Plant Geometrical Structure and Leaf Irradiance in Cotton :
I. Measurement Methodology

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ABSTRACT

Plant geometrical structure is an important factor influencing on variability of micro-environment of plant community. Amount of leaf area, spatial distribution of leaf area, and leaf orientation are generally studied as the description of plant geometry. Errors of this description had been proven to give under estimation from simple light interception model in cotton. Thus, more accurate plant geometrical descriptions are needed for cotton.

There are several methods for characterizing plant structure. The new method presented which had been used in cotton is the three dimensional electromagnetic digitizing. This method improves plant structure measurement in the field with high accuracy. The information from digitizing by using DIPLAMI data acquisition software developed by I.N.R.A. (National Institute of Agricultural Research) in France can be widely used either for plant geometrical structure analysis or light interception estimation.

Leaf irradiance measurement has also been developed. Using light and low-cost sensors has shown to be reliable for leaf irradiance measurement and allows us to get more information of light distribution in the cotton canopy. The applications of digitizing and light sensor are also discussed.

Key words : plant geometrical structure, plant architecture, digitizing, leaf irradiance, light interception, cotton

INTRODUCTION

Plant canopy structure is the spatial arrangement of the above-ground organs of plants in a plant community (Campbell and Norman, 1989). Canopy structure is important in determining the physical environment within the plant community and affects the processes of photosynthesis, transpiration, photomorphogenesis, infection by pathogens, growth and multiplication of insects, and competition between species in a plant community. Therefore, description of plant structure is needed to provide basic information for further understanding of plant-environment interactions.

Although plant canopy structure have been studied for more than 40 years, there is not much information for cotton, particularly in term of the relationship between plant structure and light interception by leaves, because of the difficulty of their measurements in the field. This paper will present the methodological development for plant

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geometrical structure and leaf irradiance measurements in cotton and their application under field conditions.

METHOD

Plant Geometrical Measurement

Plant geometry can be characterized by the size, shape, orientation and other external features of the plant organs (Ross, 1981). From a radiation interception point of view, the amount of leaf area and its spatial arrangement have been mostly concerned.

The methods of plant geometrical measurement, both direct and indirect methods in 1 (1D), 2 (2D) and 3 dimensions (3D), have been previously reported (Bacci et al., 1993; Sinoquet and Andrieu, 1993; Moulia and Sinoquet, 1993; Prévot and Brunet, 1993; Sinoquet and Rivet, 1997; among others). Description of plant geometry in 3D provides useful information for studying plant-environment interactions. However, this is difficult to measure, particularly under field condition, because of the limitation of device efficiency.

1. Amount of Leaf Area

The amount of leaf area is classically described by leaf area index (LAI), i.e. the amount of one-side leaf area above a ground area. When dealing with spatial distribution of leaf area, it is generally described by leaf area density (LAD), i.e. the amount of leaf area in a given volume (Sinoquet and Andrieu, 1993).

Leaf area can be directly or indirectly and destructively or non-destructively measured. Indirect and non-destructive measurement of leaf area is preferably used in several agrophysiological studies in order that we can follow continuously crop growth and development on the same plants. Besides the Plant Canopy Analyzer (LiCor® Model LAI-2000, LiCor, Lincoln, NE, U.S.A.) which is a

radiation sensor-based instrument for measuring LAI indirectly (e.g. Grantz et al., 1993, among others) and other devices commercially available, one of the cheap, practical, and reliable methods for leaf area measurement in cotton is the estimation of leaf area from a regression relationship between midrib length or midrib length x leaf width (Figure 1) and leaf area measured from a number of leaves by leaf area meter (Reddy et al., 1992; Reddy et al., 1993; Ball et al., 1994; Gerik et al., 1994; Samarakoon and Gifford, 1996, among others). However, this relationship might vary during the growing season due to leaf growth pattern and stage of development of cotton plant.

