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Methodology and measurement of radiation interception by quantum sensor of the oil palm plantation

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Abstract

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Interception of light by a canopy is a fundamental requirement for crop growth and is important for biomass production and plant growth modeling. Solar radiation is an important parameter for photosynthesis and evapotranspiration. These two phenomena are dependent not only on the intensity of radiation but also on the distribution of intercepted radiation within the canopy. In this study, two operational methods for estimating the amount of photosynthetically active radiation (PAR) intercepted by a canopy of the oil palm are presented. LICOR radiation sensors, model LI-190SA and model LI-191SA were used for photosynthetically active radiation (PAR) measurement above and below the canopy. We developed two methods, namely "Triangular" method and "Circular" method for PAR measurement. Results show that both methods were suitable for oil palm PAR measurement. The triangular method is recommended for PAR measurements

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with respect to the whole plantation and the circular method is recommended for specific purposes, such as growth analysis or growth modeling of the oil palm. However, practical considerations such as equipment availability, purpose of the measurement, age of the palm, and the number of measuring points to be sampled should be taken into account in the selection of a suitable method for a particular study. The results indicate that the interception of radiation was affected by spatial variation, and the radiation transmission decreased towards the frond tips.

Key words : photosynthetically active radiation (PAR), light interception (LI), radiation interception, quantum sensor, and oil palm

The interception of light by a canopy is a fundamental requirement for crop growth. Light interception and the relationship to crop growth have been important concepts applicable to virtually all crops (Monteith, 1977). Although canopy light interception (LI) is important for yield prediction and crop growth, LI is not often measured because measurements must be made close to solar noon in unobstructed, direct-beam sunlight. Despite the recognized importance of light interception, measurements of this parameter are often neglected because of the difficulty of obtaining an accurate estimate under the crop canopy (Purcell, 2000). Interception of photosynthetic active radiation (PAR) by a shoot is divided into three components: the amount of radiation coming from the sky, the transmission of radiation through the surrounding vegetation, and the shootís silhouette area facing the direction of the incoming radiation. All three components usually vary with direction. Radiation incident from the sky consists of direct and diffuse radiation (Smolander and Pauline, 2001).

The photosynthetically active radiation (PAR), defined as the wavelength band of 400 nm to 700 nm, represents most of the visible solar radiation. The proportion of global irradiance that originates from diffuse sky radiation is higher for PAR than for all solar short wave radiation (Richard *et al.*, 1996). Knowledge of PAR is necessary in different applications dealing with plant physiology, biomass production and natural illumination in greenhouses. Incident photosynthetically active radiation (400-700 nm) is required to model photosynthesis of individual plant leaves or complex plant communities. PAR is the general radiation term that covers both photon terms and energy terms. Photosynthetic photon flux density, QPAR, is defined as the photon flux density (1 μ mol photons $m^{-2}s^{-1}$ = 6.022×10^{17} photons $m^{-2}s^{-1}$ = 1 μE $m^{-2}s^{-1}$) (Alados and Alados-Arboledas, 1999). When modeling plant processes such as photosynthesis, respiration and transpiration, or microclimatic parameters such as leaf temperature, it is important to determine the radiation in the plant canopy. However, Jesper *et al.*, (1999) reported that as commercially available standard quantum sensors are relatively large, it is difficult to obtain true in situ measurements of the light environment of individual leave at different levels of a canopy. It is important to note that the spectral response of a PAR sensor is a good approximation of an ideal quantum response, which also obeys Lambert's cosine law.

Radiation capture cannot be measured directly. Early models predicted canopy light interception based on the leaf area index (LAI) and an extinction coefficient (k) that is related to the average leaf angle following the equation, which was first described by Monsi and Saeki (1953) based on Beer's Law (Campbell and Norman, 1998).

$$\text{Fractional light interception} = [1-e^{-(k*LAI)}] \quad (1)$$

In this equation, only two variables determine the light interception: the extinction coefficient, *k*, and the leaf area index (LAI). The extinction coefficient describes the angle of leaves to the sun and varies between 1 (completely perpendicular to the sun) and 0 (completely vertical to the sun). As defined, the angle between the sun and leaves depends upon the angle of leaves to the horizon and the angle of the sun to the horizon. The angle of the sun to the horizon (α) changes over the course of the day and with season of the year and latitude. To correct for the angle of the sun, k may be divided by sin (α), or measurements may be made near solar noon when sin (α) is approximately 1. The most common method used for determining LI is to measure the photosynthetically active radiation (PAR) above a canopy and below a canopy near solar noon when the light is unobstructed by cloud cover (Flenet *et al.*, 1996).

