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NAME: Mr. Jate Sathornkich

THIS THESIS HAS BEEN ACCEPTED BY

______________________________ **THESIS ADVISOR**

(Associate Professor Sornprach Thanisawanyangkura, D.Agr.)

______________________________ **COMMITTEE MEMBER**

(Associate Professor Poonpipope Kasemsap, Ph.D.)

______________________________ **COMMITTEE MEMBER**

(Associate Professor Kumut Sangkhasila, Ph.D.)

______________________________ **PROGRAM CHAIRMAN**

(Associate Professor Somnuk Wongthong, Ph.D.)

APPROVED BY THE GRADUATE SCHOOL ON ______________________________

______________________________ **DEAN**

(Associate Professor Gunjana Theeragool, D.Agr.)

THESIS

APPLICATION OF PHOTOGRAPH METHOD FOR ESTIMATING TREE STRUCTURE PARAMETERS OF RUBBER TREE (*Hevea brasiliensis* Muell. Arg.)

JATE SATHORNKICH

A Thesis Submitted in Partial Fulfillment of
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Plant canopy structure can be measured or estimated in several ways. Photographic method is an indirect method that can estimate plant height, diameter volume, total leaf area and vertical distribution of leaf area of individual tree from numerical photographs. In this study, the photographic method was used in field condition. Two types of equipments using for measuring camera parameters with taking photographs were developed. The process of taking photograph and photographic processing in the field condition have been introduced. The photographic method was applied to estimate canopy structures of young rubber trees. Nine trees of 2 to 3 years old clone of RRIM600 and RRIT251 were photographed. Plant height, diameter, volume and leaf inclination distribution of each tree were estimated with the photographic method and compared with data calculated from digitizing technique. Total leaf area was compared with data measured with a leaf area meter. The results showed that tree height, crown height, crown diameter and crown volume were overestimated by this method. Total estimated leaf area was slightly higher than measured data due to the picture zone area used by the photographic method. Estimation of photosynthetic rate of rubber canopy using RATP model has been tested. Leaf area density estimated from photographic method gave 50% overestimation compared to the digitized data when used as an input for the RATP model. Our results indicated that the photographic method can be used to estimate canopy structure of young individual rubber trees. However, for estimating photosynthesis rate using RATP model, using leaf area density estimated from photographic method as an input need to be improved.

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Student's signature Thesis Advisor's signature

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APPLICATION OF PHOTOGRAPH METHOD FOR ESTIMATING TREE STRUCTURE PARAMETERS OF RUBBER TREE (*Hevea brasiliensis* Muell. Arg.)

INTRODUCTION

Rapid increase in the demand of Natural Rubber (NR) caused expansion of the rubber plantation in Thailand at a very fast rate, especially in small farms in northern and north-eastern parts of Thailand. Many new rubber plantations are on non-traditional and on unsuitable areas with limited conditions, which produce lower yield (Peungpradit, 2005).

Plants including rubber capture and store radiance energy from the sun by the process called “photosynthesis”. In this process, the energy of light coming form the sun is captured and utilized to drive the chemical process which carbohydrate is synthesized by using water and CO_2 as substrates. Carbohydrate is then used as a source of the respiration and in synthesizing of building blocks. In case of rubber, some part of carbohydrate will be the source of latex. In the rubber plantation, how much of light is captured determine the productions. In order to characterize and model the light environment of the canopy, several parameters of the canopy (e.g. leaf area, orientation and distribution function of leaf within the canopy) were needed (Varlet-Grancher *et al*., 1993).

Many of direct methods and equipments have been developed in order to determine the canopy structure. The stratified-clipping method (Monsi and Saeki, 1953) has been used to estimate profiles of leaf area density. The silhouette method (Loomis *et al*., 1967 and 1968) was used to determine vertical distribution of leaf area and the mean of leaf angle. The point quadrat analysis (Warren Wilson, 1960) was developed for an estimation of vertical leaf area density function and distribution function of leaf normal orientation and also distribution of leaf spatial dispersion. After the development of 3D-Digitiser (3SPACE® FASTRAK®, Polhemus Inc.) and the computer software (Sinoquet *et al*., 1997), the plant geometry can be measured with more completeness and accuracy. The virtual plant images can be reconstructed form the digitising data (Sinoquet and Rivet, 1997) and also used to characterize the light environment in the canopy (Sinoquet *et al*., 1998).

Although many methods and equipments have been developed, they were still time and labor consuming and also some methods were destructive. Thus, the methods and equipments for indirect measurement had been developed for non-destructive, economic and time saving application, for example, the LAI-2000® canopy analyzer (LI-COR, 1992), the AccuPAR Linear PAR/LAI ceptometer® (Decagon, 2001) and the SunScan Canopy Analysis System® (Potter *et al*., 1996). Most of them had been proved to use with the field crops and forest strands but there are few researches that apply those methods to isolated rubber tree or the canopy of closured rubber plantation.

Recently, the photographic method (Phattaralerphong and Sinoquet, 2005) was introduced to very young rubber tree. This method could be used with isolated rubber tree to determine the canopy structure. This method is cost effective and easy to use in the rubber fields. Therefore, this should be a great benefit for the rubber researchers who study the development of young rubber tree canopy.

OBJECTIVES

1. To develop the appropriate tools to measure input values of photographic method.

2. To introduce photographic methods to study tree structures of isolated rubber tree.

3. To apply the RATP photosynthesis model on rubber trees by using tree structures estimated from the photographic method.

LITERATURE REVIEW

The Botany of the Rubber Tree

Rubber tree (*Hevea brasiliensis* Muell. Arg.) is a commercial plant grown in many countries in tropical area. In year 2005, the area of rubber plantation in Thailand was 2.16 million square km and rubber production value was 208,000 million baht (Office of Agricultural Economic [OAE], 2006). Rubber tree baring the leaves in a group or set that call flush. Flush has umbrella or hemispherical shape. Rubber leaf is trifoliate leaves. The leaf angle is about 180 degree to the petiole (Samsuddin *et al*., 1978). The leaves have long petioles which bear three leaflets. The leaflets are elliptic or obovate with the base acute and the apex acuminate. They have entire margins and pinnate venation (Webster and Baulkwill, 1989).

Description of canopy geometrical structure

1. Vegetation volumes

The vegetation volume corresponds to an envelope enclosing the foliage. In case of isolate tree or heterogeneous canopy, plant volume has been generally modeled by ellipsoids (Charles-Edwards and Thornley, 1973; Thorpe *et al*., 1978), sometimes by cones (Nilson, 1977; Whitfield and Mehlenbacher, 1982; Oker-Blom and Kellomaki, 1983).

2. Amount of leaf area

The amount of leaf area may be described by well-known parameter which is the leaf area index (LAI), defined by Watson (1947). It is the amount of one-side leaf area above a square-meter of ground area. This definition does not specify whether the old dry leaves are included. Some authors distinguish between the LAI of green leaves and dry leaves (e.g., Varlet-Grancher *et al*., 1980) and in some works the area index of stems or woody parts is taken into account, especially in case of forest canopies (e.g., Wang and Baldocchi, 1989).

3. Spatial distribution of leaf area

Spatial distribution of leaf area may be described as leaf area density function and profiles of leaf area density. Leaf area density function represents amount of leaf area in a small volume around the point. The leaf area density function is a statistical distribution describing mean display of the foliage elements and does not provide any information about the relative spatial location of leaves (Sinoquet *et al*., 2001; Nilson, 1999).

4. Leaf area orientation

Leaf area orientation may be described by leaf inclination, leaf azimuth, leaf angle distributions and leaf inclination distribution.

4.1 Leaf inclination and leaf azimuth

Leaf orientation is given by the direction of the leaf normal which is the direction perpendicular to the surface of the foliage. The leaf inclination is the angle between the normal and the vertical axis. It is generally ranged from 0-90 degrees. The distinction between both the upper and the lower side of the leaves are mostly neglected. Leaf azimuth is the angle between the projection of the leaf normal angle to the horizontal plane and a reference axis which can be the row direction of the plantation or the North-South direction. The leaf azimuth is ranged between 0 – 360 degrees. The orientation of the leaf is an important structural parameter for the light interception and partition. In many cases, the sun leaves tend to be oriented vertically while the shed leaves tend to be extended horizontally (Millen and Clendon, 1979).

4.2 Leaf angle distribution

Leaf angle distribution may be described by 2 functions. First, the leaf normal orientation density function which is represented by the relative amount of leaf area with normal in a small solid angle around the direction. Second, the leaf angle density function which gives the percentage of leaf area whose presented in the ranges of inclination and azimuth.

4.3 Leaf inclination distribution

Leaf inclination may be described by the mean of leaf angle which all of the elements are assumed to be equally inclined without dispersion around the mean value. This value is very rough and leads to over evaluation of the effect of the leaf orientation on the radiative exchanges.

De Wit (1965) defined 4 standardized distributions describing the global trends in the foliage orientation in plant canopy which are the planophile, erectophile, plagiophile and extremophile distribution. Canopy that most of the leaves have inclination angle between 0-27 degrees will be defined as planophile distribution. If most of the leaves have inclination angle between 63-90 degrees, that canopy will be defined as erectophile distribution. For plagiophile distribution, most of the leaves in the canopy have inclination angle nearly 45 degrees. For extremophile distribution, leaves in the canopy have inclination angle mixing between planophile and erectophile, with the average leaf inclination angle nearly 45 degrees.

Horizontal leaves are most frequent in planophile canopies, and vertical leaves occur most in erectophile canopies. The leaves in plagiophile canopies are most frequent at some oblique inclination, whereas those in extremophile canopies are the least frequent at oblique inclinations. The leaf distributions are important for calculation of the light interception with respect to the extinction coefficient (K). Practically, the leaf distribution may assume to be uniform and inclined with single angle (Lemeur, 1973) or the spherical distribution which area elements are inclined like those of a sphere (Gastellu-Etchegorry *et al.*, 1996).

5. Leaf dispersion

Leaf dispersion globally accounts for spatial relation between leaf elements, i.e. leaf overlapping or the pattern of leaf location relative to the neighboring foliage. The dispersion may be considered as a relative one which is related to the efficiency of light interception for a given leaf area density and a given leaf angle distribution. The leaf dispersion may be categorized into 3 types : regular, random and clumped dispersion. Regular dispersion is shown to reduce in overlapping of leaf and causes mutual shading while clumped dispersion is shown to be more overlapping and grouping. Random dispersion is between clumped and regular dispersion which the location of each leaf does not depend on the neighboring foliages.

Numerous light models assume the leaf dispersion to be random (i.e. Sinoquet *et al.*, 2001; Nilson, 1999; LI-COR, 1992) because it is difficult to derive it from field measurement of real canopies. Although the real canopies shown difference in leaf dispersion, the regular pattern was observed in vigna (Bonhomme, 1974) and cotton (Fukai and Loomis, 1976) whereas the clumped leaf dispersion was observed in sweet potato (Bonhomme and Chartier, 1972) and sugarcane (Bonhomme, 1974).

Direct methods to determine canopy geometrical parameters

1. Mechanical point quadrats

This method determines distribution of leaf area density, leaf normal orientation and distribution function of leaf spatial distribution by placing the vegetation canopy with long infinitesimally thin needles and registering number of contacts the needle made with the canopy (Levy and Madden, 1933). The advantage of this method is non-destructive but it is tedious and labor-intensive to obtain reliable data.

2. The Stratified – Clipping Method

This method can estimate profiles of leaf area density by dividing plant or strand under investigation into horizontal layers and the leaf in each layer are clipped and measured for leaf area (Monsi and Saeki, 1953). Disadvantages of this method are that experimental plants should be destroyed and the large experimental area are necessary for the time-course and replicated measurement.

3. Articulate arms

The spatial co-ordinates and orientation can be measured by the apparatus consisted of four arms which are pivoted and able to move. The angles between the arms are measured by potentiometers which are connected to the computer, and then the data are collected and calculated using relation between the length and the angles of the arms to obtain the point of the observation in the space. The point of observation usually be the specify point on the leaf can be used to calculate the area, azimuth and inclination of the leaves (Lang 1973). The advantage of this method is rapid and accuracy (±0.65 cm) but it can not be applied to the large canopy because of limitation to the length of the arms.

4. Litter-collection method

Litter collection method is not really a direct method to determine canopy geometrical parameters. It is semi-direct because this method determine leaf area of the strand by the litter not directly harvest the leaves. The litter collection was developed to study the leaf area index development of deciduous forest that have single leaf-fall season. The basket or trap with known size is used to collect the litter fall under the forest canopy. Litter will be collected and measuring leaf area or dry weight. LAI of the forest strand can be calculated by dividing the total leaf area measured from the trap with the trap size. If the litter was weighted then the area to weight relationship must be done before calculate LAI (Dufrene and Breda, 1995).

The advantage is that it can apply to the large canopy of the forest strand but this method is very labor-intensive and need a long period of time to measure LAI.

5. Ultrasonic digitiser

The ultrasonic three dimensional (3D) digitiser consists of the control unit, a mobile ultrasonic emitter and microphones. The mobile ultrasonic emitter was used as a probe to point at the observation point. The ultrasonic emitted form the probe was detected by 4 microphones placing on the plane then the spatial location of the probe was computed using the different time detected by the microphones. The data from the control was transferred and display on the computer screen. The leaf area and orientation distribution can be also calculated using computer software (Sinoquet *et al*., 1991). The limitation is the wind sensitive that make this method can not be practically used in the field.