Our study on the relationship between leaf vein length and leaf area in Gossypium hirsutum L. var. DES 119 under optimal condition in 1995 revealed that this relationship varied significantly (P<0.05) during growing season (data not shown). The relationship between left vein length measured by a ruler and leaf area measured by a scanner (Hewlett Packard Scanjet IICX®, Hewlett Packard Inc., U.S.A.) gave the highest correlation (r = 0.93-0.96). However, leaf area estimated from left vein length was not siginificantly different from that estimated from midrib length. In most calculations of plant geometry, we need the description of midrib. Therefore, we used the allometric relationship of each growth stage, i.e. LAI, between
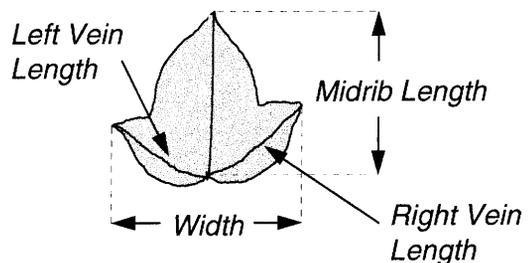

Figure 1   Cotton leaf description used for leaf area estimation.

midrib length and leaf area for estimating cotton leaf area as following :

$S_{LAI\,0.12}$ = -0.309 + 0.926 L

(n = 75, r = 0.930**)

$S_{LAI\,1.09}$ = -4.382 + 0.895 L

(n = 100, r = 0.939**)

$S_{LAI\,2.84}$ = -1.237 + 0.857 L

(n = 46, r = 0.958**)

where S is the leaf area (cm) of each stage of LAI and L is the length of midrib (cm) (Thanisawanyangkura *et al.*, 1997a).

Leaf area estimation from only one measurement of midrib length gives more rapid work in the field and permits to get more informations in the limited working time than the estimation from both leaf vein length and leaf width. Two experienced workers can measure 500-700 leaves per hour. The difficulty of measurement in the canopy is mostly due to branch obstruction.

2. Leaf Angle Distribution

Leaf angle distribution is one of the important parameters of plant geometrical structure which is difficult to measure under field condition, particularly in 3D. Thus, for simplification, in light interception models based on Beer-Lambert's law, leaf orientation is assumed to be random for leaf azimuth distribution. However, this assumption had been proven to give under-estimation of light interception for cotton (Thanisawanyangkura *et al.*, 1997a). Therefore, it is necessary to develop the accurate methodology for plant geometrical measurement in cotton for more accurate plant descriptions needed in the light interception models.

3. Instruments for Plant Geometrical Structure Measurement

The most common instrument for directly measuring the leaf angle distribution is a compass-protactor (Norman and Campbell, 1992). This is a simple device for measuring leaf inclination with a protactor and leaf azimuth with a magnetic compass. The readings from the protactor and compass are usually recorded in five to six inclination classes (e.g. 0°-15°, 15°-30°, 30°-45°, 45°-60°, 60°-75°, and 75°-90°) while eight azimuth classes (e.g. North, North-East, East, South-East, South, South-West, West, North-West) are generally used. However, there are many variations during measurement due to the instruments and operator.

In cotton, Lang (1973) had developed an << articulated arm >> apparatus which had been firstly used for leaf orientation measurement in *Gossypium hirsutum* L. This spatial coordinate apparatus consists of four linked arms which are pivoted so that they move in effect in a single plane, while the angles between the arms are measured by potentiometer (for more technical details, see Lang (1973), and Lang (1990)). This apparatus gives high linearity for angle measurement. However, it is not commercially available.

Fukai and Loomis (1976) measured cotton leaf inclination with a swinging protactor in which the vertical reference angle was maintained by a small lead weight. The inclination angle was recorded within one of six classes from 0° to 90°. Leaf azimuth were visually estimated within eight sectors by using a compass. After some practices of leaf angle measurement, within about 1 hour, two people were able to measure 100 leaves.

An ultrasonic telemetry system is one of the original methods for plant structure measurements (Sinoquet *et al.*, 1991). It had been used for measuring cotton plant structure in laboratory by J. F. Riaux and H. Sinoquet in 1994. The system commercialized by Science Accessory Corp° (Stratford, CT, U.S.A.) consists of a mobile ultrasonic emitter used as a probe which is placed at the point to be digitized, and a set of four microphones fixed within the same vertical plane.

