Measurements of Leaf Area Index Using Optical Method (LAI-2000) in Oil Palm Plantation: Accuracy and Limitation Assessment

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Keywords: Leaf area index, Plant Canopy Analyzer, accuracy and limitation

ABSTRAK

Indeks kawasan daun (LAI) merupakan parameter penting untuk pengkarakteran struktur kanopi tanaman. LAI kerap digunakan sebagai pemboleh ubah kritikal untuk menyerupai model ekosistem yang berbeza, sukar untuk diukur secara terus dalam minyak sawit. Dalam kajian ini, kaedah optik untuk menyatakan variasi kuantiti dalam LAI di bawah keadaan berbeza dinilai. Didapati ketepatan bacaan bergantung pada faktor-faktor yang berbeza seperti teknik pengukuran, penglihatan sudut litupan, pembolehubahan ruang dan ketinggian titik pengukuran. Teknik pengukuran memberikan kesan kepada pengukuran LAI. Keputusan menunjukkan kaedah Zigzag mencatatkan kurang anggaran LAI berbanding kaedah lain. LAI menggunakan kaedah Zigzag mencatatkan 11.6% kurang berbanding teknik "satu di atas dan empat di bawah" dan 5.7% kurang berbanding teknik "satu di atas dan lapan di bawah". LAI memperoleh 6.2% kurang dengan menggunakan teknik "satu atas dan lapan di bawah" berbanding teknik "satu atas dan empat di bawah". Keputusan daripada siasatan yang dibuat terhadap kesan daripada penglihatan litupan ukuran LAI menunjukkan penglihatan litupan mempengaruhi pengiraan LAI dan LAI menurun dengan peningkatan pada sudut penglihatan litupan. Nilai LAI PCA juga turut dipengaruhi oleh pembolehubahan ruang dan ketinggian sensor. Nilai LAI PCA meningkat dengan peningkatan ketinggian sensor di permukaan tanah dengan nilai LAI maksimum (2.77) pada ketinggian 2.5 meter di permukaan tanah dan nilai minimum LAI (0.932) pada ketinggian 0 meter di permukaan tanah. Nilai LAI maksimum diperoleh pada semua arah pada jarak 0.5 meter daripada batang dan nilai minimum LAI diperoleh berdekatan dengan hujung pelepah. Nilai PCA LAI meningkat 5% dengan peningkatan jarak dari hujung pelepah ke tangkai.

ABSTRACT

Leaf area index (LAI) is an important parameter for characterizing the canopy structure of a crop. The LAI, which is often used as a critical variable to simulate different ecosystem models, is difficult to measure directly in oil palm. In this study, optical methods for quantifying variation in LAI under different conditions were evaluated. It was found that the accuracy of the readings depended on different factors, such as measuring technique, view cap angle, spatial variability, and height of the measuring point. The measuring technique had an effect on the LAI measurement. Results showed that the Zigzag method underestimated the LAI compared to other methods. The LAI by the Zigzag method was 11.6% less than the LAI by the "one above and four below" technique and 5.7% less than the LAI by the""one above and eight below" technique. The LAI obtained by the "one above eight below" technique was 6.2% less

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than the LAI obtained with the "one above four below" technique. Results from the investigation of the effect of view cap on LAI measurement showed that the view cap strongly influenced the LAI calculation and LAI decreased with increase in the view cap angle. PCA LAI values were also affected by spatial variability and height of the sensor. PCA LAI values increased with increase in sensor height above ground with a maximum LAI value (2.77) at 2.5-meter height above ground and minimum LAI value (0.932) at 0-meter height from ground. Maximum values of LAI were obtained for all directions at 0.5-meter distance from the trunk and minimum LAI values were obtained near the tip of the frond. The PCA LAI values increased by about 5% - 50% with increase in distance from the frond tip to frond base.