6. 3D digitiser

The 3D-Digitiser (Polhemus, 1993) consists of an electronic unit, a receiver, a single transmitter and a power supply. The transmitter generates low frequency magnetic fields which induce current in coils included in the receiver. The value of induced current depends on the location and orientation of the receiver in the active volume around the magnetic source. The data can be collected by the computer with special software (Sinoquet *et al*., 1997). Spatial co-ordinate can then be measured with more completeness and accuracy. Virtual plant images can be reconstructed from the digitising data (Sinoquet and Rivet, 1997) and also be used to characterize light environment in the canopy (Sinoquet *et al*., 1998). Virtual plants also be used as an input in light interception models, such as Radiation Interception in Row Intercropping (RIRI) model (Sinoquet and Bonhomme, 1992; Le Roux *et al*., 1999), Parallel Projection and Z-buffer algorithms (PPZB, Wang *et al*., 2005) and GREENLAB model (Yuntao *et al*., 2008; Cournedee *et al*., 2008).This device is the most suitable for measurements on plant as it provides a precise and rapid localization of 3D coordinates (Moulia and Sinoquet, 1993). However, manual 3D studies are time-consuming and fairy imprecise (DanJon *et al*., 1999) especially for large or high density canopies.

Indirect methods to determine canopy geometrical parameters

1. Contact frequency analysis

Warren-Wilson (1960) showed that probability that a small probe penetrate into the canopy will contact to the leaves was depended on the leaf area density and leaf normal orientations. So the number of the contact along the probe will be the function of length of the probe, the leaf area density and leaf orientations.

2. Gaps fraction analysis

The gap fraction analysis used the probability that the probe will make contact (1) or not (0) to the vegetation. The advantage of this method is that it can be used the incoming light beam as a probe, so the measurement is easier by measured the light transmission through the canopy. This work was initiated by Monsi and Saeki (1953) and developed by Anderson (1966), Chartier (1967) and Warren-Wilson (1960). This method assumed that leaves are randomly distributed and leaves are small compared to the vegetation volume. The probability that the light with zenith angle will cross the vegetation canopy without being intercepted by the vegetation depends on the orientation and density of leaves, and also the distance of the light that crosses the canopy.

Many devices have been developed for determination of leaf area index and leaf angle using the gap fraction analysis method, for example, the LAI-2000 canopy analyzer (LI-COR, 1992), the AccuPAR Linear PAR/LAI ceptometer (Decagon, 2001) and the SunScan Canopy Analysis System (Potter *et al*., 1996).

2.1 LAI-2000 canopy analyzer

The LAI-2000 estimates the leaf area index (LAI) and mean leaf tilt angle (MA) from radiation of sky detected by 5 detector rings located under the fish-eye lens. These 5 detectors are used to determine the transmission of radiation at the angle 7, 23, 38, 53 and 68 degrees. The inversion of gap fraction is used to estimate the LAI and MA from the transmission with the assumption that leaves are black, small compared to the canopy volume and randomly distributed and azimuthally oriented (LI-COR, 1992). The LAI estimated from LAI-2000 is also included with area of branches for stem. The estimation generally gives bias that might be affected by crown shape (Barclay and Trofymow, 2000).

2.2 AccuPAR Linear PAR/LAI ceptometer and SunScan Canopy Analysis System

These two equipments are similar in that they are line quantum sensor in which the photo sensors are arrange in the line. The AccuPar have 80 of photodiodes while SunScan have 64 photodiodes. The photodiodes are used to measure the photosynthetically active radiation (PAR) in the wave band of 400-700 nm. After the measurement of PAR on the top and bottom of the canopy, the transmission is calculated and used to estimate LAI according to Beer's law and equation derived by Campbell (1986), assuming ellipsoidal leaf angle distribution.

3. Image analysis

Two types of images are used to estimate canopy structure of plant. One is the hemispheric photographs or fisheye photographs which are taken by camera with fisheye lens, enabled picture to have hemispherical view. The other one is the orthogonal photographs, the photograph is that all of the incoming light beams are parallel and the direction of the light beam is perpendicular to the plane of the images. In fact, this type of photograph cannot be taken by any camera but it may assume that the photograph taking with long focal length is likely to be the orthogonal photograph (Andrieu and Sinoquet, 1993).

3.1 Hemispherical images

The work of Anderson (1964) about the characterization of light in the plant canopies by using hemispherical photographs led other workers to use the hemispheric photographs to estimate foliage area of the canopies (Bonhomme and Chartier, 1972; Lemeur and Yoon, 1982; Wang and Miller, 1987). In fact, this method is based on the method of gap fraction analysis. The picture is taken upward by the camera with fisheye lens which have very wide angle of view (>150 degrees). Calculation of gap fraction is done by dividing the image into sectors, each sector acts as a probe that inclines in specified angle, then the gap fraction is the sum of sky area in that sector (Wang and Miller, 1987) because the angle of view is very wide so that it gives the ranges of probe angle required for calculation of LAI by gap fraction method.

3.2 Orthogonal photograph

Smith *et al*. (1977) demonstrated that orthographic image may be used to estimate leaf inclination angle distribution. The photographs are taken at 10 degrees increment from vertical, and then used to analyze the gap fraction. The Fredholm integral equation is used to solve for the cumulative frequency distribution of leaf angles with assumption of uniform azimuthally angle distribution. However, this method is too sensitive to the variation in gap fraction from the sampling. The variation in gap fraction of 20% will give the deviation in leaf angle distribution of about 5 degrees.

Estimation of canopy geometrical parameters using photographic method

A photographic method for estimation of canopy structure has been developed by Pattaraleurpong and Sinoquet (2005). This method can be used to estimate canopy dimension, volume, total leaf area and spatial distribution of leaf area (Pattaraleurpong, 2006). This method needs a set of digital photographs of a tree and associated geometrical parameters as input parameters. All calculations and algorithms have been implemented using Tree Analyser software written in C++ (Pattaraleurpong, 2006).

Photographic method uses photographs taken in different directions around the tree. Photographs must be black and white Bitmap file format. Each photograph must contain only vegetative parts of the targeted tree (black) on the white background. Each photograph must involve associated geometrical parameters. Those parameters are the distance between the camera and the tree trunk, camera height, camera elevation, camera azimuth around the tree and focal length (Pattaraleurpong and Sinoquet, 2005).

With one photograph, canopy height, diameter and total leaf area can be estimated. Canopy volume and spatial distribution of leaf area can be estimated using 4 or more photographs (Pattaraleurpong and Sinoquet, 2005; Pattaraleurpong, 2006). Canopy height and diameter are estimated using topmost, bottommost, rightmost and leftmost vegetated pixel location. Canopy volume is estimated by using Ray/Box intersection algorithms (Glassner, 1989), investigation of a series of vegetated voxel in the bounding box. Total leaf area estimation is based on the inversion of gap fraction (Pattaraleurpong, 2006). Two models of inversion are introduced, namely Beer's and binomial model. Spatial distribution of leaf area is estimated by nonlinear least square optimization technique using L-BFGS-B algorithm (Byrd *et al.*, 1995).

Pattaraleurpong and Sinoquet (2005) tested photographic method using sets of photographs those constructed from 3D digitised plants. Five plant species (walnut, peach, mango, olive and rubber) were used. Virtual photographs of each tree were created in different view angle. Sets of 3, 4, 6, 8, 9, 24, 54, and 100 photographs were used to test the effect of the number of photographs. The results showed the good relationship between measured data and values inferred from the photographs. The canopy structures estimated by the photographic method decreased with increasing number of photographs. Pattaraleurpong and Sinoquet (2005) suggested that the use of four to eight photographs appears to be a good compromise between accuracy and practical applicability in the field condition.

Photographic method can be used as a fast and non-destructive method to monitor growth and development of isolated tree canopies. But this method still requires equipments to obtain photographs and associated parameters in field condition (Pattaraleurpong and Sinoquet, 2005). It also needs some methods being able to separate tree vegetated pixels from the picture background (Mizoue and Inoue 2001), as in the processing fisheye photographs of crown projected area (e.g., Frazer *et al.* 2001).

Photosynthesis model

Photosynthesis model is the mathematical functions being used to describe photosynthesis of plant in many scales, such as organ scale, leaf scale, canopy scale and plantation scale (Odum and Odum, 2000). The model of carbon and water exchanges between the vegetation and atmosphere can used for applications ranging from the assessment of carbon sequestration, net primary production and water use at the plantation scale, and use at the canopy or organ scale. However, the assumptions used in the models may have difference implications according to the scale used (Varlet-Grancher *et al*., 1993).

Sinoquet *et al*. (2001) introduced plant functional-structural model named Radiation, Absorption, Transpiration and Photosynthesis (RATP) model. This model simulating carbon and/or water exchange between plants and the atmosphere at the intra-canopy. This model gives the canopy transpiration and photosynthesis according to the spatial distribution of leaf area, physiological properties and climatic parameters. Inputs for this model are the density of leaf area within the canopy, leaf optical properties, sun position, light intensity during the day, and parameters for photosynthesis model those given in Le Roux *et al*. (1999). This model has been tested and used in crown of an isolated walnut tree. The model was showed to simulate satisfactorily intra-crown distribution of radiation regime, transpiration and photosynthesis rates at shoot or branch scales. Daudet *et al*. (1999) used this model to simulate spatial variations of transpiration, photosynthesis and leaf-to-atmosphere for walnut tree crown.

RATP model can use two types of the density of leaf area within the canopy : 3D and 2D distribution of leaf area (Sinoquet *et al*., 2001). 3D distribution of leaf area can be measured using direct method such as 3D digitizer and it gives more details of leaves distributed within the canopy. So, the estimation of canopy transpiration and photosynthesis will be more accurate. 2D distribution of leaf area can be obtained using indirect method such as hemispherical photographs (Bonhomme and Chartier, 1972; Lemeur and Yoon, 1982; Wang and Miller, 1987), gap fraction analysis (Anderson, 1966; Chartier, 1967; Warren-Wilson, 1960) and photographic method (Pattaraleurpong, 2006).

MATERIALS AND METHODS

Experiment 1: Equipment design for measuring input values of photographic method

Materials

1. Tape measuring
2. Laser distance meter (Leica DISTO ™ A2, Leica Geosystems, Switzerland)
3. Tubular level (EM8™, Empire®, USA)
4. Laser level (BDL205S™, Black&Decker®, USA)
5. Protractor (Inca960™, Inca®, Taiwan)
6. Compass (54LU, Brunton™, Sweden)
7. Digital compass (Nomad™, Brunton®, Sweden)
8. Digital inclinometer (Smart Tool™, M-D Building Products®, USA)
9. Digital camera (Nikon® Coolpix885™, Konica-Minolta® Dimage A2™)
10. Tripod (055XB™, Manfrotto®, Italy)

Field measurement methods for photographic method

Photographic method used a set of digital photographs of a tree (e.g., eight images taken from N, S, E, W, NE, NW, SE and SW direction). Photographs must be taken so that image processing allows classifying pixels as vegetation or background, i.e., in order to binarise the image like in fisheye photography methods (e.g., Frazer *et al*., 2001; Mizoue, 2001). In addition to photographs, the method involves geometry parameters associated with each photograph, namely the distance between the camera and the tree trunk, camera height from the tree base, camera elevation, camera azimuth around the tree and the camera focal length.

The tools and the method to measure camera inclination, camera azimuth, distance between the camera and the tree trunk, and camera height from the tree base were introduced and test. The method to take photographs in the filed with the good foreground and background has been introduced.

Equipment designed for photographic method technique

Using several tools measuring camera position in the field at the same time is inconvenient. Equipments to hold the camera still while taking photograph and allow measuring tools to stay still for measuring camera position has been developed. These equipments were designed to help taking photographs and measured camera position quickly and accurately. These tools should hold the camera still while taking photographs and also hold the tools to measure camera position. Two types of equipments were developed and tested in the field. The differences of the 2 designs were the cost of the measuring tools and the accuracy for measurements.

Digital photo processing for photographic method technique

Photographic method uses binarize photographs to estimate canopy structures. Photograph from digital camera is color and coming in jpeg format. To use those photographs with photographic method, color photographs need to be converted to 2 bits black and white bitmap format with black represented plant canopy and white represented background. The background in each photograph needs to be removed and the tree canopy needs to be converted to black color. The method for background separation and to convert photograph to use with photographic method were developed.

Experiment 2: Application of photographic method to young isolated rubber trees

Plant materials

Two-year-old rubber trees cultivar RRIM600 and RRIT251 (8 trees for each cultivar) were chosen from the germplasm plot in Surat Thani Rubber Research Center, Surat Thani Province, 560 km South of Bangkok, Thailand (9° 40’ 24.7” N, 99° 6’ 19.94” E). Trees were 2 year-old and planted at 3 x 7 m. spacing.

Three-year-old rubber tree cultivar RRIM600 was chosen from the experimental plot in National Corn and Sorghum Research Center, Nakhon Ratchasima Province, 150 km. East of Bangkok, Thailand (14° 38’ 41.1” N, 101° 19’ 18.6” E). Tree was 3 year-old and planted as individual tree.