LI = (PAR above canopy - PAR below canopy) / (PAR above canopy)

Or,

LI = [1-(PAR below canopy) / (PAR above canopy)] (2)

Line quantum sensors are available commercially; they integrate PAR along a 1-m length. The sensor may be placed perpendicular to the row (Egli, 1994). If the sensor cannot be placed evenly from the middle of one row to another, then a portion of the sensor may be covered with a material that blocks light. Alternatively, the sensor may be placed parallel to the row beneath the canopy, and multiple measurements made between rows, which are then averaged (Board *et al.*, 1992).

A more direct method involves measuring the photosynthetically active radiation (PAR) above and below a plant canopy with a line quantum sensor as described by Gallo and Daughtry (1986). The inherent difficulties in measuring LAI or PAR throughout a canopy and the advances in radiometric techniques have led to the development of methods for remotely sensing radiation capture. Radiometric methods rely on differences in the spectral reflectance of vegetation and soil. Vegetative indices based on reflectance in broad wavebands have provided good estimates of radiation capture, LAI, and yield in crop plants (Hatfield *et al.*, 1984; Gallo *et al.*, 1985). Vegetation indices have also provided good estimates of fractional ground cover (Boissard *et al.*, 1992; White *et al.*, 2000). The main objective of this study was to develop a method that is suitable for PAR measurement in oil palm.

Materials and Methods

Experimental site

The experiment was conducted at Malaysian Oil Palm Board (MPOB) research station. The station is located at about 35 km north from Kuala-Lumpur, Latitude 2º 58′ 36″ N, Longitude 101º 44′ 26″ E) at an average altitude of 66.5 m above mean sea level.

Equipment for above and below canopy light measurement

A Li-Cor Li-190SA quantum sensor (Li-Cor, Lincoln, NE) attached to a data logger (Li-Cor 1400, Li-Cor, Lincoln, NE) was placed on a horizontal surface above the ground in an open field adjacent to the study field for obtaining above-canopy light measurements (Figure 1).

The LI-1400 data logger combines simple operation, compact size, and 10 channel data logging to produce an instrument that is both powerful and easy to use.

A variety of sensors can be used with the LI-1400 data logger including Li-Cor radiation sensor, air and soil temperature sensors, and many meteorological sensors. Three external light sensor connectors allowed fast set-up with Li-Cor radiation sensors. Two additional current channels, one pulse counting channel, and several regulated and unregulated voltage supplies provided high input impedance for measuring a wide range of sensors. We connected radiation sensor and logged data according to the operation manual.

The below canopy PAR was measured using the LI-191SA Line Quantum Sensor (Li-Cor,

Figure 1. Quantum sensor for above-canopy measurement of PAR.

Figure 2. Quantum sensor for below canopy measurement of PAR.

Lincoln, NE). The LI-191SA (Figure 2) is designed for measuring the photosynthetically active radiation (PAR) in applications where the measured radiation is spatially non-uniform (such as within plant canopies). To achieve this, the sensor features a sensing area that is one meter in length. The LI-191SA has a quantum (photon) response through the wavelength range of 400-700 nm for PPFD (photosynthetic photon flux density) as generally preferred for PAR measurements, and has an output in units of micromoles per second per square metre where:

$$1\ \mu mol\ m^{-2} s^{-1} = 1\ ^{o}E\ m^{-2} s^{-1} = 6.02\times10^{17}\ photons\ m^{-2} s^{-1}$$

The flux density measured on a given plane can vary considerably due to shadows and sun flecks. Neglecting this in measurements can introduce errors up to 100%. Multiple sensors or sensors on track scanners can be used to minimize this error. The LI-191SA Line Quantum Sensor, which spatially averages radiation over its 1 meter length, minimizes the error and allows one person to easily make many measurements in a short period of time. The sensor can also be used for permanent monitoring of radiation within the crop canopy. The sensor is fully weatherproof (except the BNC connector) and can be left unattended.