INTRODUCTION

Leaf area index (LAI) is a dimensionless index, which can be defined as the assimilative leaf area relative to the projected ground area for a plant community (one-side area for broad-leaved trees) (Lang *et al.*, 1991). Accurate and fast non-destructive measurements of leaf area index (LAI) of plant canopies are essential to environmental applications such as water and carbon cycle modeling. A commonly used technique to acquire LAI in situ is based on measurements of radiation transmittance through the canopy with optical instruments. The LAI-2000, which obtains measurements of effective LAI based on gap fraction at five view angles, is designed to work under diffuse light conditions (Leblan and Chen, 2001). Direct methods, such as destructive sampling, may provide the best estimates of LAI, but they are time consuming, difficult, with higher labor cost. Several non-destructive methods have been developed that utilize light attenuation through the plant canopy to estimate the amount and, in some cases, the orientation of foliage (Feldkirchner and Gowe, 2001). In the past few years, a number of systems for making indirect canopy structural estimates have become commercially available. These include linear sensors that require specific illumination conditions, such as the DEMON (CSIRO, Center for Environmental Mechanics, GPO Box 821, Canberra, ACT, Australia), Line quantum sensors (Decagon Devices, Box 835, Pullman, WA 99163, USA), and hemispherical sensors, such as the LAI-2000 ((Plant Canopy Analyzer, LI-COR, Lincoln, Nebraska, USA), the Leaf Laser, and CI-100 (4018 NE 112th Ave. Suite D-8, Vancouver, WA 98682, USA). The performance of these instruments as reported

in the literature is reviewed for forest, row crops and individual trees (Welles and Cohen, 1996).

One of the instruments is the LAI-2000 (Plant Canopy Analyzer, LI-COR, Lincoln, Nebraska, USA), which makes use of diffuse light and should, in principle, avoid direct sunlight. Therefore, the measurements should be taken on uniform sky conditions found on overcast days, or near sunset or sunrise to avoid the interference of direct sunlight. The LAI-2000 has been used in a wide range of plant canopies: coniferous and deciduous species (Gower and Norman, 1991), different pines (Law *et al.*, 2001) and boreal forests in Canada (Chen *et al.*, 1997). Many of these studies showed that the LAI-2000 generally underestimates the LAI from direct measurements. Indirect methods of determining LAI which relate total leaf area to the radiation environment below the canopy are generally less time consuming as well as non-destructive. However, indirect LAI measurements are sensitive to a range of external and internal factors, often inducing difficult-to-define errors in the final LAI estimate at the scale of interest, such as the oil palm plantation. The objectives of this study were to determine the effects of different factors such as PCA measuring technique, sky condition, height and direct light on the measured LAI.

Study Site

Measurements were made at the Malaysian Palm Oil Board (MPOB) ENOVECY research plot in Bangi situated about 30 km South from Kuala-Lumpur, (Latitude 2° 58′ 0.36″ N, Longitude 101° 44′ 26″ E) at an average altitude of 66.5m above sea level. The

commercial D x P palms with 148 planting density were planted in 1998 and managed according to the standard estate practices. The 6 years old uniform palms were used for this study.

Instrument Description

The LAI-2000 Plant Canopy Analyser (LI-COR, USA) is an instrument designed to measure LAI of green canopies. The instrument's sensor is incorporated with fisheye optics to project a hemispheric image onto five silicon detectors, arranged in concentric rings. The sensor also contains an optical filter to restrict sensed radiation of wavelengths below 490 nm, in order to minimize the contribution of radiation that has been scattered by foliage. The control box records the sensor's data and executes the calculation necessary for determining LAI. The basic technique combines a measurement of sky brightness from a levelled sensor above the canopy with a second measurement taken beneath the canopy. The ratio of each ring's signals (below to above) is then assumed to be equivalent to the canopy's gap fraction at that ring's viewing angle. Although the LAI-2000 potentially "views" a full 360° of azimuth, it can be restricted by a view cap of 270°, 180°, 90°, and 45°, attached onto the sensor head to limit sensor view for special purposes (Welles and Norman, 1991). The LAI-2000 consists of five sensors, which simultaneously measures the PAR light intensities in five concentric Field of Views (FOVs) centred at zenith angles of 7, 23, 38, 53 and 68 degrees, and respectively referred to as PCA Sensors 1, 2, 3, 4 and 5. Usually, below and above-canopy readings are simultaneously acquired to calculate the canopy gap fraction, which represents the probability of light penetration. Gap fraction values are then converted to contact frequency values that are used for further analysis (LI-COR 1992).