Measurement of canopy structure parameters

Due to the time and labor consumption of digitising technique, only 5 trees were measured for canopy structures; 2 trees of 2-year-old RRIM600, 2 trees of 2-year-old RRIT251 and 1 tree of 3-year-old RRIM600. The spatial co-ordinates of the leaf was measured with an electromagnetic 3D digitiser (3 Space®, Fastrak®, Polhemus, Inc., Colchester, VT, U.S.A.) and data acquisition software Pol 95 (Sinoquiet *et al*., 1997). In details for digitising is described by Thanisawanyangkura *et al*. (1997). In the same time as the digitising, the midrib length of each leaflet was measured with a ruler for estimated leaf area. Tree height, crown height, crown width, crown volume and vertical profile of leaf area for each tree were calculated from digitised data.

Eight trees were chosen for measuring total leaf area. Those trees come from 4 of 2-year-old trees digitised, another 2 trees of 2-year-old RRIM600, and 2 trees of 2-year-old RRIT251. Each tree was photographed using photographic method. Then total leaf area of each tree was measured by cutting all the leaves and measured using leaf area meter (LI-3100 Leaf Area Meter®, Li-COR, Lincoln, Nebraska, USA).

Taking photographs

In Nakhon Ratchasima site, 3-year-old RRIM600 was photographed in 8 directions around the tree. Photographs were taken according to the description in Phattaralerphong and Sinoquet (2005) using Nikon Coolpix 885® with a 2048 x 1536 (3 Mpixels) resolution in JPEG formatted with an Extra Fine image quality at ISO 100. Camera was placed on a tripod so the camera parameters could be measured after taking photographs. Camera inclination was measured using protactor equipped with pendulum. Camera azimuths were recorded using lensatic sighting compass. Camera height was record using tape measurement and camera were level to the base of the tree using water levelling method. Camera distance to the trunk was measured using tape measuring. The focal length of the lens for each photograph was automatically stored in EXIF data (Exchangeable Image File format for Digital Still Cameras, Japan Electronic Industry Development Association, JEIDA).

In Surat Thani site, due to the spacing and surrounding trees, 8 trees were photographs in 4 directions around the tree. Photographs were taken according to the description in Phattaralerphong and Sinoquet (2005) using Konica-Minolta DiMAGE A2 with a 2560 x 1920 (5 Mpixels) resolution in JPEG formatted with an Extra Fine image quality at ISO 200. Camera was placed on a tripod so the camera parameters could be measured after taking photographs. Camera inclination was measured using digital inclinometer. Camera azimuths were recorded using digital compass. Camera height was recorded using tape measurement and camera was leveled to the base of the tree using laser levelling tool. Camera distance to the trunk was measured using laser distance meter. The focal length of the lens for each photograph was automatically stored in EXIF data.

A red cloth (about 3 x 5 m) was used as background on both experimental sites for background separation process. To setup the background, one side of the cloth was tided with a bamboo stick with the rope at each end of the stick. The cloth with the stick was pull up to the top of the canopy supported by two bamboo stick equipped with pulleys. All photographs were processed manually to Black and White Bitmap file format using GIMP for Windows Version 2.2.9 (GNU Image Manipulation Program, http://www.gimp.org).

Canopy structure estimation

Processed black and white photographs from previous step have been used to estimate canopy structure. Canopy structures were estimated by photographic method using Tree Analyser software (see Phattaralerphong *et al*., 2006). Tree height, crown height, crown diameter, and crown volume, were estimated from sets of 4 photographs for 2-year-old rubber trees and 8 photographs for 3-year-old rubber tree. Canopy structures were estimated using 25 cm x 25 cm x 25 cm voxel size.

Leaf area was estimated from sets of 4 photographs. Eight trees of 2 year-old rubber tree were used. Leaf area was estimated using 25 cm x 25 cm x 25 cm voxel size. Binomial law inversion method was used for leaf area estimation. Mean leaf inclination and mean leaf size for each cultivar were calculated from the digitised data. Mean leaf inclination and mean leaf size for each cultivar were used in the Tree Analyser software for the estimation leaf area. Other parameters were set to default values in the Tree analyser software.

Experimental 3 : Use of the RATP model to simulate canopy photosynthesis

Plant materials

Digitising data and inclination distribution estimated from photographic method of 9 rubber trees were used as parameters in RATP model. Leaf optical properties, three key parameters of the Farquhar *et al*., (1980) leaf photosynthesis model (maximum carboxylation rate V_{cmax}, maximum electron transport capacity J_{max} and dark respiration rate R_d), key parameter of stomatal conductance model (reference stomatal conductance, g_{sref}) and the parameters of the photosynthesis-stomatal conductance model for rubber are in Sangsing (2004). Climatic data were collected from the rubber flux experimental site at Chachoengsao Rubber Research Center (CRRC), Chachoengsao Province, Thailand.

Estimation of photosynthesis

The crown volume is divided into $0.25 \times 0.25 \times 0.25$ m^3 cubic cells in which the leaf area is distributed. Leaves were characterized by their mean angle of inclination calculated from digitising data and optical properties from Sangsing (2004). Same photosynthesis parameters and climatic data, in 30 minutes interval, were used in all estimations.

Estimation of photosynthesis using RATP model was separated into 3 groups. The first group used digitising data as the canopy geometry input for the model. This group was used as the control to compare with the other groups. The second group used LAD that calculated from digitising data as the canopy geometry input for the model. This group will explain the effect of the LAD as an input for the RATP model. The third group used LAD that estimated from photographic method as the canopy geometry input for the model. This group will be compared to the first and the second group to study the probability to use photographic method to estimate photosynthetic rate of rubber canopy instead of using 3D digitising data.

RESULTS AND DISCUSSION

Equipment designed for measuring input values of photographic method

Field measurement methods for photograph method

The equipments for measuring camera positions were chosen and tested. The measurements for photographic method are camera inclination measurement, camera azimuth measurement, camera distance from the tree trunk measurement and camera height from the base of the tree.

1. Camera inclination measurement

To measure camera inclination, angle meter should be used. Angle meter or inclinometer has several models. The simple model is a protactor (Figure 1A). Protactor can be use to measure angle from 0 to 180 degrees or 360 degrees in some model. In order to use protactor to measure camera angle, it needs a tubular level to find the zero-degree-plane (Figure 1B). To measure camera inclination, protactor should be placeed on the top of tripod base where the camera placed. Then use the tubular level to find the zero-degree-plane and read out the angle.

Inclinometer is a more convenient tool for measuring camera inclinometer. Inclinometer is the integrated of protactor and the pendulum scale (Figure 2A). There are several models of inclinometer varied by size and accuracy. The small model is compact but it can give the readout about 1-2 degree difference. The bigger model can give the readout around 0.5 degree difference. There is another type of inclinometer, the digital inclinometer (Figure 2B). Digital inclinometer can give the angle value instantly on their screen. The accuracy of digital inclinometer is vary from 0.5 to 1 degree difference depend on the model.

Protactor, inclinometer and digital inclinometer has been tested in the field condition. Camera was placed on the tripod and adjusts to have around 15 degrees inclination. Protactor, inclinometer and digital inclinometer were placed one by one on the base of the camera to measuring angle. Protactor gives the bad result due to unstability when placing and it need tubular leveling to read the degree. Inclinometer and digital inclinometer seems to be the best tool for measuring camera inclination. They can be placed easily at the camera base and the angle can be read instantly. Digital inclinometer gives the best result in the reading time due to the readout screen that can be read instantly. Inclinometer needs about 5 seconds to make the scale stays still enough to read the angle value.

A **B**

Figure 1 Protactor with 180 degree measurement and tubular level

A **B**

Figure 2 Scale inclinometer (A) and digital inclinometer (B)

2. Camera azimuth measurement

Camera azimuth value used is based on the geographical direction (north, west, east and south). The value that using in Tree Analyser software is degree from East direction (East = 0 degree, West = 180 degrees). To measure geographical direction, magnetic compass has been used. Several models of compass has been chosen and tested to measure camera azimuth. Base-plate map compass (Figure 3A), lensatic sighting compass (Figure 3B) and digital compass (Figure 3C) were used to measure camera azimuth.

To measure camera azimuth, compass was hold still behind the camera. The direction of the compass is headed to the tree trunk as a straight line between the compass, the camera and the tree trunk, then read out the degree from North from the compass. The test showed that base-plate map compass took the longest time of measurement due to the difficulty of aiming plus the difficulty of readout the angle while holding the compass. Digital compass had the same difficulty of aiming as base-plate compass but the readout is easy due to the numeric screen. The lensatic sighting compass is the best tools to measuring camera azimuth due to the lensatic sighting that made the aiming easy and it can readout the degree at the same time.

A **B** **C**

Figure 3 Base-plate map compass (A), lensatic sighting compass (B) and digital compass (C)

3. Camera distance from the tree trunk measurement

Camera distance from the tree trunk can be measured using tape measuring. The distant measurement starts from the focusing point of the camera lens to the tree trunk. Due to the difficulty of finding focusing point that located inside the camera, the back of the camera was used instead. Two types of distance measuring tool were tested, normal tape measuring (Figure 4A) and laser distance meter (Figure 4B).

These two tools were difficult to compare due to the positive and negative experience when using in the field condition. Tape measuring is a lot cheaper than laser distance meter. Tape measuring can be used in every field condition, such as the field with tall grass or a very bright sunlight. But tape measuring needs time to drag the tape from tree trunk to camera and needs two persons to operate. Laser distance meter is fast and very accurate distance measuring tools. Laser distance meter uses laser beam to measure the distance, so it can operate by only one person. To measure the distance using laser distance meter, just aim the laser beam to the tree trunk while the laser distance meter placed aside the camera then press the button. The distance value will show on the screen. With the laser beam to measure distance, laser distance meter cannot apply in the field with tall grass. Laser distance meter cannot be used in very bright sunlight condition too because the light will interfere the sensor and the operator cannot see clearly the laser beam. There are some laser distance meters that can use in very bright sunlight. Those tools equipped with very strong laser beam and small view finder to aim the target. But the prices of those tools are relatively very expensive.

Figure 4 Tape measuring (A) and laser distance meter (B)

4. Camera height measurement from the base of the tree.

Measuring camera height from the base of the tree is very difficult in field condition. Terrain slope and roughness make the tripod base level different to the tree trunk. To measure camera height, the leveling point between camera and tree trunk must be marked. To mark the leveling point of the camera and to the tree trunk, leveling tool will be used. In the experiment, two types of leveling tools were test, water leveling tools (Figure 5A) and laser level tools.

Water leveling tools is simple and easy to find but to make the leveling is difficult. To make a leveling, long clear tube filled with water will be placed one side below the camera and other side to the tree trunk. At one side (either at camera or tree trunk side) the end of the tube should be moved up or down to avoid water leak out of the tube. When water inside the tube stilled, mark the leveling point on both camera and tree trunk side. The leveling using water leveling method was shown in Figure 6. Water leveling can be use in almost any field condition except the distance from the camera is very far from the tree trunk.

Laser leveling tools have several models. The simple model is the tubular level equip with dot laser emitter (Figure 5B). The advance model can do auto leveling and emitted the line laser beam. The simple model is suitable to the field condition because it is easy to setup and moving in the field. To measure camera height by using laser leveling tool, laser leveling tool must be placed on the tripod and placed between the camera and the tree trunk. First step was to mark the referent point to the tree. It can be done by aiming the laser beam to the tree trunk, leveling the laser leveling tool, and then marked the referent point at the tree trunk. Second step was to measuring camera height based on the height of the referent point. It can be done by turning the laser beam to the camera, leveling the laser leveling tool, and then measured the vertical distance from the camera to the laser beam. Last step was to calculate the camera height. Camera height was the summaries of the vertical distance from referent point to the tree base plus the vertical distance from the camera to the laser beam. The leveling using water leveling method was shown in Figure 7. Laser leveling tools cannot be used in the field with tall grass because the grass will mask the beam. This tool is difficult to use in the strong sunlight due to the unclear red dot in the field. This problem can be solved using laser target card (Figure 8A) and red filter laser glasses (Figure 8B).

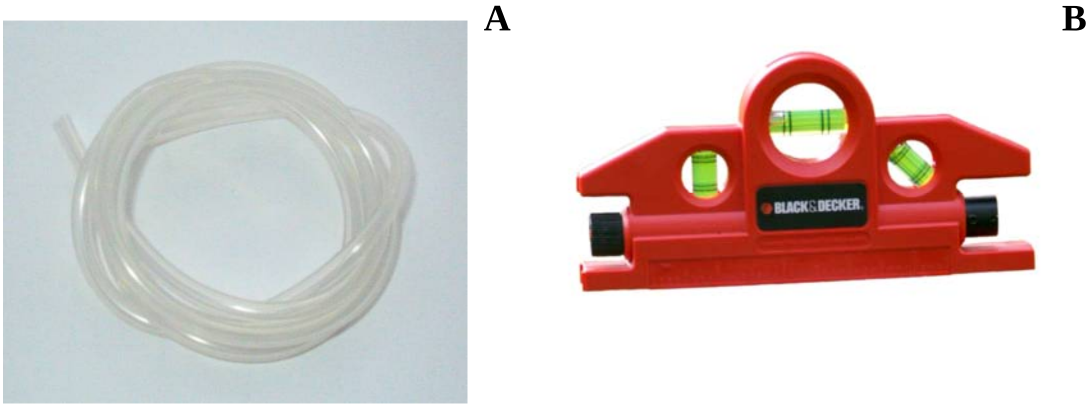

Figure 5 Water leveling tube (A) and Laser leveling tool (B)

Figure 6 Water leveling method performed in the rubber plantation.

Figure 7 Laser leveling method performed in the rubber plantation.