The plant geometry is calculated from measuring the time elapsed between the sound emission by the probe and the reception on each microphone. Then, the times are converted into distances using the speed of sound in still air (for more details, see Sinoquet et al., 1991 and Moulia and Sinoquet, 1993. The information from sonic digitizing system had been used for generating virtual plants of cotton with L-system (Room et al., 1996). These virtual plants are expected to have the applications in research, education, extension, and decision-support. However, this system is sensitive to echos, masking, and very sensitive to air motions (Sinoquet et al., 1991; Moulia and Sinoquet, 1993). Thus, this system can be used efficiently in laboratory but not for field measurement.

One of the most recent systems used for 3D digitizing is low frequency magnetic field sensing system. It has been firstly used for measuring plant geometrical structure of cotton under field condition since 1995 (Thanisawanyangkura, 1995, Thanisawanyangkura et al., 1997a, Thanisawan-yangkura et al., 1997b). The electromagnetic digitizer (Polhemus® 3Space®, Fastrak®, Colchester, VT, U.S.A.) has been used with data acquisition software DIPLAMI developed by P. Rivet (I.N.R.A.- National Institute of Agricultural Research - Centre de Clermont-Ferrand, France). The system provides information of orientation angles and spatial coordinates of the digitized elements (Sinoquet and Rivet, 1997). This is a new method for plant geometrical structure measurement in 3D in cotton which gives high accuracy and insensitiveness to wind and masking under field condition.

The digitizing device consists of a system electronic unit (SEU), one (extendable to four) receiver(s), a single transmitter, and a power supply. The transmitter generates low frequency magnetic fields which induce currents in coils included in the receiver. Values of induced currents depend on the location and orientation of the receiver in the active volume around the magnetic source. The cartesian coordinates, i.e. x, y, and z, and Euler orientation angles, i.e. azimuth, elevation, and twist angles, of the receiver are determined with a resolution of 0.0005 cm/cm of range, and 0.025° (when the receiver is located within 76 cm of the transmitter). Operation with a separation of 305 cm between the transmitter and the receiver is possible with reduced accuracy (Polhemus Inc., 1993).

In order to get the information of node position, and leaf blade and petiole positions and orientations, digitized positions on cotton plant with this digitizer are the nodes on main stem and branches, the insertion of the leaves with petiole orientation, and the proximal and distal tips of the midrib with blade orientation and midrib direction (Figure 2).

For characterizing diurnal change in plant geometry due to heliotropism of cotton, digitizing was conducted three times a day by assuming that the leaves did not change significantly their orientation during the two hour measurement period: in the morning (07h00-09h00 True Solar Time), at noon (11h00-13h00), and in the afternoon (15h00-17h00) every 5 days. After some practice of digitizing, two people were able to measure 190 leaves on different cotton plants on different rows or 250 leaves on consecutive plants on the same row within about two hours with minimal disturbance of the canopy.

In our studies of plant geometrical description, cotton leaf is assumed to be a plane. Azimuth of midrib (ϕ_l) is defined as the angular distance of the projection of the midrib onto the horizontal plane relative to the North direction (Figure 3). Inclination of midrib (α_l) is defined as the angle between the midrib and the horizontal plane. Twist of leaf blade (θ_l) is a rotation angle around midrib.
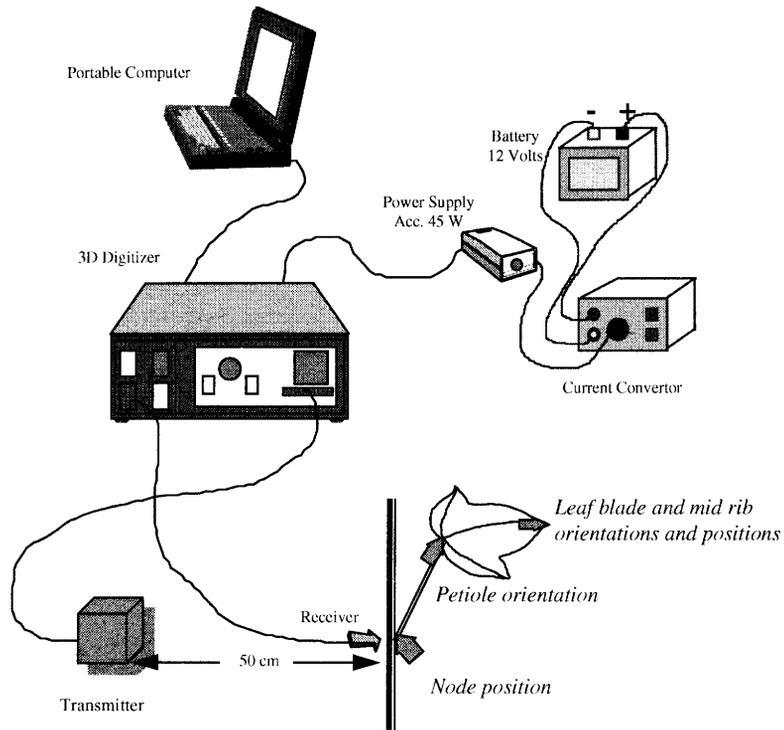
Figure 2   Schematic diagram of digitizer installation and digitized positions for cotton plant geometry measurement in the field.