Basic Theory Related to Light Interception and Leaf Area Index

In an ideal diffusing medium, receiving a radiant flux I at the surface, the flux I at an optical depth F is an inverse exponential function of the extinction coefficient k,

$$I = I \exp(-k * F). \tag{1}$$

Monsi and Saeki (1953) equated LAI with F, explored extensively both the theoretical geometric and practical reasons for variation of k in different plant covers; k being a function of leaf angle and direction of the incident beam. When leaves are grouped in clumps, or regularly rather than randomly distributed, k changes. The combination of theory and practice of measurement of the various components, the foliage area F, flux I, extinction coefficient k, and foliage angle has since been extensively explored (Warren, 1963).

Light traveling through a vegetation canopy is attenuated by leaves interception. The fraction of photosynthetically active radiation (PAR) transmitted through the canopy is related to the distribution and amount of leaves in the canopy. If the leaves are assumed to be randomly distributed in the canopy and opaque in the PAR wavelengths of the irradiance at the bottom of the canopy, then Equation (1) can be written as:

$$I = I_o * \exp(-k * LAI) \tag{2}$$

Where I_o is the incoming irradiance, LAI is the leaf area index, and k is an extinction coefficient. The exponent, (k * LAI), is the area of the shadow of the leaves projected onto a horizontal plane. Assuming a spherical leaf angle distribution, then the distribution of leaf inclination and orientation angles is similar to those found on the surface of a sphere and k, can be calculated from the solar zenith angle, Θ:
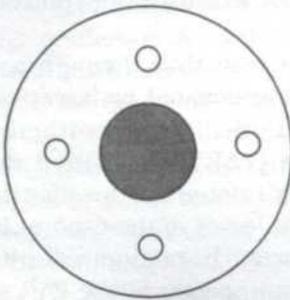
K is a function of zenith angle (Θ) and the leaf inclination angle distribution. Theoretically, k simplifies to
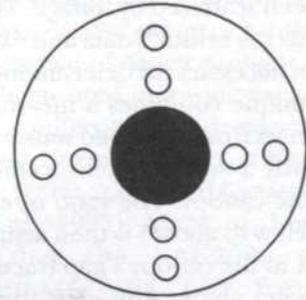
$$K = 1/2 \cos \Theta \tag{3}$$

If a spherical leaf angle distribution is assumed (Campbell, 1986), these equations

Trunk

Measuring
Point
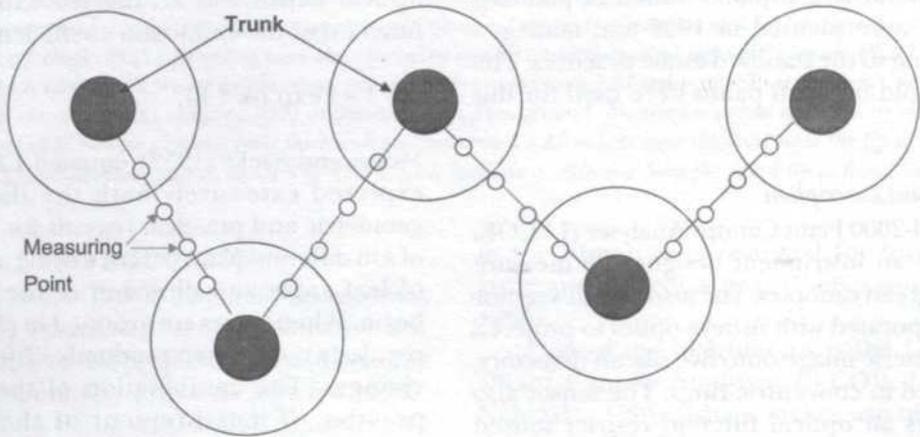
i) Zigzag methods

ii) One above four below methods

iii) one above eight below methods

Fig. 1: Experimental design for below reading measurements

can be combined to solve for LAI from line sensor measurements of PAR transmittance from measurements above and below the canopy.