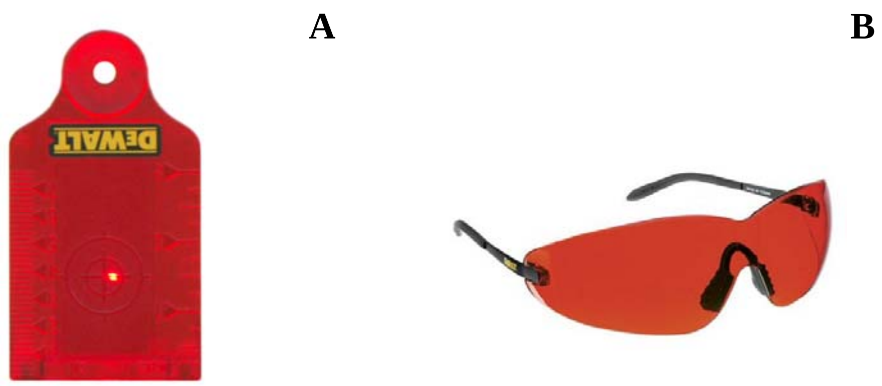

Figure 8 Laser target card (DEWALT DW0730, MD, USA) (A) and Red filter laser glasses (DEWALT DW0730, MD, USA) (B)

5. Taking photographs of the rubber tree

Taking photographs of rubber canopy in the field is difficult. Trees near by and trees behind the target tree always stay in the photograph. With the other trees in the photographs, background separated is difficult to perform (Figure 9). To avoid the unwanted subjects, artificial background need to be applied to every photograph. Red cloth was chosen to use as a background because of the red colour. Red colour can easily separated from green colour of leaves. To setup the background behind the tree, background size should be bigger than the tree canopy. Red cloth can be attached to the stick and pull up to the top of the canopy using other two stick (Figure 10). With this method, target tree can be separated from the other tree (Figure 11).

Figure 9 Photograph taking with natural background. Target tree is blended to the background.

Figure 10 The photograph shows the setting of red background.

Figure 11 Photograph taking with red cloth background. Target tree is isolated.

Equipments designed for photographic method

Due to inconvenient practice of measuring camera position on the tripod, the special equipments were designed and tested to help measuring camera position. Equipments had been designed by following criteria: the stability of camera, the convenient measurement of camera position such as camera inclination, camera azimuth, camera height, accuracy of measurements and mobility of equipments in the field. Photographic method uses the photographs taken in different direction around the tree. These photographs need very precise position to take: 1) photograph must align to horizontal plane, 2) base of the tree must align to the middle of the photograph and 3) photograph must contain as much as possible the canopy area. From those criteria, the equipments designed for photograph method should allowed camera to be easily adjusted to horizontal. These equipments also allowed the alignment of the frame to be in the middle of the tree base while taking the canopy photos. For camera inclination and azimuth measurements, angle meter and compass can be attached to the tripod and moving together with camera. Camera height and distance from the tree trunk should be made separately due to the moving of camera around the tree.

The first prototype equipment was built to test the idea of the method to align the camera and how to attach the inclinometer to the base of the camera. The prototype was build by 1 cm. thick acrylic plate that placed on top of the tripod head. One vial leveling was attached in the back of the plate for helping horizontal alignment of the camera. Another vial leveling was attached at the front side of the plate. With these 2 vials, this plate can be adjusted to align to horizontal plane. In the right side of the plate, another acrylic plate was attached vertically to hold the angle meter. During the first design of this equipment, inclinometer was very difficult to find. One 90 degree protactor was use instead. Protactor was attached to the vertical plate and adjusted until zero degree aligns with the horizontal plate. The pendulum with the string was attached at the corner of the protactor to measure inclination angle. The prototype equipment was shown in Figure 12.

Figure 12 Prototype equipment designed for photographic method.

The prototype model was test and used to take photographs of the 3 year-old rubber tree var. RRIM 600. The prototype model allowed camera to be stilled while taking photograph and while measuring the inclination angle. This model also made the adjustment of the camera to the alignment plane easier.

With the prototype model, another 2 types of the equipments were created. The first type was the analog model and the second type was the digital model. The analog model was the camera holder plate equipped with the self designed inclinometer and compass. This model was built together with tilt tripod head. This tripod head allow camera and the plate to swing vertically without changing the horizontal plane. The inclinometer in the right side was design to read from -15 to 45 degree of inclination at 0.5 degree increments. At the bottom of the inclinometer, the compass holder was attached. This compass holder was placed 15 cm away from the camera and the tripod to avoid the interference of magnetic to the compass. This compass holder also allow compass rotate vertically, this will allow compass to be horizontal while camera is incline. The analog model can be attached to any tripod with pan head or ball head. The analog model designed for photographic method was shown in Figure 13.

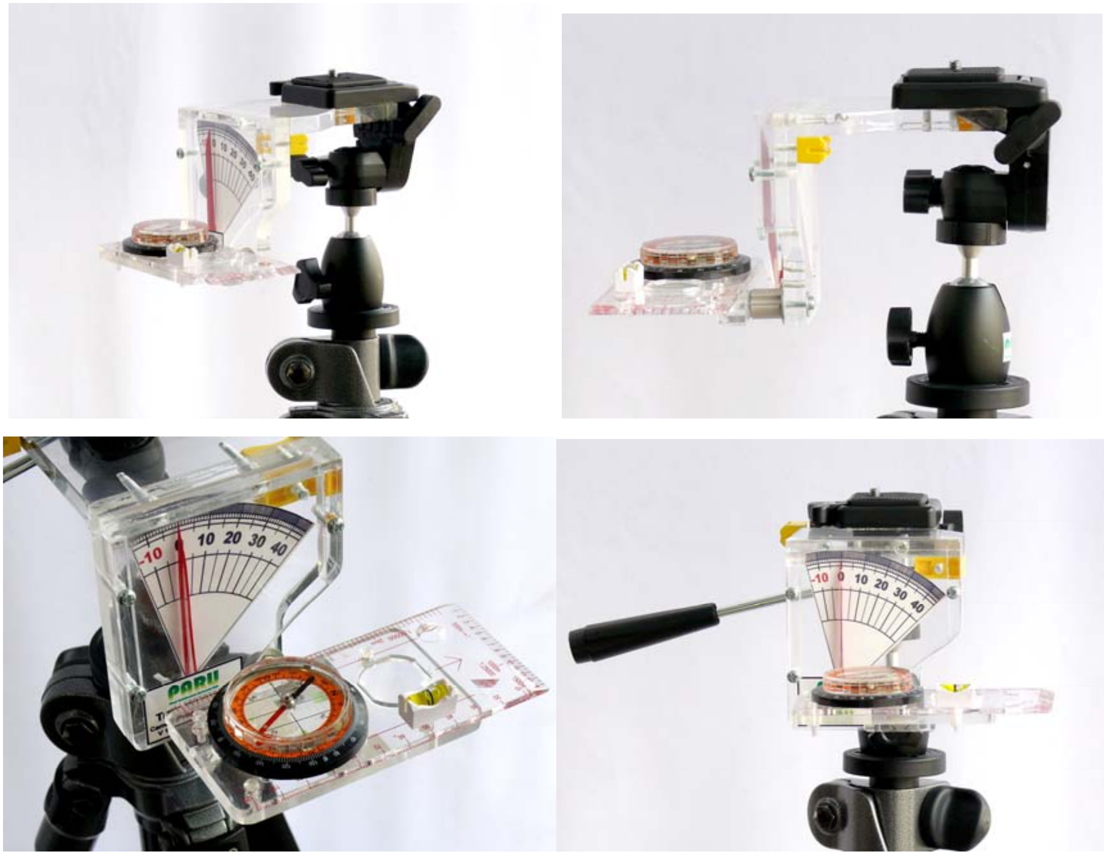

Figure 13 The analog model designed for photographic method.

The digital model designed for photographic method had the same components as the analog model. The digital model replaced the inclinometer with a digital inclinometer. The inclinometer was attached to the vertical plate with 2 screws. These 2 screws allow inclinometer to adjust vertically for finding horizontal plane. Compass holder was placed at the same position as analog model. Normal compass was replaced by digital compass. The plate that holds the digital compass has 2 layers. Top layer can be rotated horizontally, allow the digital compass to self calibrate without taking it out of the holder. The 2 plates can be locked together by screwing the bottom screw under the plate. The digital model designed for photographic method was shown in Figure 14.

Figure 14 The digital model designed for photographic method.

Digital photograph processing for Tree Analyser technique

All photographs were processed manually to black and white bitmap file using GIMP for Windows Version 2.2.9 (GNU Image Manipulation Program, http://www.gimp.org/, Figure 15). The method for removing red background was as follows.

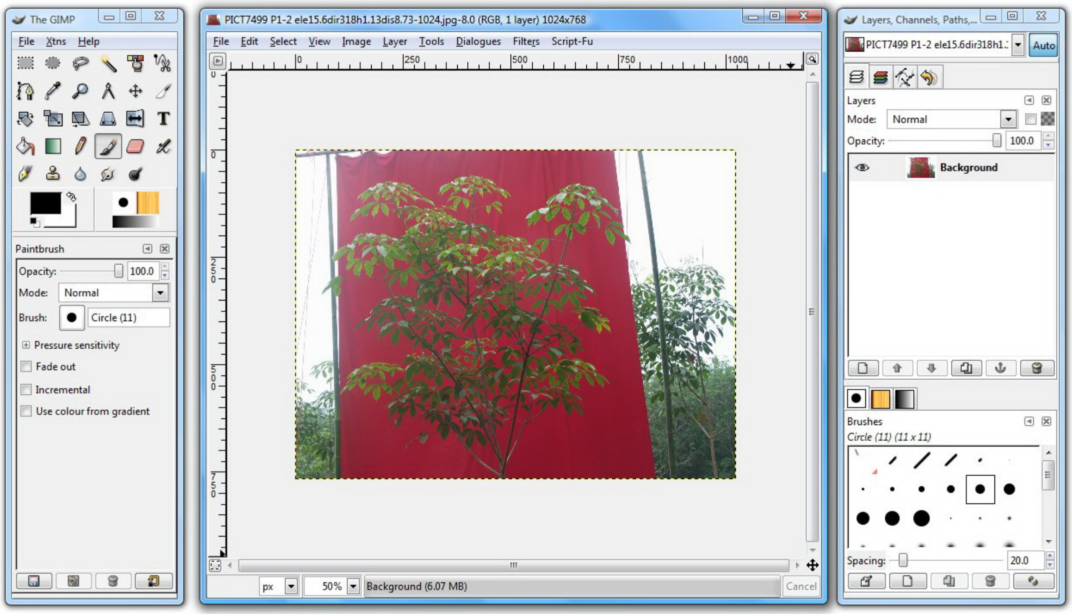

Figure 15 GIMP for Windows Version 2.2.9. This software contain 3 windows; Tools window (left window), File window (center window), and Layer, Channels, Pattern window (Right window).

First, the unwanted parts those were located outside red background were removed using “Select rectangular regions” (Figure 16). Then selected area was erased by using “Clear” command (located in menu Edit -> Clear). Figure 17 shows the results of removing unwanted parts by using “Select rectangular regions”. In Figure 17, there are still unwanted parts left in the photograph. Those parts must be erased using “Erase to background” tool (Figure 18). The results of removing unwanted parts by using “Erase to background” tool was shown in Figure 19.

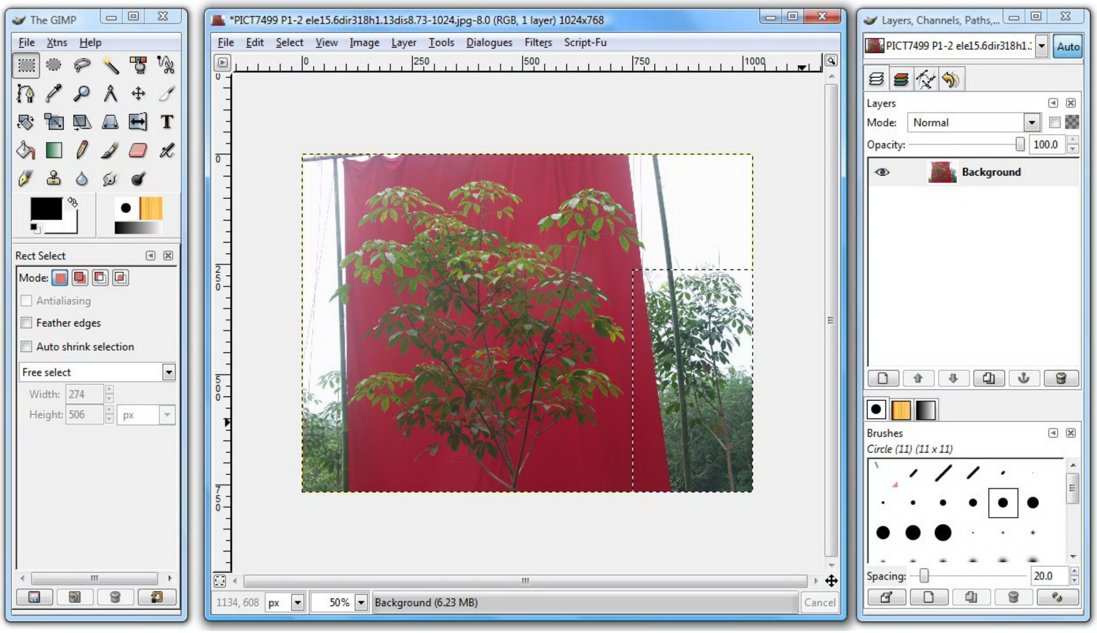

Figure 16 GIMP for windows shows the “Select rectangular regions” tool on the left windows. The unwanted part was selected in the center window.