Normally when a single user is measuring radiation within a crop canopy, he/she supports the sensor with one hand and cantilevers it into the canopy. The sensor should be maintained in a level position as much as possible. Since radiation levels vary considerably, the user error introduced by not levelling exactly is usually very small in relation to the total radiation error, which might occur due to variations within the canopy. At every data measurement, the sensor was placed 1 m above the ground according to the experimental procedure.

Calibration of the point quantum sensor

The point quantum sensor (Li-Cor Li-190 SA) was calibrated using a Line quantum sensor (Li-Cor Li-191 SA). Calibrations were necessary due to the need for replacement of all point quantum data by line quantum data, or to match two sensor data in the same value. Before each calibration, both the quantum sensors were levelled. Point quantum sensors were calibrated under clear sky conditions during midday. Measurements were taken every 5 seconds for at least 15 minutes. For low light and high light intensity calibration, an approach proposed by Gendron *et al*., (1998) was adopted. With this technique, the sensors measured light intensity over several days to capture a wide range of solar angles and sky conditions. Linear regression analysis between point quantum data and the line quantum data was performed in order to generate a conversion factor between the outputs of the point quantum sensor and the output of the line quantum sensor (PPFD in $\mu mol\ m^{-2}\ s^{-1}$). Less than 700 nm was considered as low light intensity and more than 700 nm was considered as high light intensity. At both low light intensity and high light intensity, the relationship was linear. Two conversion factors were determined, one for low light intensity and another for high light intensity.

Measurements of Radiation Interception

1. Measurement outline

As part of the detailed study of PAR measurement for oil palm plantation, six groups of oil palm trees (2, 3, 7, 9, 12, and 16 years old) were selected for the investigation. At least five replicates were used to determine the effects of spatially variable over-story light competition on the oil palm canopy. The areas of the 3 and 7 year old oil palm plantations were less than one hectare and those of 2, 9 12 and 16 years were 3, 1.6, 4.3, and 12 hectares, respectively. Five replications were used both for the 3 and 7 years old palm trees, whereas ten replications were used for the 2, 9, 12

Table 1. Calculation of radiation interception

PQ sensor reading	Conversion factor	Above canopy reading	Below canopy reading	Radiation interception
1000.10	0.95	950.10	287.20	0.6977
967.81	0.95	919.42	256.34	0.7211
1007.40	0.95	957.03	220.30	0.7698
1013.20	0.95	962.54	216.37	0.7752
938.68	0.95	891.75	215.10	0.7587
989.41	0.95	939.94	346.80	0.6314
1025.90	0.95	974.61	296.60	0.6956
1065.10	0.95	1011.81	301.26	0.7022
1064.10	0.95	1010.89	299.35	0.7038
1036.00	0.95	984.20	289.35	0.7060
1013.70	0.95	963.02	276.31	0.7130
1052.80	0.95	1000.16	274.21	0.7258

and 16 year old palms. Data were collected using the triangular and circular methods (details & methodology are in following section). The below canopy data were collected by the line quantum sensor at 15-second intervals on average for all the palm groups and for both methods. The above canopy data were collected using the point quantum sensor, attached to a data logger (Li-1400). The data logger measured radiation every 15 seconds. After data logging, data were downloaded into the computer using a special software. The logged data were multiplied by a conversion factor for matching them with the line quantum data and for calculating the radiation interception at every point of measurement (Table 1).

2. Measurement procedure

Squire (1984a) used a square method for the determination of PAR interception under oil palm tree. Twenty-five points are normally used with the PAR sensor around each palm tree for small areas, and selected measuring points for large areas. However, two different measuring techniques were evaluated in this study. In most commercial plantations, palms are planted by the triangular system. For this reason, the triangular measuring technique was adopted for the whole plantation (in both small and large areas), and the circular method for individual palm measurements.