MATERIALS AND METHODS

The experiments were conducted in May to June 2003 at the Malaysia Palm Oil Board (MPOB) research plot. Six-year old palms were chosen for this investigation. Five uniform palm trees were chosen at random for measurement. Four different types of tests were conducted in this study. For each test, an above-canopy sensor (A) logged readings in a nearby large opening (no vegetation at greater than

15 degrees above the horizon) while a below-canopy sensor (B) was used to log readings within the experimental plot. Various factors affecting the LAI measurement were also evaluated by the experiments.

Different Measuring Technique

Three techniques were used for accuracy assessment of the PCA LAI-2000, i.e. the Zig-zag method, "one above reading - four below readings" and "one above - eight below readings". Lamade and Setiyo (1996) used zigzag methods for indirect measurement of LAI by PCA (LAI-2000). They selected eight measuring points between two adjacent palms. Roslan et al. (2002) used one above canopy

reading followed by four readings under canopy at $^1/_2$ frond length distance from the palm base. In this study, four equal measuring points between two adjacent palms were selected for the zigzag method (*Fig. 1*). For the "one above four below" technique, one above reading followed by four below readings was chosen. Below readings were chosen accordingly in the North-South and East-West direction. Sometime, it is difficult to choose the justified sensor position for below reading measurements along the frond. A homogeneous position was chosen for the below reading measurements. The readings represented the whole palm tree. For the "one above eight below" technique, data were taken in same compass directions as in the previous method. For this technique, two below readings were taken at 1/3 and 2/3 of frond length from frond base (*Fig. 1(iii)*). All PCA LAI-2000 readings were taken with the sensor-facing north at 1.4 meters above the ground and with a 180-degree view cap attached.

Sensor Height
The effect of vertical height (sensor distance from ground to lowest frond) on PCA LAI was evaluated at six different heights under the palm canopy. The first measurement was taken at ground surface and the last measurement taken at least 0.5-meter distance below the lowest frond (*Fig. 2*). Other measurements were then taken at every 0.5-meter interval from the first measurement.
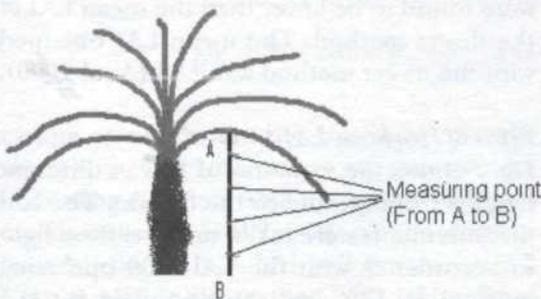

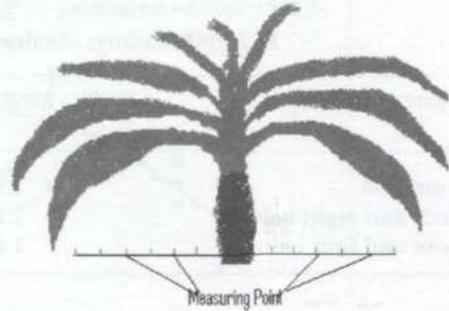*Fig. 2: Vertical distance between ground to the lowest frond*

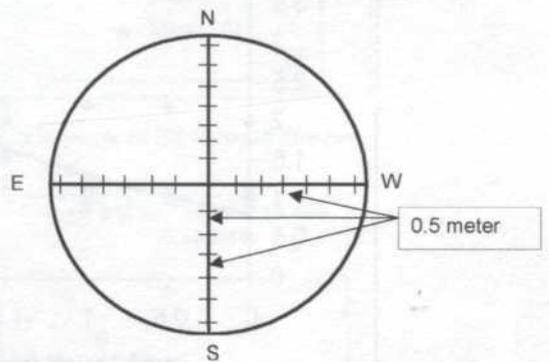*Fig. 3: Spatial variation of PCA reading under canopy*

Fig. 4: Experimental design for spatial variation of PCA reading

Distance from Trunk to Frond Tip
To evaluate the effects of spatial variation on LAI at different positions under the palms, measurements were taken at 0.5-meter intervals distance from trunk (*Fig. 3*). Measurements were taken in the North, South, East and West side of the trunk (*Fig. 4*).