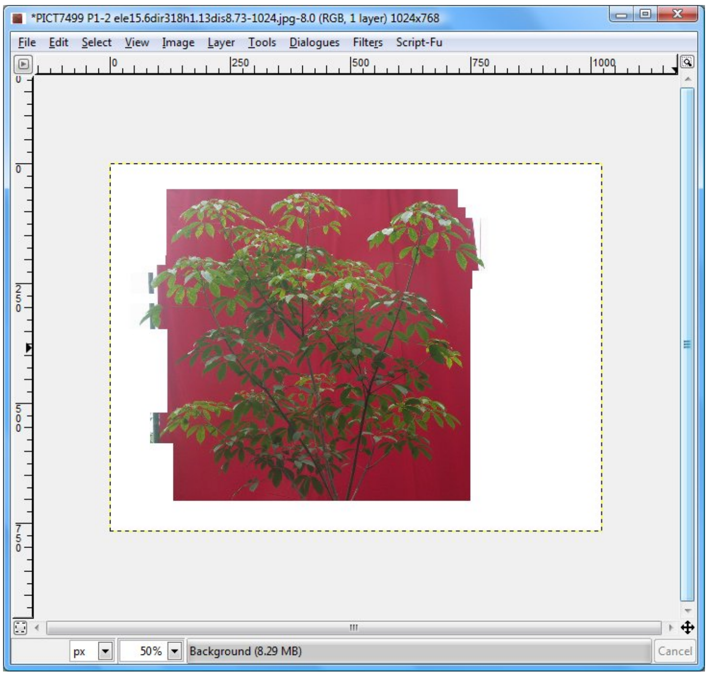

Figure 17 Photograph after removed all unwanted parts by using “Select rectangular regions” tool.

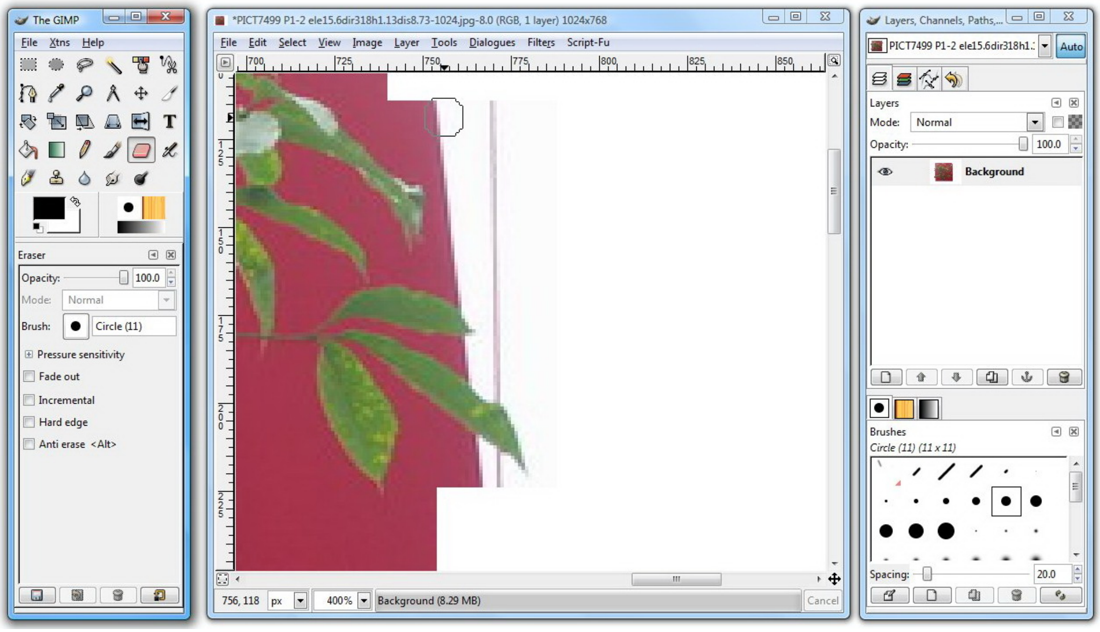

Figure 18 GIMP for windows shows the "Erase to background" tool on the left windows. The unwanted part was erased in the center window.

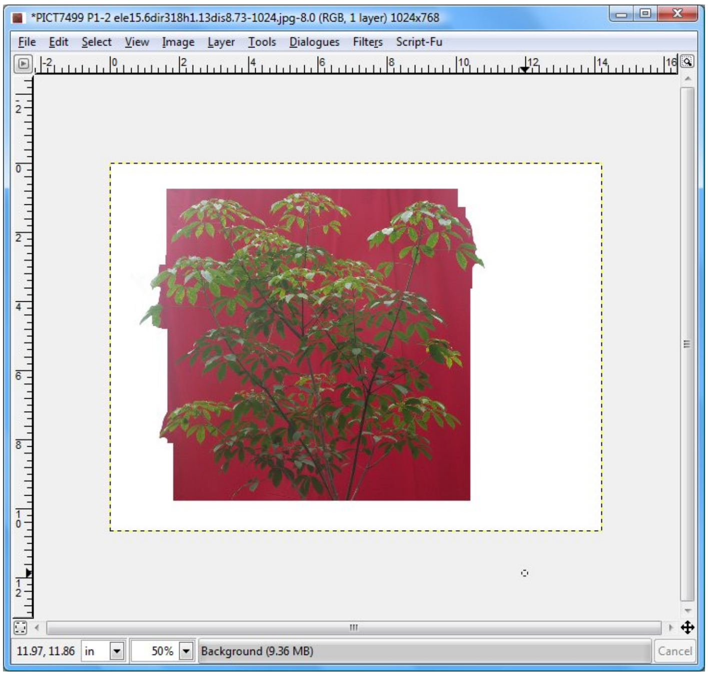

Figure 19 Photograph after removed all unwanted parts by using "Erase to background" tool.

Second, to remove red background from the photograph, “Select regions by colour” tool was used (Figure 20). This tool will select the pixel those contained the specific colour values. This tool allowed user to adjust the threshold of colour. So the range of colour will be selected from the photograph instead of only one colour. Choosing right threshold will decreased the time of removing red background. To remove red background, red colour were selected using threshold value in the range of 19-22 (Figure 21). Then the selection was erased using “Erase to background” tool. This step must be repeated using smaller range of threshold until all the red colour was removed from the photograph. All red colour must be removed even the very light red colour around the leaf edge (Figure 22). The results of removing red background was shown in Figure 23.

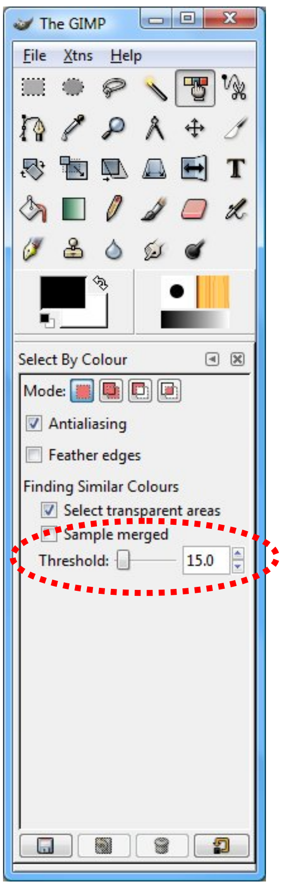

Figure 20 Tool window of GIMP for windows, shows the “Select regions by colour” tool. Threshold adjustment was shone in red circle.

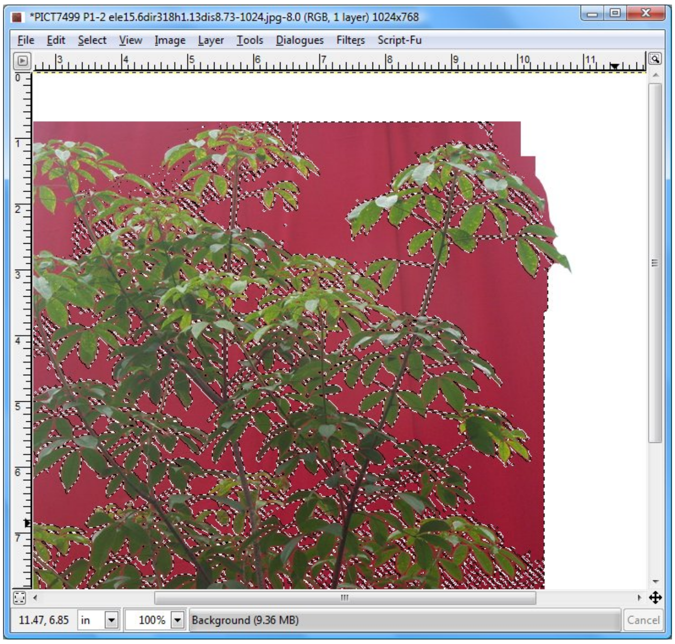

Figure 21 Red colour on the photograph was selected using “Select regions by colour” tool.

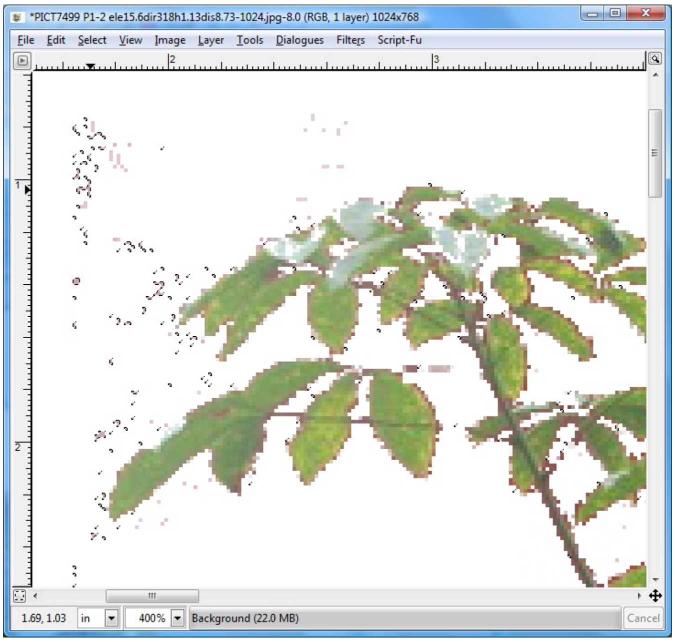

Figure 22 Photograph during the removing of red colour. The pink dots still appear in the background and at the leaves edge. Those dots must be removed completely.

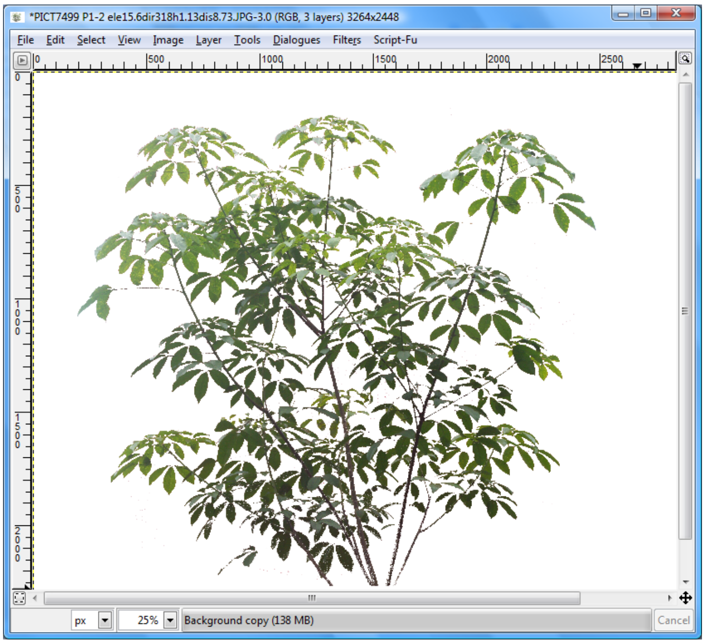

Figure 23 Photograph after remove red background by using “Select regions by colour” tool.

Third, the other unwanted parts such as main stem, main benches and other unwanted objects were erased using “Erase to background” tool. This step should be done manually. The results of removing other parts using “Erase to background” tool was shown in Figure 24.

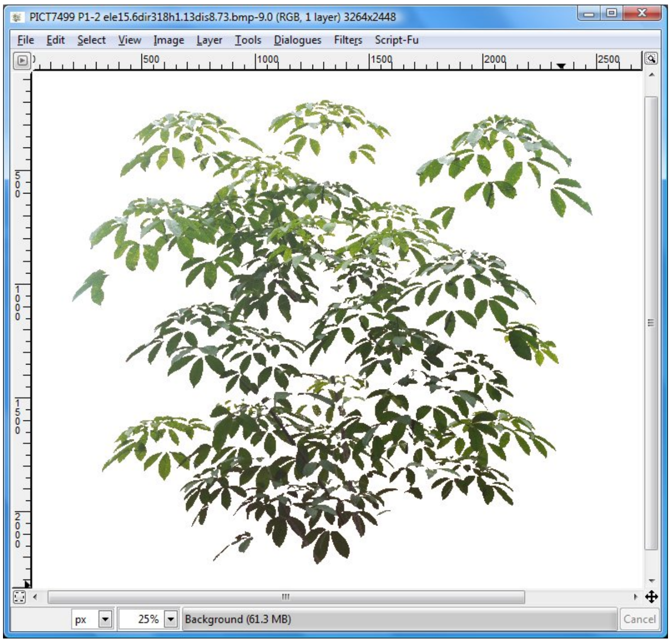

Figure 24 Photograph after remove unwanted parts such as main stem, main benches and other unwanted objects by using "Erase to background" tool.