2.1 The triangular method

A triangle was formed using plastic rope connecting three palms. Every arm of the triangle was divided into six equal parts. Each marking point of the triangle was joined by a plastic rope as shown in Figure 3. Every intersection point was treated as a measuring point, where the quantum sensor was placed for the below canopy radiation data recording.

2.2 The circular method

In the circular method, a circular area under the palm tree was considered. The outermost circle corresponds to the frond tip while the frond base considered as the centre point of the circle. This circle was divided into sectors according to zenith and azimuth angles for proper PAR estimation of spatial variation. Each circle and line were drawn by white marking powder according to Figure 4. A total of twenty-four measuring points were used for every palm tree in order to measure the below canopy radiation.

In both the triangular method and the circular method, the quantum sensor was placed 0.5 meter above the ground for the below canopy data recording. The line quantum sensor was used for the below canopy recording. To minimize spatial variation, the sensor was carefully placed in the same azimuthal direction during data recording.

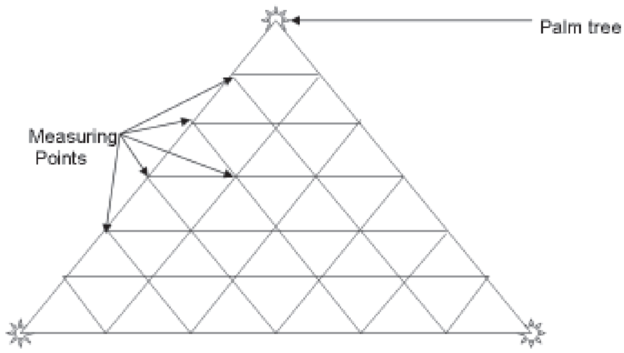

Figure 3. Triangular method among three-palm trees.

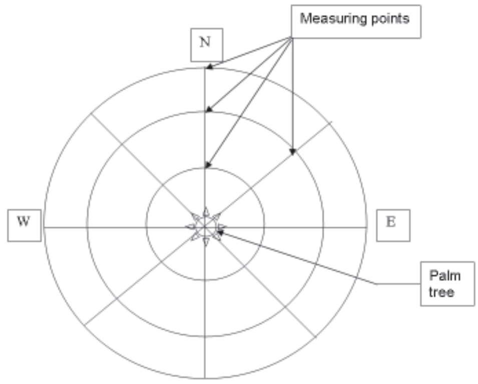

Figure 4. Circular method for PAR measurement.

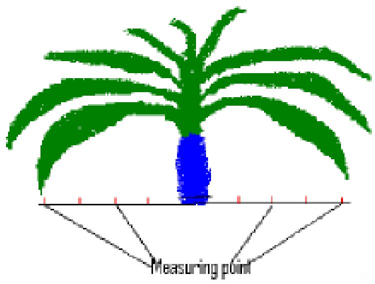

Figure 5. Design layout for spatial variability effect on radiation interception

Experimental design for spatial effect

Figure 5 shows the experimental design layout for investigating the effect of spatial variability on radiation interception along the frond. The line quantum sensor was placed at half-meter intervals from the frond base (trunk) towards the frond tips. Four points were taken for recording the below canopy radiation for each frond side.

Results and Discussion

The first column of Table 1 shows the above canopy reading of the point quantum (PQ) sensor while the second column shows the sensor calibration factors. After multiplications of the above canopy reading by the calibration factors, the actual above canopy radiation data were recorded. Radiation interceptions were calculated using Equation 2.

Tables 2a shows the summary results of radiation interception data as measured by the circular method. Tables 3a shows the summary results of radiation interception and measured by the triangular method.

1. Relationship between radiation interception and LAI

A multiple regression analysis was performed to evaluate the relationship between average radiation interception and average leaf area index (LAI) with respect to age of the palm. Average radiation interceptions were plotted against average LAI for each palm age group for 2-16 year old palm trees when the circular method was used (Figure 6). Results show that radiation interception and leaf area index were not linearly related. The multiple correlation coefficient (R) was 0.91 and the coefficient of determination (R^2) was 0.82, the

Table 2a. Average fractional radiation interception obtained by the circular method.