4. Leaf Orientation Calculation

Angular determination is defined as shown in Figure 3. The azimuth of leaf normal (ϕ_n) is the angle between the projection of the leaf normal onto the horizontal plane and the North direction. ϕ_n was calculated as follows :

$$\phi_n = \phi_l - \arctan(\tan \theta_l / \sin \alpha_l)$$

where ϕ_l is the azimuth of midrib, α_l is the inclination of midrib, and θ_l is the twist of leaf blade around midrib.

The inclination of leaf normal (α_n) is the angle between the leaf normal and the vertical axis. It was calculated as follows:

$$\alpha_n = \arccos(\cos \theta_l * \cos \alpha_l)$$

5. Cosine of the Angle of Incidence

The cosine of the angle between leaf normal and sun direction (angle of incidence; β) indicates how the leaf faces the sun, thus it is generally used as an indicator for characterizing heliotropic behavior (leaf movement in response to change of sun direction). A value of $\cos \beta$ close to 1 indicates a leaf with a strong diaheliotropic behavior, i.e. leaf movement perpendicularly to sun direction. In contrast, the leaf with a $\cos \beta$ close to 0 shows strong paraheliotropic behavior, i.e. leaf movement in parallel of sun direction. The cosine ($\cos \beta$) is calculated as (Ross, 1981):
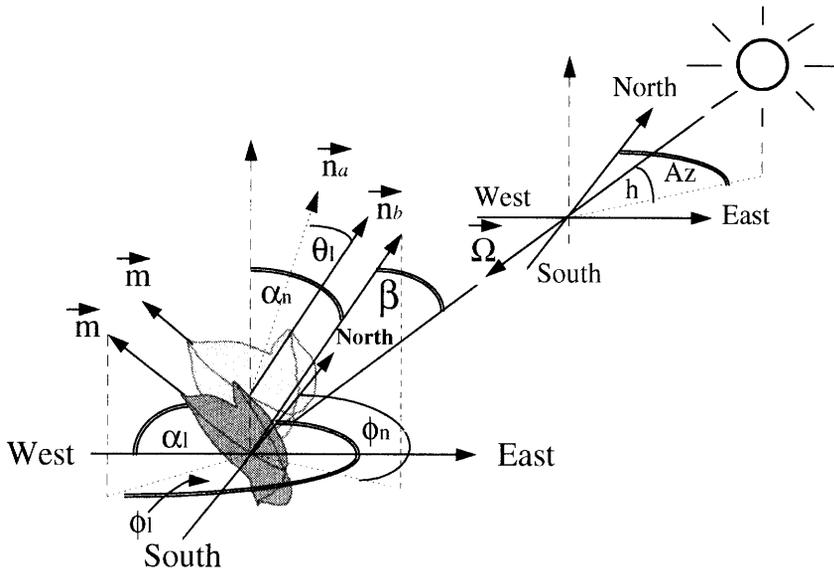
Figure 3 Schematic diagram showing angular determination of leaf orientation and sun position with leaf normal azimuth (ϕ_n) , leaf normal inclination (α_n) , azimuth of midrib (ϕ_l) , inclination of midrib (α_l) , leaf twist (θ_l) , normal of midrib (m) , normal of leaf blade ($\vec{n}$) , solar azimuth (A_z) , solar elevation (h) , and solar direct beam ($\vec{\Omega}$) . The leaf changes from position a to position b by twisting without change in leaf azimuth and leaf orientation. Thus, $\vec{n}$ changes from $\vec{n}_a$ to $\vec{n}_b$ and θ_l is the difference between $\vec{n}_a$ and $\vec{n}_b$ angle.

$$\cos \beta = \cos \alpha_n * \sin h + \sin \alpha_n * \cos h * \cos (A_z\text{-}\phi_n)$$

where h is the solar elevation and A_z is the solar azimuth.