View Cap
As Welles (1990) pointed out, the use of a view cap is required to prevent direct sunlight from hitting the sensor and causing increased variability and underestimation in LAI measurements with the PCA instrument. Lastly, for testing the effect of view cap, different view cap sizes (7°, 45°, 90°, 180° and 270°) were used under the same conditions (i.e. same height, same palm, same direction

TABLE 1
PCA LAI readings obtained from the different techniques

Measurement technique	Mean PCA LAI	Reference LAI (LAI obtained with direct method)
Zig-zag method	1.14±0.09	
One above and eight below	1.21±0.09	2.38
One above and four below	1.29±0.15	

$$y = 0.8356e^{0.4598x}$$
$$R^2 = 0.9624$$

Vertical height from ground (meter)
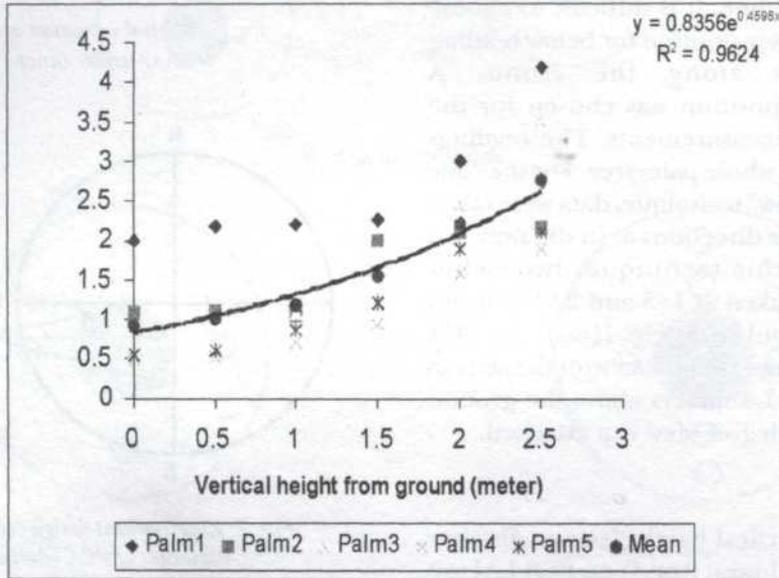
♦ Palm1 ■ Palm2 Palm3 × Palm4 ✳ Palm5 ● Mean

Fig. 5: Variation of PCA reading (LAI) with different height from ground to the lowest frond

and same sky condition). The canopy diameter was 8-meter (the distance between trunks to frond tip was 4 meters) and the lowest average canopy height was 3.5-meter from the ground.

RESULTS AND DISCUSSION

Effect of Different Measuring Technique

Three techniques were compared to investigate the effects on PCA LAI. The results in Table 1 show that the LAI measured with the Zig-zag method was lower as compared to two other methods. The LAI obtained with zig-zag method was 11.6% less than the LAI obtained with the "one above and four below" technique and 5.7% less than the LAI obtained with the "one above and eight below" technique. The LAI obtained with the "one above eight below" technique was 6.2% less than the LAI obtained with the "one above four below" technique. The mean PCA LAI values for the three techniques investigated were found to be lower than the mean LAI of the direct method. The mean LAI obtained with the direct method was 2.38 (Awal 2006).

Effect of Height on LAI

Fig. 5 shows the variation of LAI at different heights from ground to the frond. The LAI measurements were taken under diffuse light in accordance with the LAI-2000 operating manual. A 180-view cap was used for the measurement and the "above-canopy" reference measurements made outside the
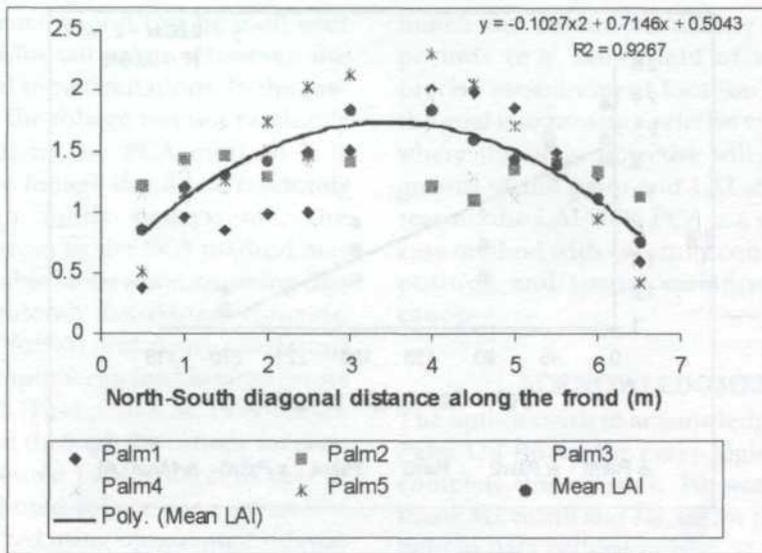
$$y = -0.1027x^2 + 0.7146x + 0.5043$$
$$R^2 = 0.9267$$