Palm age	Average fractional radiation interception (r)	Standard deviation	95% of confidence interval Lower	Upper
2 years	0.6789±0.00969	0.10708	0.6597	0.6981
3 years	0.8405±0.01618	0.10856	0.8079	0.8731
7 years	0.8699±0.00513	0.05618	0.8598	0.8801
9 years	0.9429±0.00143	0.02269	0.9461	0.9457
12 years	0.9122±0.00225	0.03562	0.9078	0.9166
16 years	0.9238±0.00142	0.02252	0.9210	0.9266

Table 2b. Average fractional radiation transmission obtained by the circular method.

Palm age	Average fractional radiation interception (1-r)	Standard deviation	95% of confidence interval Lower	Upper
2 years	0.3211±0.00969	0.10708	0.3019	0.3403
3 years	0.1595±0.01618	0.10856	0.1269	0.1921
7 years	0.1301±0.00513	0.05618	0.1199	0.1402
9 years	0.0571±0.00143	0.02269	0.0543	0.0597
12 years	0.0878±0.00225	0.03562	0.0834	0.0922
16 years	0.0762±0.00142	0.02252	0.0734	0.0789

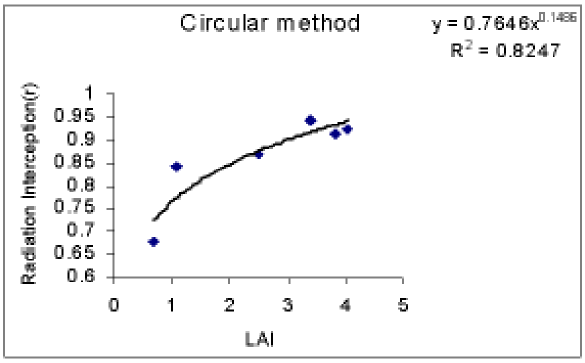

Figure 6. Relationship between radiation interception and LAI for circular method.

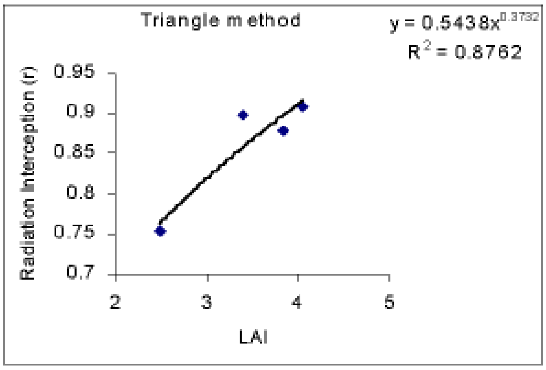

Figure 7. Relationship between radiation interception and LAI for triangular method.

F test (F = 18.819) and t-test (t = 4.335) for the adjusted model were significant and the standard error of estimation of coefficient was low (0.05).

Figure 7 shows the relationship between radiation interception and LAI for the triangular method. Average radiation interceptions were plotted against average LAI for mature palms. A non-linear relation was found between radiation interception and LAI. The multiple correlation coefficient (R) was 0.93 and coefficient of determination (R^2) was 0.88, the F test (F = 14.157) and t test (t = 3.763) for the adjusted model were significant and the standard error of estimation of coefficient was low (0.03).

Table 3a. Average fractional radiation interception obtained by the triangular method.

Palm age	Average fractional radiation interception (r)	Standard deviation	95% of confidence interval Lower	Upper
7 years	0.7541±0.02027	0.23989	0.7140	0.7942
9 years	0.8991±0.00547	0.08643	0.8884	0.9099
12 years	0.8781±0.00393	0.06231	0.8703	0.8858
16 years	0.9076±0.00294	0.04660	0.9018	0.9134

Table 3b. Average fractional radiation transmission obtained by the triangular method.