In most radiative transfer models, the distribution of leaf azimuth is assumed to be uniform. In order to test the effect of this assumption on cos β, a value of cosine of incidence $(\cos \beta)^u$ with uniform leaf azimuth distribution was also calculated for each individual leaf as follows (e.g. Sinoquet et al., 1993):

when solar elevation is higher than leaf inclination:

$$(\cos \beta)^u = \cos \alpha_n * \sin h$$

when solar elevation is less than leaf inclination:

$$(\cos \beta)^u = \cos \alpha_n * \sin h * [(2\zeta / \pi) - 1]$$

when $\zeta = \{ [\text{arccos}(\text{-tan } h / \tan \alpha_n)] - \tan [\text{arccos} (\text{-tan } h / \tan \alpha_n)] \}$

For a population of N leaves, the average values of cos β and $(\cos \beta)^u$ called G-functions (see Ross, 1981) were computed by weighting individual cos β and $(\cos \beta)^u$ by leaf area S:

$$G = \sum_{i=1}^{N} S_i \cos \beta_i / \sum_{i=1}^{N} S_i$$

and

$$G^u = \sum_{i=1}^{N} S_i (\cos \beta)^u_i / \sum_{i=1}^{N} S_i$$

6. Diurnal Change of Leaf Blade Location

From digitzing data, we can also quantify the diurnal change in leaf blade location for more understanding of plant behavior. Motion of the central point of leaf blade between two observation times can be calculated as follows:

$$D_{a-b} = \sqrt{(Xa - Xb)^2 + (Ya - Yb)^2 + (Za - Zb)^2}$$

where D_{a-b} is the change in blade location between observation times a and b, $[X_a, Y_a, Z_a]$ and $[X_b, Y_b, Z_b]$ are the spatial coordinates of the central point of the leaf blade at observation times a and b, respectively.

7 Sunlit Leaf Area and Light Interception Estimation

In addition, the information from digitizing data can be used for estimating sunlit leaf area and light interception. The method of this estimation was described by Thanisawanyangkura et al. (1997a).

Firstly, the coordinates of leaf elements in space are calculated in order to create an image of the plant with actual leaf orientation and leaf position. Sunlit leaf area is estimated from pictures of the plants viewed in the sun direction, made by the << smooth curve >> function of Microsoft Excel® Version 5.0 (Microsoft Corp., U.S.A.). Leaves seen on the picture are then colored by hand in order to measure the sunlit leaf area S_P with a Licor 3100 Leaf Area Meter® (Licor Inc., Lincoln, NE, U.S.A.). On the plant pictures, a reference area S_R has to be defined ; this is the soil surface area occupied by a plant. It is estimated as the smallest ellipse including the leaf area projected onto the soil surface. Plant pictures allow us to derive light interception probability from sunlit leaf area estimated from digitizing (P_{Digit}):

$$P_{Digit} = S_P / (S_R * \sinh)$$

where h is the solar elevation at a given time of measurement. Therefore, this is a simple methodology for studying light interception of a plant or a canopy.