Fig. 6: PCA LAI with spatial variation of PCA sensor in North-South direction

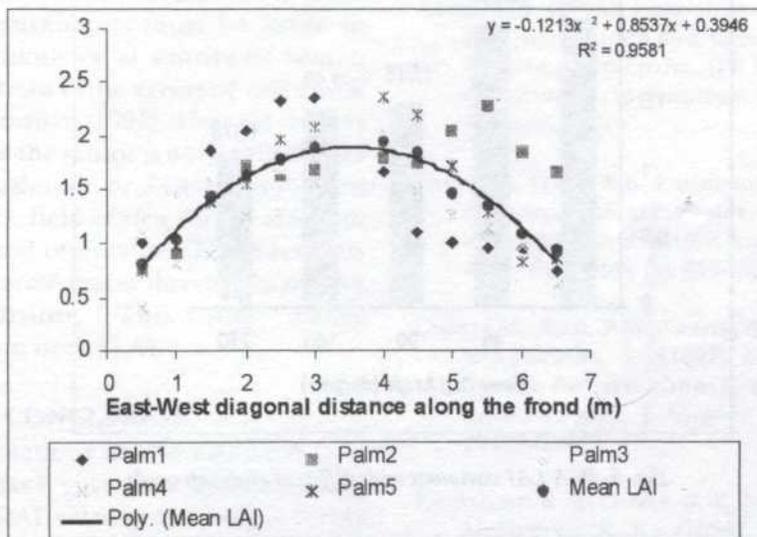$$y = -0.1213x^2 + 0.8537x + 0.3946$$
$$R^2 = 0.9581$$

Fig. 7: PCA LAI with spatial variation of PCA sensor in East-West direction

canopy were taken at the same time. Results show that the LAI values increased with increasing distances from ground to the lowest fronds and a strong (R^2 =0.98) relationship was found between PCA LAI and Sensor height. Results also indicate that PCA LAI related exponentially to the sensor height from ground.

Effect of Distance from Trunk to Frond Tip

The assessment of the variation of LAI at different positions beneath the canopy along the North -South and East-West axis are illustrated in *Figs.* 6 and 7. Results show that the LAI decreased from frond base to frond tip in both North-South and East-West directions. Data showed that LAI increased on
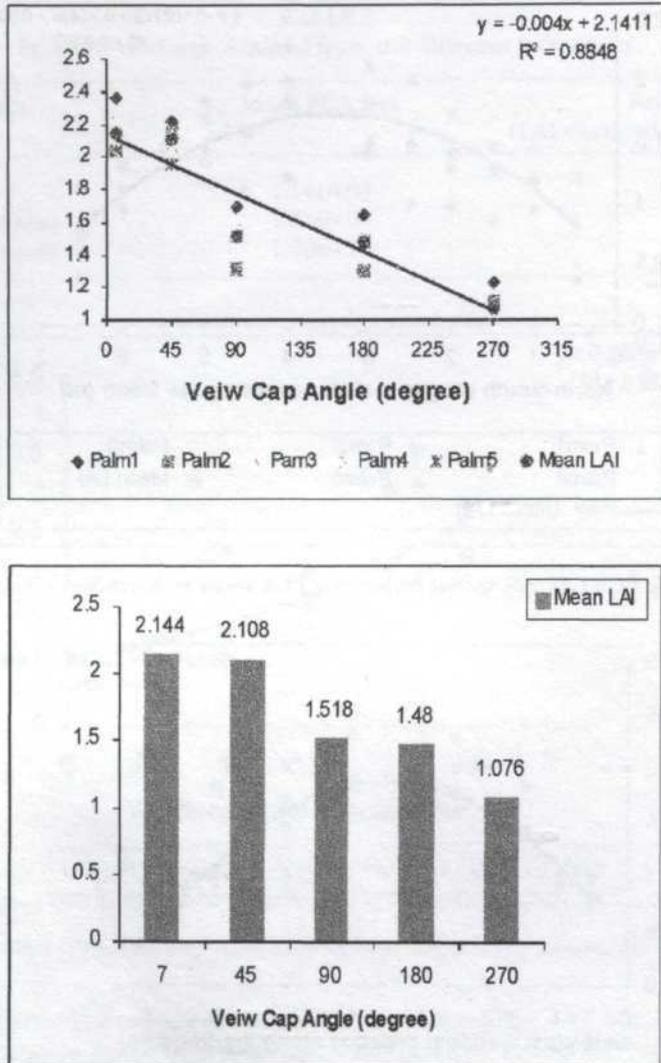
Fig. 8: PCA LAI variation with different view cap angle