Forth, the photograph should be converted to black and white. But if the photograph was converted directly to black and white or converted from gray scale to black and white, some parts of leaves those have light colour will become white instead of black. To avoid that, special conversion method must be used. The objective of this method is to select only colour parts of the photograph and then change them to black colour. To apply this method to the photograph, "Select regions by colour" tool was select and the threshold value must be set to zero. Then select any white area in the photograph. This step will make the selection specified only white colour. After white area was selected, selected colour area using menu Select -> Invert. Now colour area will be selected instead of white area. Next step is to change all colour area to black colour. Before changing to black colour, colour area must be cleared using "Erase to background" tool (Figure 25). Then empty area was filled with black colour using "Fill with a colour" tool (Figure 26). Select black as a filled colour and filled to the selected area. Now the colour area becomes pure black colour (Figure 27).

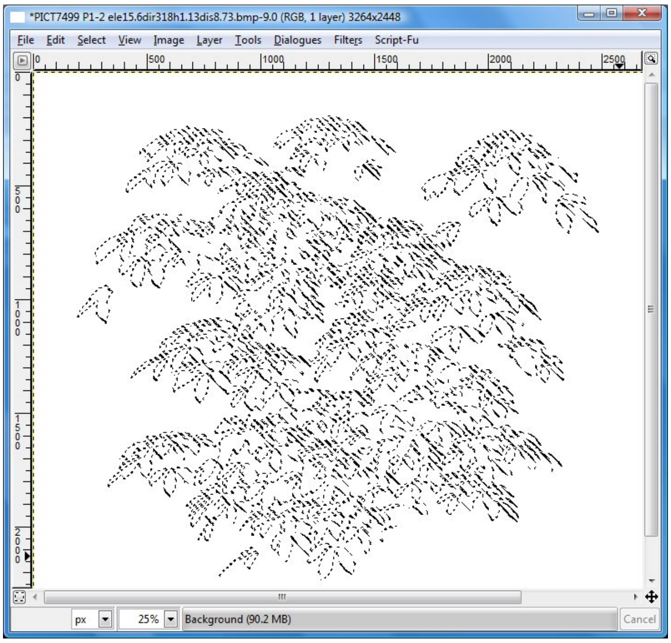

Figure 25 Photograph after clearing colour area by using “Erase to background” tool. The vegetative part was selected.

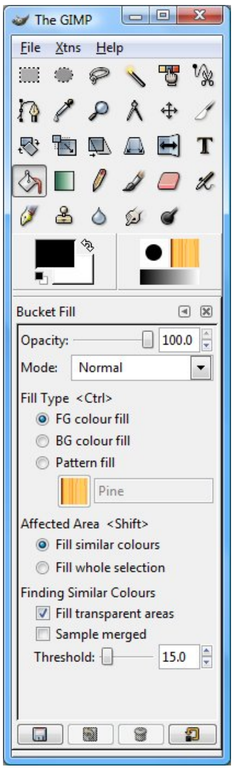

Figure 26 Tool window of GIMP for windows, shows the “Fill with a colour” tool.

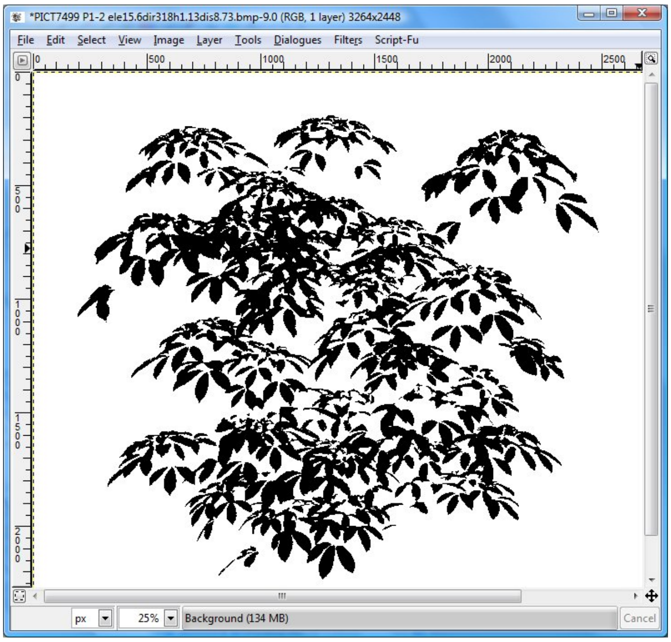

Figure 27 Photograph after converted to black and white by using special conversion method. This photograph contains only two colours, black and white. Black represented vegetative part and white represented background.

Finally, the photograph was converted to black and white (index colour conversion) without dithering option and saved as Bitmap file. Bitmap file can be saved by using menu Image -> Mode -> Index, then select “Use black and white (1-bit) palette”, then press “OK”. The photographs before and after removing background were shown in Figure 28.

Figure 28 Photographs of 2 year-old rubber tree var. RRIM600 with red background (A) and the same photograph after removing background and converted to black and white (B).

Application of photographic method to young isolated rubber trees

Measurement of canopy structure parameters

Table 1 shows variations in rubber canopy structure parameters analyzed from digitised data. For 2-year-old RRIM600, mean leaf inclinations varied from 28.62 to 27.27 degree. Tree heights were 4.85 m and 4.26 m, crown height were 2.88 m and 1.7 m, crown diameters were 2.55 m and 1.24 m, and crown volumes were 6.45 m^2 and 2.16 m^2, respectively. These 2 trees had different canopy size. The crown volume of the first tree was 66% higher than the second tree. Tree height crown height and crown diameter of the first tree also larger. The different of canopy structure of 2-year-old RRIM600 could come from the variation of growth and development of tree in field condition. For 3-year-old RRIM600, mean leaf inclinations was 36.96 degrees. A tree height was 5.3 m, crown height was 3.33 m, crown diameter was 3.9 m, and crown volume was 24.43 m^2. Canopy size of 3-year-old RRIM600 was a lot larger than 2-year-old trees. Mean leaf inclination of 3-year-old RRIM600 was also increased. This means the 3-year-old RRIM600 have more vertical leaves than the 2-year-old trees. This may caused by the increasing of leaves within the canopy or the acclimation of the trees in different location.

For 2-year-old RRIT251, mean leaf inclinations were 30.23 and 30.84 degree. Tree heights were 5.33 m and 3.8 m, crown height were 2.92 m and 3.25 m, crown diameters were 3.72 m and 2.32 m, and canopy volumes were 16.88 m^2 and 5.03 m^2, respectively. The canopy size of these 2 trees was also different. The difference of canopy size could come from the variation of growth and development of tree in field condition. The mean leaf inclination of 2-year-old RRIT251 is higher than those of 2-year-old RRIM600. This may be the difference of clones.

Table 2 shows variations of number of leaflet, total leaf area and average leaflet area of rubber measured by leaf area meter (for 2 year-old trees) and by allometric relationship (for 3-year-old RRIM600). For 2-year-old trees, average leaflet area ranged from 31.72 cm^2 to 39.03 cm^2 for RRIM600 and 29.4 cm^2 to 43.95 cm^2 for RRIT251. Whereas number of leaflet ranged from 693 to 1,564 leaves for RRIM600 and 1,203 to 3,053 leaves for RRIT251. Total leaf area ranged form 2.2 m^2 to 5.03 m^2 for RRIM600 and 4.89 m^2 to 12.97 m^2 for RRIT251. These data indicates that there are variation of leaf let size, leaflet number and total leaf area among the same clone and the different clone. The Mean leaflet area of 2-year-old RRIM600 seems to be smaller than the 2-year-old RRIT251. The Mean leaflet area of 3year-old RRIM600 is smaller than 2-year-old RRIM600.

Figure 29 shows the different shape and size of the digitised rubber canopy. Two-year-old RRIM600 plant1 (Figure 29A) has non-uniform canopy shape. There are 2 large gaps in the left and in the upper right of the canopy. These gaps caused by the two big branches those grown out of the trunk at the base of the canopy. Those branches bent down while the top branches did not. For 2-year-old RRIM600 plant 2 (Figure 29B) and 2-year-old RRIT251 plant2 (Figure 29D), they both have cone-shape canopy with the non-uniform height on the top of the canopy. These caused by the different length of the top branches of the canopy.

For 2-year-old RRIT251 plant 1 (Figure 29C), the canopy shape is slightly uniform. But the right side of the canopy is smaller than the left side. Several medium size of gap found in the middle of the canopy. These gaps caused by the branches those grown out of the trunk with the leaf only on the top of the branches. No leaf grows on the bottom of the branches make the gap in the middle of the canopy. For 3-year-old RRIM600 plant 1 (Figure 29E), canopy shape is uniform. There is no medium or large gap found within the canopy. This may be caused by the high amount of branches, sub branches and leaves those grows within the canopy.

Table 1 Canopy structure parameters of 3D-digitised rubber trees.

Rubber Trees	Mean leaf inclination (degree)	Tree height (m)	Crown height (m)	Crown Diameter (m)	Crown Volume (m^3)
2-yr RRIM600-1	28.62	4.85	2.41	2.55	6.45
2-yr RRIM600-2	27.27	4.26	1.70	1.24	2.16
2-yr RRIT251-1	30.23	5.33	2.92	3.72	16.88
2-yr RRIT251-2	30.84	3.80	2.08	2.32	5.03
3-yr RRIM600-1	36.96	5.30	3.33	3.90	24.43

Table 2 Leaf parameters of rubber trees measured from leaf area meter.

Rubber Trees	Number of leaflet per plant	Leaf area (m^2)	Mean leaflet area (cm^2)
2-yr RRIM600-1	1564	5.03	32.16
2-yr RRIM600-2	693	2.20	31.72
2-yr RRIM600-3	700	2.73	39.03
2-yr RRIM600-4	731	2.47	33.78
2-yr RRIT251-1	3053	12.97	42.50
2-yr RRIT251-2	1203	5.28	43.95
2-yr RRIT251-3	1216	5.06	41.59
2-yr RRIT251-4	1664	4.89	29.40
3-yr RRIM600-1	12141	32.1	26.4

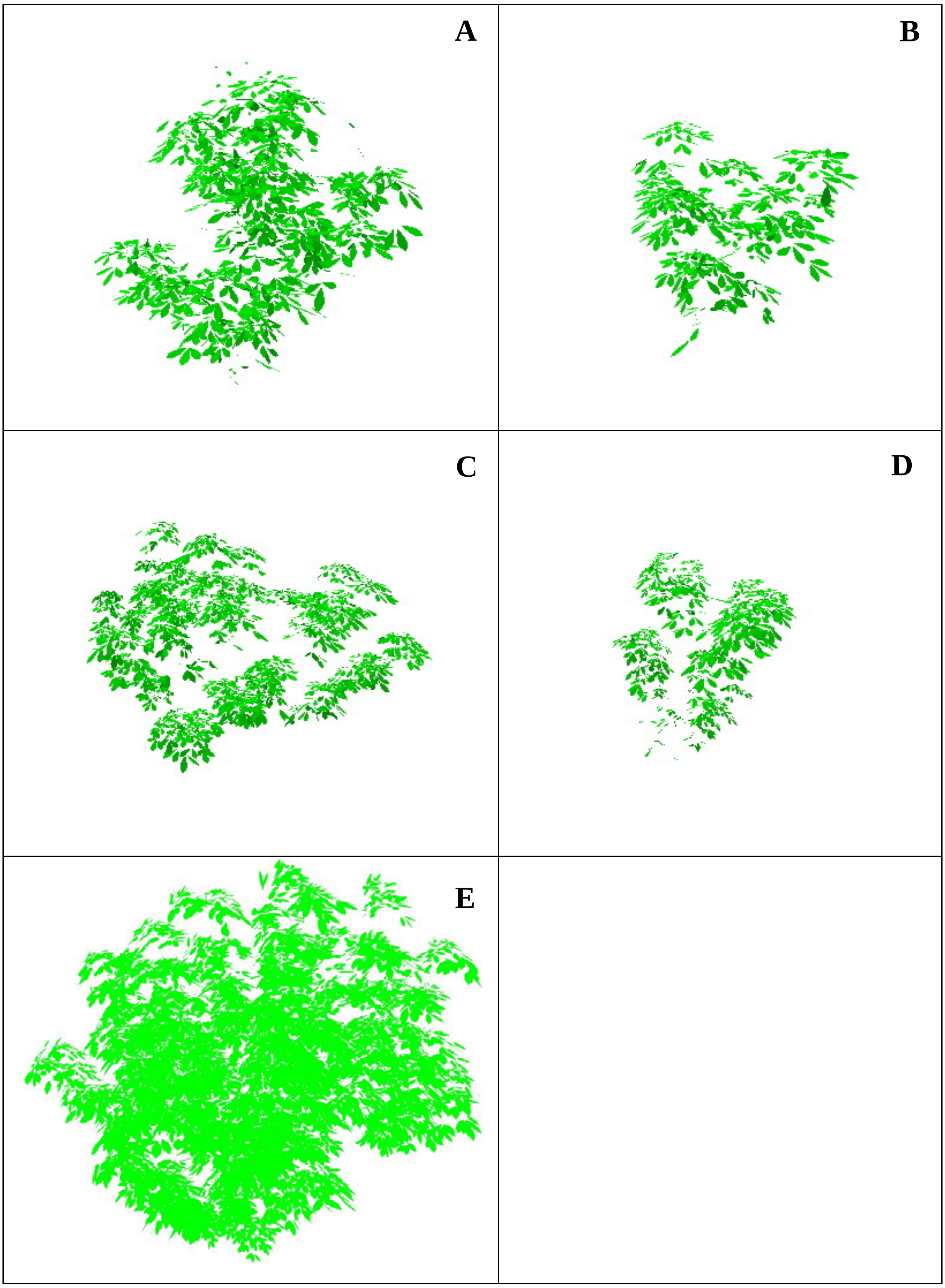

Figure 29 3D pictures of digitising rubber canopy. (A) 2-year-old RRIM600 plant1, (B) 2-year-old RRIM600 plant2, (C) 2-year-old RRIT251 plant1, (D) 2-year-old RRIT251 plant2 and (E) 3-year-old RRIM600 plant1.