This methodology has been improved for higher accuracy for light interception estimation by using the digitizing information with plant image synthesis with freeware POV-RAY® (Persistence of Vision Raytracer, Version 2.2, developed by POV-RAY team coordinated by C. Young in 1993) (Sinoquet and Rivet, 1997). With the application of POV-RAY, cotton plant images can be created. The geometry (i.e. location and direction) of the light sources illuminating the scene and that of the camera looking at the scene have to be defined and the digitizing information of plant geometrical structure has to be converted into the input file format of POV-RAY. Then, we can
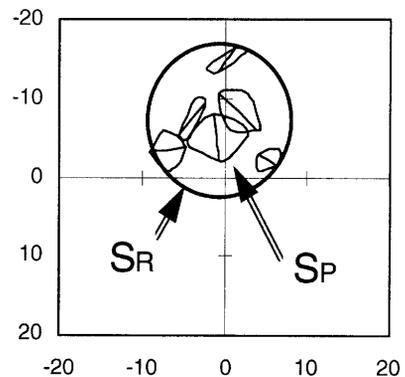

Figure 4   Reconstruction of plant pictures from digitzing data : S_P is the sunlit leaf area projected perpendicularly to sun direction and S_R is the reference area defined by the soil surface area occupied by a plant as the smallest ellipse including the leaf area projected onto the soil surface.

compute and describe light distribution in the vegetation canopy.

The methods of plant geometrical structure measurement presented in this paper can be simply applied and may be widely used for studying the relationship between changes in plant geometrical structure and light interception or micro-environment for other crops.

Leaf Irradiance Measurement

Irradiance or incident radiant flux density is defined by the radiant incident flux on a unit surface from all directions, which has the appropriate SI unit of Watt per m (W m^{-2}). In photobiology, photon flux density which is the net number of photons (discrete packet of electromagnetic radiation; 1 mol of photon = 6.02×10^{23} photons) per unit of area emitted or absorbed per unit of time is always considered. Photon flux density of Photosynthetically Active Radiation (PAR), i.e. radiation in the 400-700 nm waveband, or Photosynthetic Photon Flux Density (PPFD) is measured as the number of photons (400-700 nm) incident per unit time on a unit surface (McCree, 1972). The SI unit is mol m^{-2} s^{-1} (the unit of μmol m^{-2} s^{-1} is usually used).

The measurement of leaf irradiance is necessary for ecophysiological study in order to understand the temporal complexity of plant x environment interaction. Leaf irradiance estimated from the irradiance measured by a standard sensor on a fixed (usually horizontal) surface might hardly relate to that on inclined leaf surface. Moreover, the informations of actual leaf irradiance, taking leaf area distribution into account, is also needed for validating radiative transfer models for the canopies.

In order to get accurate information on the flux variability over space and time on leaves in the canopy, ones have to employ numerous sensors for the irradiance measurement with simultaneous record. The high cost of commercial small size and low weight sensors is often prohibitive and places a limit on the extent to which the canopies can be studied (for more details of light sensors, see Chartier et al., 1993a and Chartier et al., 1993b). Therefore, I.N.R.A. Bioclimatologie - P.I.A.F., in France, developed the low-cost sensor application for leaf irradiance measurement (Adam and Sinoquet, 1997) which allows us to study more about leaf irradiance variability in cotton canopies.

The low-cost light sensor presented is a photoelectric sensor made of amorphous silicon (Solems®, ZI Les Glaises, Palaiseau, France). It had been proven to show good linear voltage response to PAR flux density (Chartier et al., 1989).

The sensor has a small size (1.2x1.2x0.12 cm) with sensitive surface of 0.4x1.2 cm. This characteristic can avoid undesirable spatial averaging (Gutshick et al., 1985). Because of its light weight (0.4 g), the sensor can be mounted on a leaf. This allows free leaf movement and thus recording of realistic temporal fluctuation of leaf irradiance. However, the voltage response to PAR flux of the sensor is saturated at photon flux higher than 1,500 μmol/m^{2}/s. This disadvantage is compensated by using some materials put over the sensor surface as a flux reducer and diffuser. This allows to get the linear response of the photon flux beyond 1,500 μmol/m^{2}/s.

Rhodorsil® (Rhône-Poulenc, France) : an elastomer of bi-component silicone, is one of the materials which had been used as a flux reducer and diffuser of the sensor. In addition, it is waterproof. Thus, the sensor was coated with Rhodorsil® and attached with 2 m lacquer-insulated copper wire leads : its diameter is 0.25 mm with linear mass of 0.45 g/m. The sensor in its mounting weighs only about 1 g. The voltage response of the sensor was shown in Figure 6 (a) and (b). 75 % of the Rhodorsil® coated sensors tested showed

the high linearity of voltage response compared to a SKP 215® Quantum Sensor (Skye Instruments Ltd., Powys LD1 6 DF, U.K.) (R>0.99) (Figure 5 a) while somes of them showed the effects of non-uniformity of coating (Figure 5 b). However, with the Rhodorsil®, the cosine response of the sensor is doubtful because the coated surface is not plane and Rhodorsil® itself is brillant which may affect the specular reflectance.