average by about 5% to 50%. A good linear relationship (R^2 = 0.84 for N-S and R^2 = 0.84 for E-W) was found between PCA LAI and position of the sensor along the frond.

View Cap Effect on Measuring LAI

Different angles of view cap (7°, 45°, 90°, 180° and 270°) were used to investigate their effects on LAI measurement. *Fig. 8* shows the relationships between view cap angle and PCA LAI. Results showed that the view cap angle selection had great effect on PCA LAI value.

Maximum LAI value was obtained for 7° view cap and minimum LAI value for 270° view cap. A linear relationship (R^2 = 0.94) was found between PCA LAI and view cap. Results showed that the view cap angle strongly influenced o PCA LAI. PCA LAI decreased with increasing view cap angle.

The performance of the LAI-2000 Plant Canopy Analyser (PCA) was evaluated under different conditions for indirect LAI measurements of oil palm. Compared to the direct methods, the PCA method was more

rapid, non-destructive and can be used over larger areas and for tall palms. However, the PCA method had some limitations. In the case of the oil palm, the foliage was not randomly distributed, but in the PCA method it is assumed that the foliage should be randomly distributed. In many ecosystems, the measurement errors by the PCA method may be within acceptable limits when assuming that the foliage is randomly distributed. However, in open-canopy forests and many coniferous forests, this assumption can lead to large errors in excess of 100% (Fassnacht *et al.*, 1994). Since light transmission through the canopy for non-randomly distributed foliage exceeds that of randomly distributed foliage for a given leaf area, LAI calculated using optical methods was often underestimated for non-random or clumped, foliage distributions. Other limitations to the use of the LAI-2000 PCA were that the measurements must be made in overcast conditions or at sunrise or sunset; direct sunlight can cause errors of up to 50% (Welles and Norman, 1991). User errors may be substantial if the sensor is not levelled, held at the correct azimuth, or if view caps that are used to limit the field of view do not match in terms of size and orientation. Measurements will not be accurate under direct light or very sunny condition. This may cause underestimation of the LAI.

CONCLUSION

The main limitations of the LAI-2000 PCA method was that it gave underestimated and inconsistent LAI values, and was severely affected by sunlight conditions, spatial variability, and sensor position. However, the ability to easily obtain data without having to correct for limitations of the LAI-2000 PCA method or other optical methods will likely depend on the ultimate use of the data. For example, the LAI-2000 PCA data can be used as an effective means of comparing relative differences among treatments within a system or for examining changes throughout or among seasons, provided that care is taken to

match the conditions among measurement periods (e.g. same field of view, azimuth, precise measurement location). Moreover, if the goal is to measure relative variation in LAI, where the main objective will be to monitor growth of the palm and LAI variation within season, the LAI-2000 PCA is a very quick and easy method with carefully considered sensor position and spatial variation under palm canopy.

ACKNOWLEDGMENTS

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