Palm age	Average fractional radiation interception (1-r)	Standard deviation	95% of confidence interval Lower	Upper
7 years	0.2459±0.02027	0.23989	0.2058	0.2860
9 years	0.1009±0.00547	0.08643	0.0901	0.1116
12 years	0.1219±0.00393	0.06231	0.1142	0.1297
16 years	0.0925±0.00294	0.04660	0.0866	0.0982

Squire (1984b) carried out an experiment on measurement of solar radiation interception and found that the relation between solar radiation and LAI was approximately linear for mature palms (LAI = 8). The relationship between LAI in immature palm (LAI = 2) and radiation interception was less clearly defined. The fraction of the solar radiation transmitted through a canopy depends upon the amount, the distribution and the orientation of the foliage. For a uniform canopy of mature palms this is related to LAI, but for immature palm (LAI is less than 2), the relation is not very good. However, the results show that the fractional radiation interception is linearly related to LAI, both for mature and immature palms.

2. Relation between radiation interception and palm age

Again, a multiple regression analysis was used to establish the relationship between radiation interception and palm age. Figure 8 shows the results for the circular method, which indicates that the relation between radiation interception and palm age was non-linear. The multiple correlation coefficient (R) was 0.87 and the coefficient of determination (R^2) was 0.75, the F test (F = 12.469) and t-test (t = 3.531) for the adjusted model were significant and the standard error of estimation of coefficient was low (0.06).

Figure 9 shows the relationship between radiation interception and palm age for the triangular method. It shows that the relation between radiation interception and palm age was again non-linear. The multiple correlation coefficient (R) was 0.77 and the coefficient of determination ($R^{2)}$ was 0.59, the F test (F = 2.967) and t-test (t = 1.723 for the adjust modeled were significant and standard error of estimation of coefficient was low (0.06).

Corley and Gray (1976a) reported that the leaf area increases rapidly with palm age to reach a stable maximum after about 10 years. At the best sites, maximum frond area was 10 m^2 or more, which at 40 fronds per palm and 148 palms per hectare will give rise to a LAI of at least 6. Squire (1984a) used this data and converted it to radiation interception and found maximum r = 0.96 and the palm stand achieves 90% of the maximum radiation interception after about 6 years. Of course the growth of the leaf is not only dependent on age of

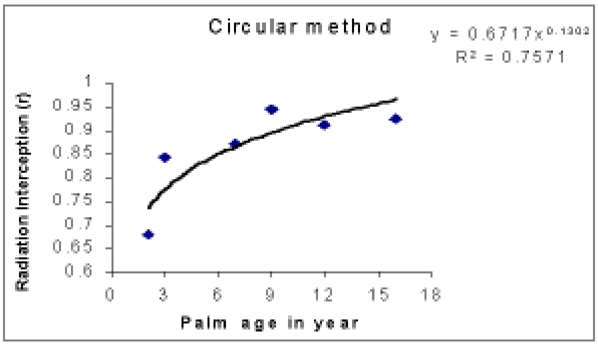

Figure 8. Relationship between palm age and radiation interception for the circular method

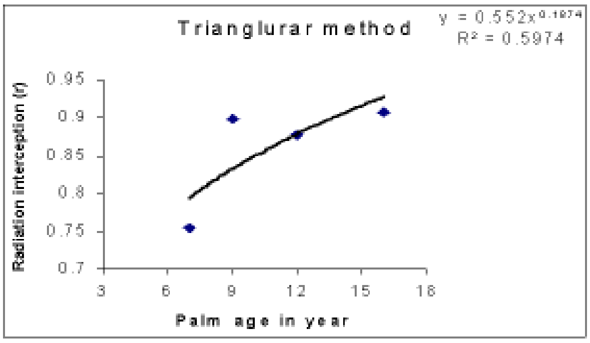

Figure 9. Relationship between palm age and radiation interception for triangular method