60 Rhodorsil® coated sensors had been used for leaf irradiance measurement in cotton (Thanisawanyangkura, 1995). They were mounted on cotton leaf with double-face elastomer tape. The voltage signals from the individual sensors plugged into 4 junction boxes were recorded by data logger CR10® (Campbell Scientific Ltd., Logan, UT, U.S.A.) with a multiplexer AM 416® (Campbell Scientific Ltd., Logan, UT, U.S.A.). The sampling frequency was programmed for every 15 seconds and the average of 5 minutes with the standard deviation of each sensor were recorded. Some of the variability of leaf irradiance measured by these sensors are shown in Figure 6.

During measurement, the surface of this Rhodorsil® coated sensor was needed to be cleaned and it might also be scratched by leaf movement due to the wind. This might modify the uniformity of sensor surface and led to measurement errors.

In order to improve the drawbacks of the sensor coated with Rhodorsil®, Adam and Sinoquet (1997) used a white paper the weight, of which is negligible (<0.02 g/cm), as a photon flux reducer and diffuser. They also used a transparent thermoretractable tube sealed with a mastic silicone without acetic acid as a waterproof protector of sensor surface (Figure 7). This allows to get more uniformity of sensor surface, better cosine response, and better linear voltage response (R >0.995) (Adam and Sinoquet, 1997). Moreover, it can be used longer time without frequent change of the materials while Rhodorsil® coated sensor has to be recoated and recalibrated every 2-3 months depending on using condition.

This later type of sensor had been used for leaf irradiance measurement in walnut trees and showed the Standard Error of the Mean less than 30 μmol of photon/m²/s in measuring PFD between 0-1,800 μmmol of photon/m²/s under natural

$y = 452.82x + 6.1213$
$R^2 = 0.999$ Sensor A (mv)

$y = 461.28x + 57.811$
$R^2 = 0.9561$ Sensor B (mv)

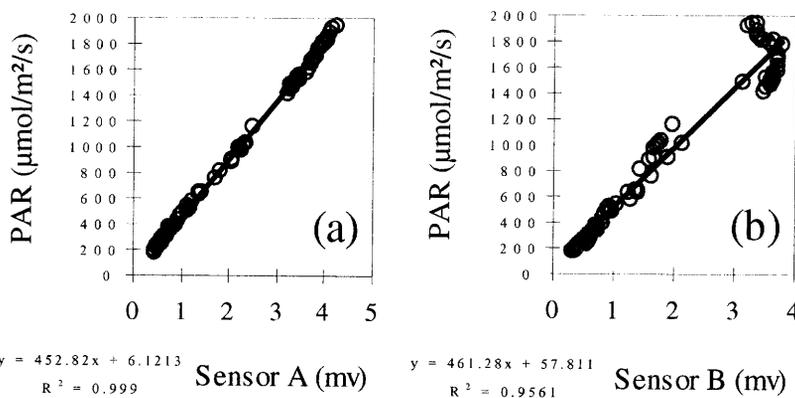**Figure 5** The relationship between voltage output of some sensors and PAR (μmol/m²/s) measured by SKP 215 Quantum Sensor : (a) sensor with uniform coated Rhodorsil® with good voltage response, (b) sensor with non-uniform coated Rhodorsil®
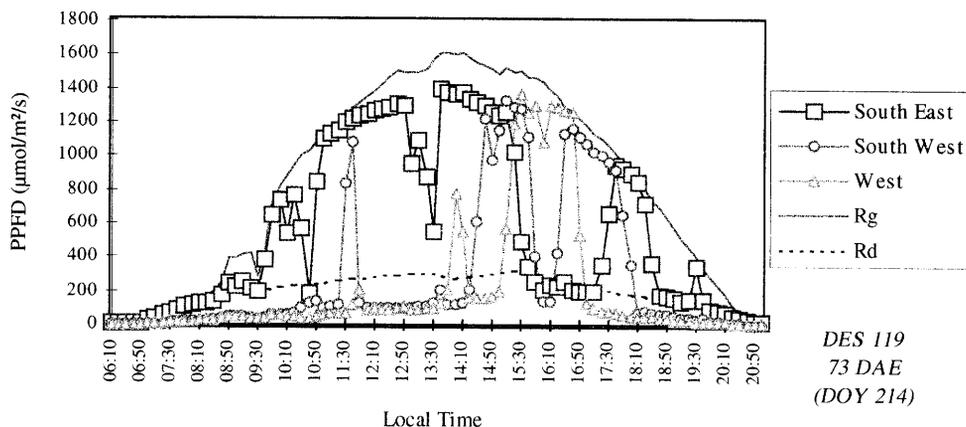
Figure 6 Irradiance of some cotton leaves on different positions : South-Eastern positioned leaf (South East), South-Western positioned leaf (South West), and Western positioned leaf (West), on a cotton plant (Variety DES 119) measured by microsensors fixed on leaf blade at 73 days after emergence (DAE) or 214 days of year (DOY). Rg is global incident radiation. Rd is diffuse radiation.