Estimation of canopy structures from photographic method

1. Estimation of tree height, crown size and crown volume

Table 3 shows the canopy structure parameters estimated from photographic method. For 2-year-old RRIM600, estimated tree heights were 4.82 m and 4.36 m, crown height were 2.88 m and 1.88 m, crown diameters were 2.55 m and 1.56 m, and crown volumes were 6.14 m^2 and 1.92 m^2, respectively. For 3-year-old RRIM600, estimated tree height was 5.5 m, crown height was 3.75 m, crown diameter was 4.65 m, and crown volume was 29.58 m^2. For 2-year-old RRIT251, estimated tree heights were 5.24 m and 4.22 m, crown height were 3.32 m and 2.33 m, crown diameters were 3.92 m and 2.58 m, and canopy volumes were 18.46 m^2 and 7.17 m^2, respectively.

When compared the estimated data with digitising data, estimated tree height were slightly overestimate by 2.9% (SD=4.93) (Figure 30A). Two-year-old RRIT251 plant 2 has the highest overestimation. The overestimation may cause by the non-uniformity of the canopy shape (Phattaralerphong and Sinoquet, 2005). Because the canopy of 2-year-old RRIT251 plant 2 (Figure 29D) had several top branches those bent out of the trunk. When taken photographs, the top of the branches those bent out in the same direction as the camera will stay closer in the photographs and masking the real point of tree height. This will make the overestimation of tree height.

The estimation of the crown heights were overestimated by 8.5% (SD=8) (Figure 30B). The overestimation maybe caused by the non-uniformity of the canopy shape and also the distance of camera from the tree trunk. If some branches on the top or the bottom of the crown bent out of the crown and masking the real top and bottom point, the crown height will overestimated. The distance of the camera from the trunk can effect the estimation if the crown shape is very wide. When taken the photographs too close to the tree, the edge of the crown will masked the real top and bottom point of the canopy. To avoid this error, increasing the distance of camera to the trunk or changing the direction of the camera to the tree will avoid masking in that direction (Phattaralerphong and Sinoquet, 2005).

The estimation of the crown diameter were overestimated by 12.6% (SD=10.3) (Figure 30C). The 2-year-old RRIM600 plant 2 has the highest overestimation followed by the 3-year-old RRIM600. This may be caused by the shape of the crown and the direction of photographs. When the crown shape is not round, taking from the different direction gave the different crown diameter values. The overestimate of crown diameter can be reduced by using more photographs from different direction (Phattaralerphong and Sinoquet, 2005).

Estimation of the crown volumes was overestimated by 11.5% (SD=21.37) (Figure 30D). Two-year-old RRIT251 plant 2 showed the highest overestimation followed by the 3-year-old RRIM600. Both of the 2-year-old RRIM600 showed an underestimation. The overestimation of crown volumes may be caused by the overestimation of crown height and crown diameter. The voxel size chosen is also affecting the estimation of crown volume (Phattaralerphong and Sinoquet 2005).

Table 3 Canopy structure parameters estimation using photographic method.

Rubber Trees	Tree Height (m)	Crown Height (m)	Crown Diameter (m)	Crown Volume (m^3)
2-yr RRIM600-1	4.82	2.88	2.55	6.14
2-yr RRIM600-2	4.36	1.88	1.56	1.92
2-yr RRIT251-1	5.24	3.32	3.92	18.46
2-yr RRIT251-2	4.22	2.33	2.58	7.17
3-yr RRIM600-1	5.50	3.75	4.65	29.58

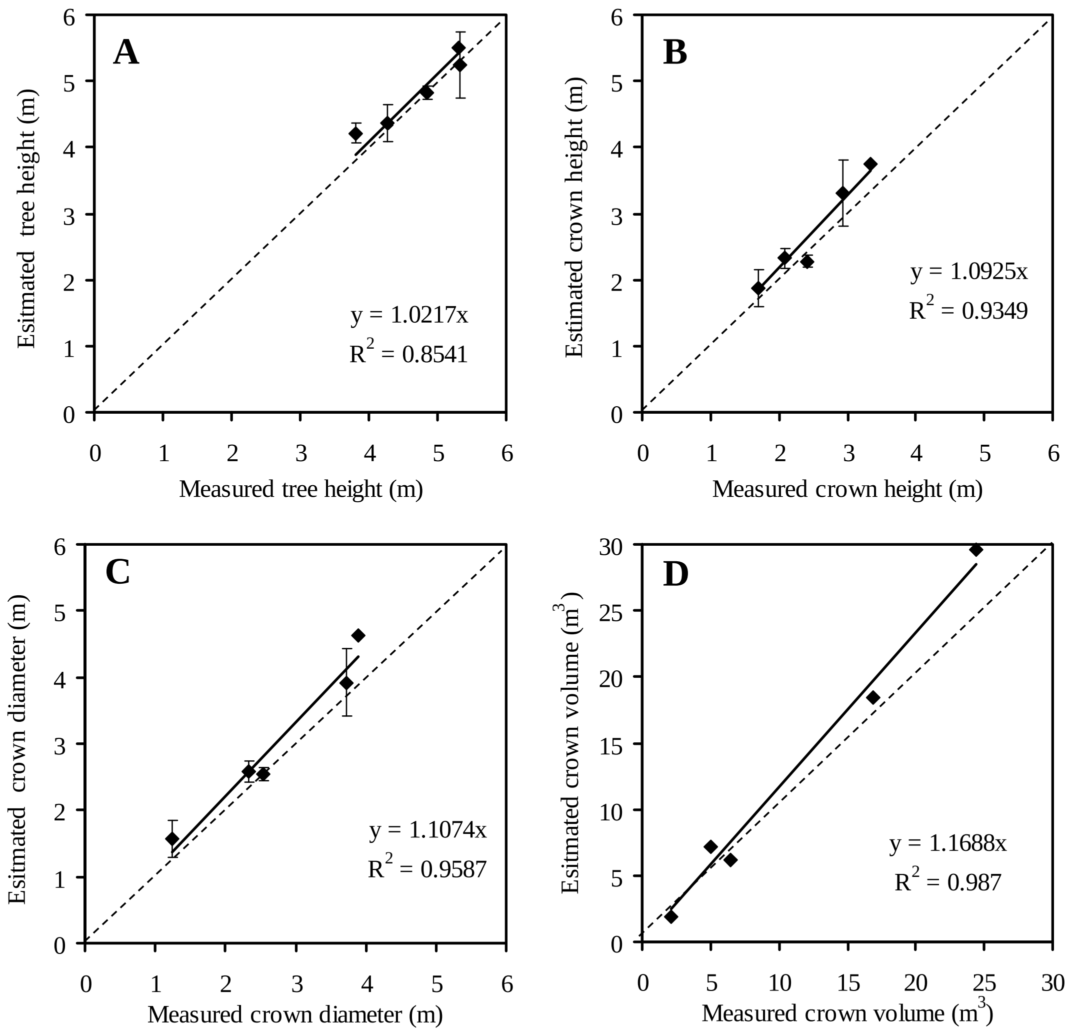

Figure 30 Comparison between canopy parameters of 5 rubber trees, as measured from 3D-digitising data and estimated from photographic method. (A) Tree height, (B) crown height, (C) crown diameter from a mean value of N-S and E-W direction, and (D) crown volume.

2. Estimation of total leaf area

Table 4 shows the total leaf area measured by leaf area meter and total leaf area estimated from photographic method. 8 trees were used in this experiment. Four trees of 2-year-old RRIM600 and 4 trees of 2-year-old RRIT251 were photographs from 4 directions around the tree by photographic method. Then all leaves were removed and were measured leaf area using leaf area meter. Estimation of total leaf area using photographic method gives higher total leaf area than the measurement in all trees. Two-year-old RRIT251 plant 1 gave the highest overestimation (16%) while 2-year-old RRIM600 plant 3 gave the lowest overestimation (2.5%).

Figure 31 shows the comparison between leaf area estimated from photographic method and leaf area measured by leaf area meter. The average of estimation of leaf areas in all trees were overestimated by 15.7% (SD=7.4). The result shows that, the percent of overestimation in each tree ranged from 109% to 124%. The error of the estimation of total leaf area can cause by picture discretization, leaf inclination, and leaf size. Voxel size does not effect the estimation of total leaf area (Phattaralerphong *et al*., 2006). In this experiment, leaf inclination and leaf size those were use for the estimation came from real measurement. The error of the estimation of total leaf area should be the picture discretization.

Table 4 Leaf area estimation of 9 rubber trees using photographic method.

Rubber Trees	Measured total leaf area (m^2)	Estimated total leaf area (m^2)
2-yr RRIM600-1	5.03	5.51
2-yr RRIM600-2	2.20	2.49
2-yr RRIM600-3	2.73	3.02
2-yr RRIM600-4	2.47	3.07
2-yr RRIT251-1	12.97	16.11
2-yr RRIT251-2	5.28	6.52
2-yr RRIT251-3	5.06	5.32
2-yr RRIT251-4	4.89	5.64

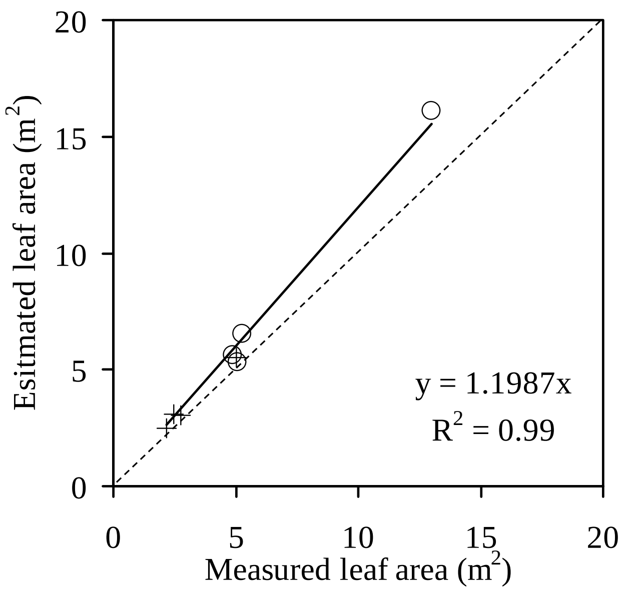

Figure 31 Comparison between total leaf area of 8 rubber trees, as measured leaf area meter and estimated from photographic method.

The picture discretization is the size of the picture zones at will be used to compute the gap fraction. Instead of using size of the picture zones directly, Phattaralerphong *et al*. (2006) presented the Picture Zone Area (PZA) as the unit of the zone area compared to the actual leaf area within the canopy. The experiment above used PZA value equal to 17. This value gave the +- 10% error of total leaf area estimation when test in mango, olive peach and walnut canopy (Phattaralerphong et al. 2006). In 2-year-old rubber tree, this value shows 15% over estimation of total leaf area. Testing of different PZA values from 10 to 300 was shown in Figure 32. At PZA 10, the overestimation of leaf area ranged from 10 to 30 %. At range of PZA 150 to 270, the over and underestimate of leaf area were between 10%. The linear regression analysis of estimated leaf area from PZA 60 to 300 with the error of estimation value showed that PZA 207 gave the best value of estimated leaf area for 2-year-old rubber tree. Figure 33 shows the comparison of estimated leaf area from 8 trees using PZA 207 with the data measured by leaf area meter. The estimated leaf area show good relations with measured data and the estimated leaf area of large tree shows slightly overestimated.