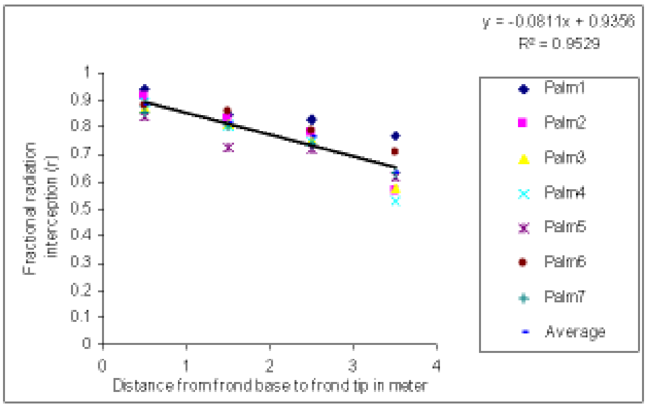

Figure 10. Spatial variability effect on "Fractional radiation interception" for 7-year old palms

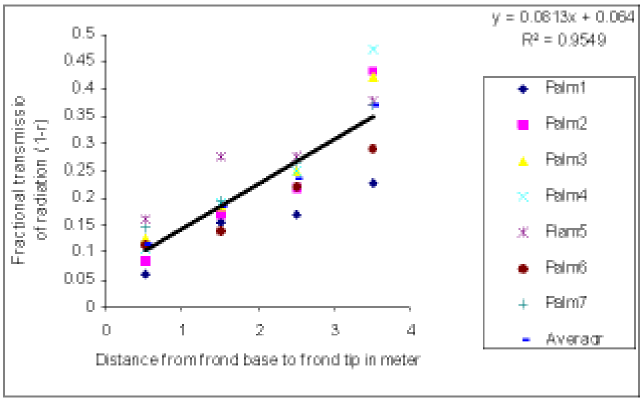

Figure 11. Spatial variability effect on "Fractional radiation transmission" for 7- year old palms

the palm, but it is also affected by soil quality. Phang Sew *et al*., (1977) showed that the production of leaf area might vary by a factor of 2 depending on type and depth of soil. However, the results in this study showed that the relationship between fractional radiation interception and palm age is non-linear for all ages of palm.

3. Effect of spatial variation on radiation interception

Figure 10 shows the effect of spatial variation on radiation interception under the canopy of the oil palm. A good relationship was found between radiation interception and distance along the frond, with the radiation interception decreasing with increasing distance from the frond base. Data indicate a high degree coefficient of determination (R^2 = 0.95) and a low standard error of estimation (0.02).

4. Effect of spatial variation on radiation transmission

Figure 11 shows the effect of spatial variation on radiation transmission under the canopy of the oil palm. A good direct relationship was found between radiation interception and distance along the frond with the radiation transmission increasing with increasing distance from the frond base. From this observation, it is clear that the radiation transmission gradually increased towards the frond tips. Data indicate a high degree coefficient of determination (R^2 = 0.95) and a low standard error of estimation (0.02).

Conclusions

Sunlight is an important parameter for photosynthesis and evapotranspiration. These two phenomena are dependent not only on the intensity of radiation but also on the distribution of intercepted radiation within the canopy. Radiation absorption is a more fundamental indicator in plant growth and yield prediction model. Not only this, but also radiation interception is the most important factor for intercropping systems, because when two or more plants are grown on a certain piece of land, competitions occur for the growth resources such as solar radiation, water, CO_2, O_2 and nutrients. As such, the measuring method of radiation interception depends on the purpose of its use. For intercropping evaluation, one of the main objectives is to evaluate light competition under the canopy. The "Triangular" measuring method is not suitable to evaluate radiation interception for immature palm tree (2-5 years) because at this stage the palm canopy is not fully opened and a large space remains among three palms. However, this method provides a good spatial arrangement among palm trees at their mature stage. The radiation interception is strongly related to dry matter production (Squire, 1984a) and the canopy area of the oil palm can be considered as a circle. The results of this study showed that radiation interception is strongly affected by spatial variation. It should be pointed out that the circular measuring method provided very good spatial arrangement (both in zenith and azimuthal directions) and measurements can be taken for an individual palm tree. Hence, it is therefore recommended that the "circular" measuring technique should be used for the measurement of radiation interception for growth modeling of the oil palm.

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