The electro-optical light intensity scanner is a preferred method as it is not subjected to such errors. In addition it is less laborious and takes the shortest time to decode a picture. It requires about 5 min for one person to decode the picture which included the recording of the reading registered on the counters. To decode the same picture by either the digitiser or the 'spider web' grid overlay would require two to three times as long.

Leaf area index from hemispherical pictures decoded by the digitiser calculated on eight viewing angles *(Equation 4)* and on one viewing angle *(Equation 5)* showed no differences. Although both equations could be used, better correlation with LAI obtained from *in situ* leaf litter collection was achieved with the eight viewing angles than with one viewing angle. Leaf area index calculated on eight viewing angles from hemispherical pictures decoded by the electro-optical light intensity scanner was highly correlated with LAI obtained from *in situ* leaf litter collection. The correlation coefficient was higher than that obtained from the digitiser. A highly significant correlation beween LAI obtained from hemispherical pictures and LAI obtained from *in situ* leaf litter collection in poplar was reported by De Cleene[13] and Van Elsacker *et al.*[15] However, the results of De Cleene indicated that the poorest correlation was obtained with the electro-optical light intensity scanner and also a lower correlation coefficient was obtained with LAI calculated on eight viewing angles than on one viewing angle.

The canopy light penetration values obtained from hemispherical pictures and actual field measurements for diffuse radiation were highly correlated. The regression line was linear and approached closely to the 1 : 1 line. The results concurred with those of Van Elsacker *et al* on poplar[15].

This study has shown that hemispherical photography can be used to estimate LAI and canopy light penetration in the *Hevea* stand. The technique is accurate and less laborious than *in situ* field measurements.

It is useful tool to evaluate changes in the canopy due to cultural practices such as pruning and tree density.

ACKNOWLEDGEMENT

One of the authors, W. Leong wishes to thank the Director and Board of the Rubber Research Institute of Malaysia for his scholarship to enable him to carry out part of this work at the State University of Ghent, Belgium. The authors also thank Ir G. Eckhaut, Mr M. Drubbel, Mr G. Renneboog, Mr H.T. Leong and Mrs Y.H. Phun for their capable assistance.

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and
State University of Ghent
Belgium *September 1981*

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