condition (Adam and Sinoquet, 1997). In cotton, this sensor had been used for leaf irradiance measurement in Thailand and also showed good linear voltage response. Because of its low price (about 125 Bahts in France, 5 times cheaper than gallium arsenide phosphide photodiode, GaAsP), the amorphous silicon cell is convenient for leaf irradiance measurements under field condition with a large number of sensors. This allows us to get more information on the variability of light distribution in the canopies.

CONCLUSION

The relationship between plant geometry and leaf irradiance has been studied for understanding the variability of light distribution in the canopy which influences plant growth and development. There are several methods for measuring plant geometrical structure. A new method is the electromagnetic digitizing system which has shown high accuracy of field measurement. This digitizing system has been used for plant geometrical structure measurement in cotton since 1995.

Light and low-cost sensor has also been developed by I.N.R.A. in France for leaf irradiance measurement. It has been used in cotton since 1995. Because of its light weight, the sensor can be mounted on leaf surface and this may still allow free leaf movement of cotton. Moreover, its cost is cheaper than other types of sensor generally used. These advantages allow us to get more directly actual leaf irradiance information which are very useful for studying the relationship between diurnal changes in plant geometrical structure due to leaf orientation behavior and variability of leaf irradiance in the cotton canopy.

ACKNOWLEDGEMENTS

White Paper

< 0.02 g/cm²

Thermoretractable
Transparent Tube

φ 0.9 cm

Sensitive Surface

0.4x1.2 cm   +   −

Amorphous Silicon
Sensor "SOLEMS"

Lacquer-insulated
Copper Wire Leads

1.2x1.2x0.1 cm
Weight : 0.4 g

φ 0.25 mm, 0.45 g/m

Data Logger (with Multiplexer)

Data Acquisition : 15 seconds
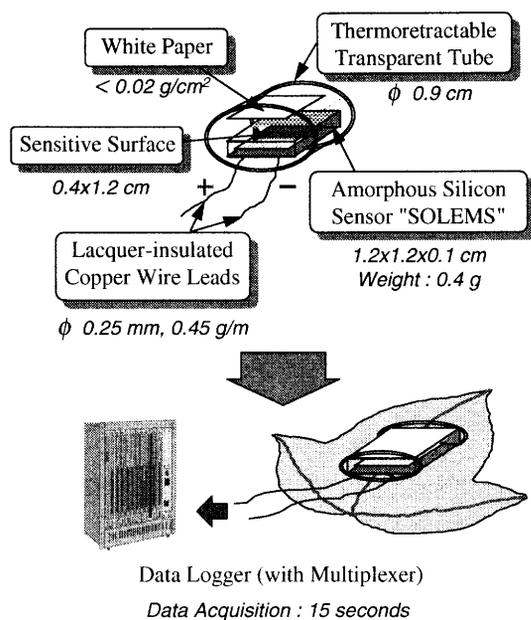
Figure 7 Light sensor used for leaf irradiance
measurement (adapted from Adam and
Sinoquet, 1997)

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