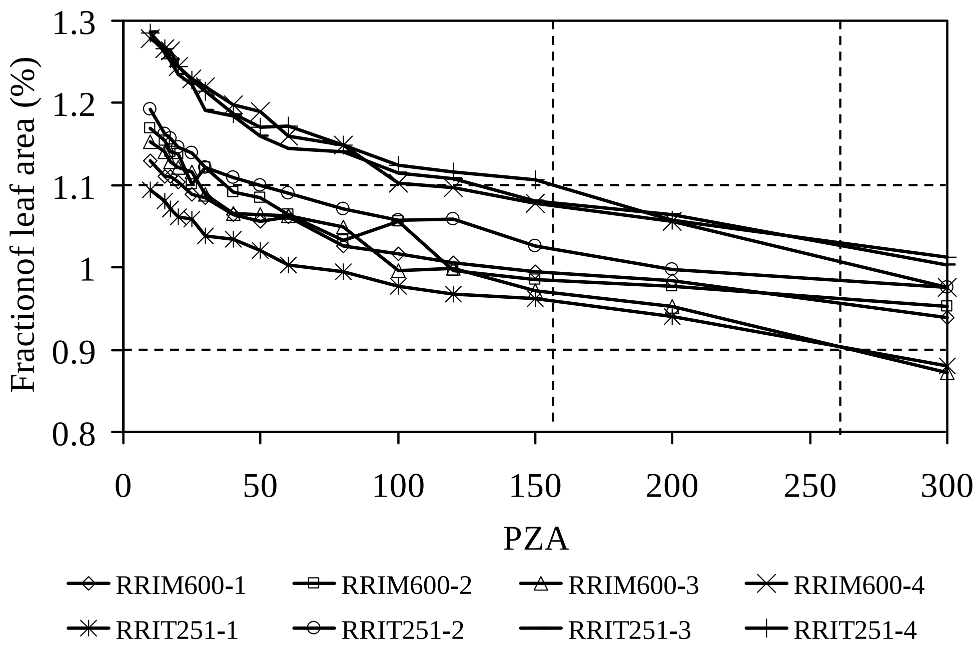

Figure 32 Effect of picture zone area (PZA) on leaf area estimated from binomial model on 8 rubber trees.

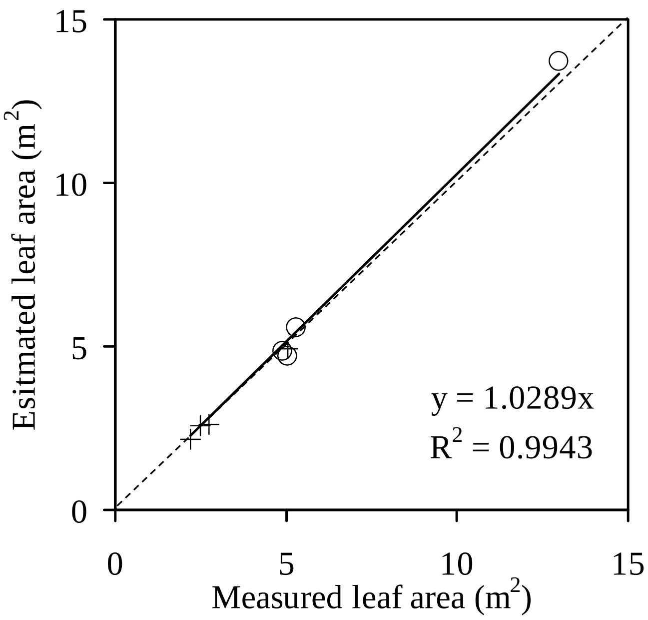

Figure 33 Comparison between total leaf area of 8 rubber trees, as measured leaf area meter and estimated from photographic method, Using PZA = 207.

3. Estimation of vertical profile of leaf area

Vertical profiles of leaf area of the trees estimated from photographic method were compared with those calculated from digitising data. Five digitised trees were used in this experiment. Vertical profile of leaf area was computed into 25 cm layers. 2-year-old RRIM600 plant 1 (Figure 34A) showed good relation between estimated and digitise value. The density of leaf area at 4 m height shows different density. This error may happen when the layer calculated from digitising data was not at the same height of the estimated data. This error also comes from the non uniform leaf position within the canopy such as in Figure 29A and 29C. The top of the crown estimated from photographic method were 50 cm lower than digitising data and the bottom of the crown was 25 cm lower. These under estimations were due to the under estimation of crown height (Figure 30B).

Two-year-old RRIM600 plant 2 (Figure 34B) and 2-year-old RRIT251 plant 2 (Figure 34D) showed good relation between estimated and digitising value. The density of leaf area shows the same amount in every height. The crown height estimated from photographic method was slightly lower than digitising data. These under estimations were due to the under estimation of crown height.

The estimated vertical profile of leaf area of 2-year-old RRIT251 plant 1 (Figure 34C) shows the different pattern to the digitised data. The crown height is also shorter than the digitising data. This error may be caused by short distance of the camera to the tree trunk. Photographic method uses the photographs taken horizontally to estimate the vertical profile of leaf area. If the tree is tall and the distance of the camera is near, the horizontal photographs of the canopy cannot be obtained (Phattaralerphong *et al*., 2006). With non horizontal photograph, the vertical profile was compute thought the path of the beam that is not horizontal. This will cause the merging of vertical profile from layer above or layer under the target layer.

The estimated vertical profile of leaf area of 2-year-old RRIT251 (Figure 34E) showed good relation between estimated and digitising value. The estimated vertical profile moved down about 25 cm due to the different base of the crown.

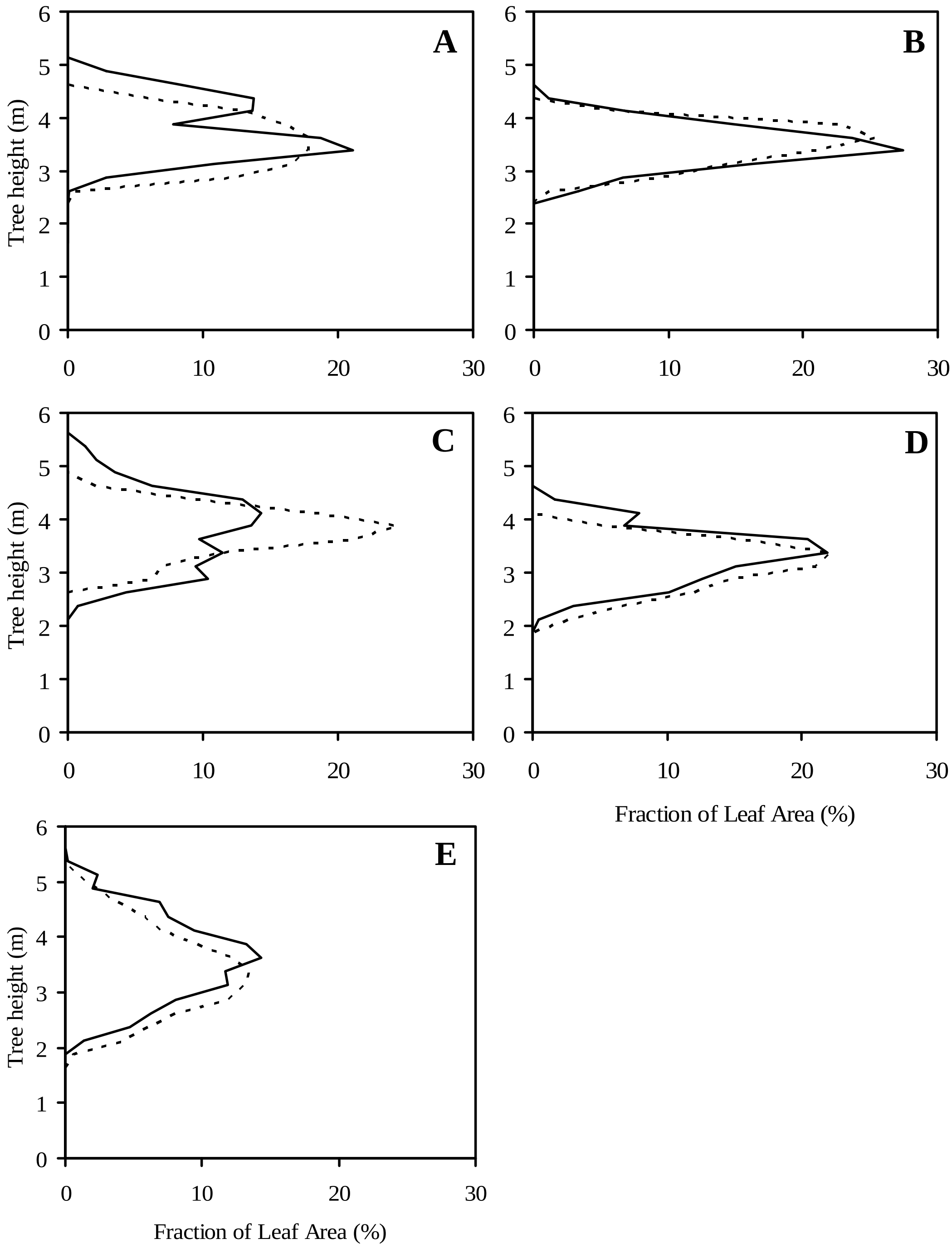

Figure 34 Comparison of vertical profile of leaf area from 5 rubber trees, as measured from 3D-digitising data (solid line) and estimated from photographic method (dot line), from 2-Year-old RRIM600 plant 1 (A) and plant 2 (B), 2-Year-old RRIT251 plant 1 (C) and plant 2 (D), and 3-Year-old RRIM600 (E).

Use of the RATP model to simulate photosynthesis

Diurnal course of photosynthetic rates of rubber canopy were estimated using RATP model (Sinoquet *et al*., 2001). Three types of canopy data were used and compared for the efficiency of estimation. First canopy data was the 3D leaf file obtained from digitising data. This dataset will be use as the control of this experiment. Second canopy data was the LAD layers those calculated from digitising data. Third canopy data was the LAD estimated by photograph method. These data sets were inputs to the RATP model with the other parameters. Solar radiation those were used in this estimation has been shown in Figure 35F.

Figure 35 shows the diurnal course of photosynthetic rates of canopy during an overcast sky day. Photosynthetic rates of every tree were changed in the same pattern. The pattern was changed according to the amount of solar radiation. In 2-year-old RRIM600 plant1, the photosynthetic rate estimated from digitised data increased rapidly from 0.3 to 1.6 g CO_2/h during 07h00-09h00. After 09h00, it ranged approximately 1.6 g CO_2/h. The rate started decline after 15h00 and it peaked again at 17h00 followed to the irradiance. After that, the rate gradually declined until 18h00 (Figure 35A). Other trees had the same pattern as the 2-year-old RRIM600 plant1. Two-year-old RRIM600 plant 2 had the highest photosynthetic rate approximately 0.8 g CO_2/h (Figure 35B). Two-year-old RRIT251 plant 1 had the highest photosynthetic rate approximately 4 g CO_2/h (Figure 22C). Two-year-old RRIT251 plant 2 had the highest photosynthetic rate approximately 1.6 g CO_2/h (Figure 35D). And 3-year-old RRIM600 had the highest photosynthetic rate approximately 7.5 g CO_2/h (Figure 35E).

The simulated values of photosynthesis from LAD calculated from digitising data and LAD estimated by photograph method were all overestimated. The pattern of diurnal course was the same in all trees. The overestimate of photosynthetic rate estimated using LAD calculated from digitising data ranged from 0.1 g CO_2/h (2-year-old RRIM600 plant 2) to approximately 3 g CO_2/h (3-year-old RRIM600). The overestimate of photosynthetic rate estimated using LAD estimated by photographic method ranged from 0.3 g CO_2/h (2-year-old RRIM600 plant 2) to approximately 5 g CO_2/h (3-year-old RRIM600).

Figure 36 shows the comparison of estimated photosynthetic rate estimated using digitise data, photosynthetic rate estimated using LAD calculated from digitising data and photosynthetic rate estimated using LAD estimated by photograph method. In 2-year-old RRIM600 plant 1, the estimation of photosynthetic rate using LAD calculated from digitising data was 18% overestimated. The estimation using LAD estimated by photograph method was 39% overestimated (Figure 36A). In 2-year-old RRIM600 plant 2, the estimation of photosynthetic rate using LAD calculated from digitising data was 5% overestimated. The estimation using LAD estimated by photograph method was 28% overestimated (Figure 36B). In 2-year-old RRIT251 plant 1, the estimation of photosynthetic rate using LAD calculated from digitising data was 22% overestimated. The estimation using LAD estimated by photograph method was 56% overestimated (Figure 36C). In 2-year-old RRIT251 plant 2, the estimation of photosynthetic rate using LAD calculated from digitising data was 16% overestimated while 58% overestimation was found when using LAD estimated by photographic method (Figure 36D). In 3-year-old RRIM600, the estimation of photosynthetic rate using LAD calculated from digitising data was 27% overestimated. The estimation using LAD estimated by photographic method was 59% overestimated (Figure 36E).

The overestimation of photosynthetic rate estimated using LAD calculated from digitising data and photosynthetic rate using LAD estimated by photographic method was caused by the calculation method for canopy geometry of RATP model. The RATP model using 3D grid cells to represent the canopy geometry. The size of the cell can be defined by user and should be equal in every cell. Each cell may be empty or contain the canopy component (Sinoquet *et al*., 2001). When using 3D digitising data as an input for canopy geometry, cells those located inside the crown volume contained the amount of leaf area those located within the cells. Cells those located outside crown volume were empty cells. But when using LAD as an input for canopy geometry, RATP used only one cell to represent the canopy geometry of each layer. For example, LAD of 2-year-old RRIM600 plant 1 had separated into 7 layers. With this data, there are 8 cells to input to RATP. The first to the seventh cells contained LAD for each layer and the eighth cell is empty that represents the lower part of the tree. These cells will create the square shaped crown instead of real crown shape. The density of the leaf will scatter throughout the cell make its density lower than the digitised canopy. The low density cause the light to transmit more into the lower cell compared to the digitised canopy. When the cell had more light, the photosynthesis increased.

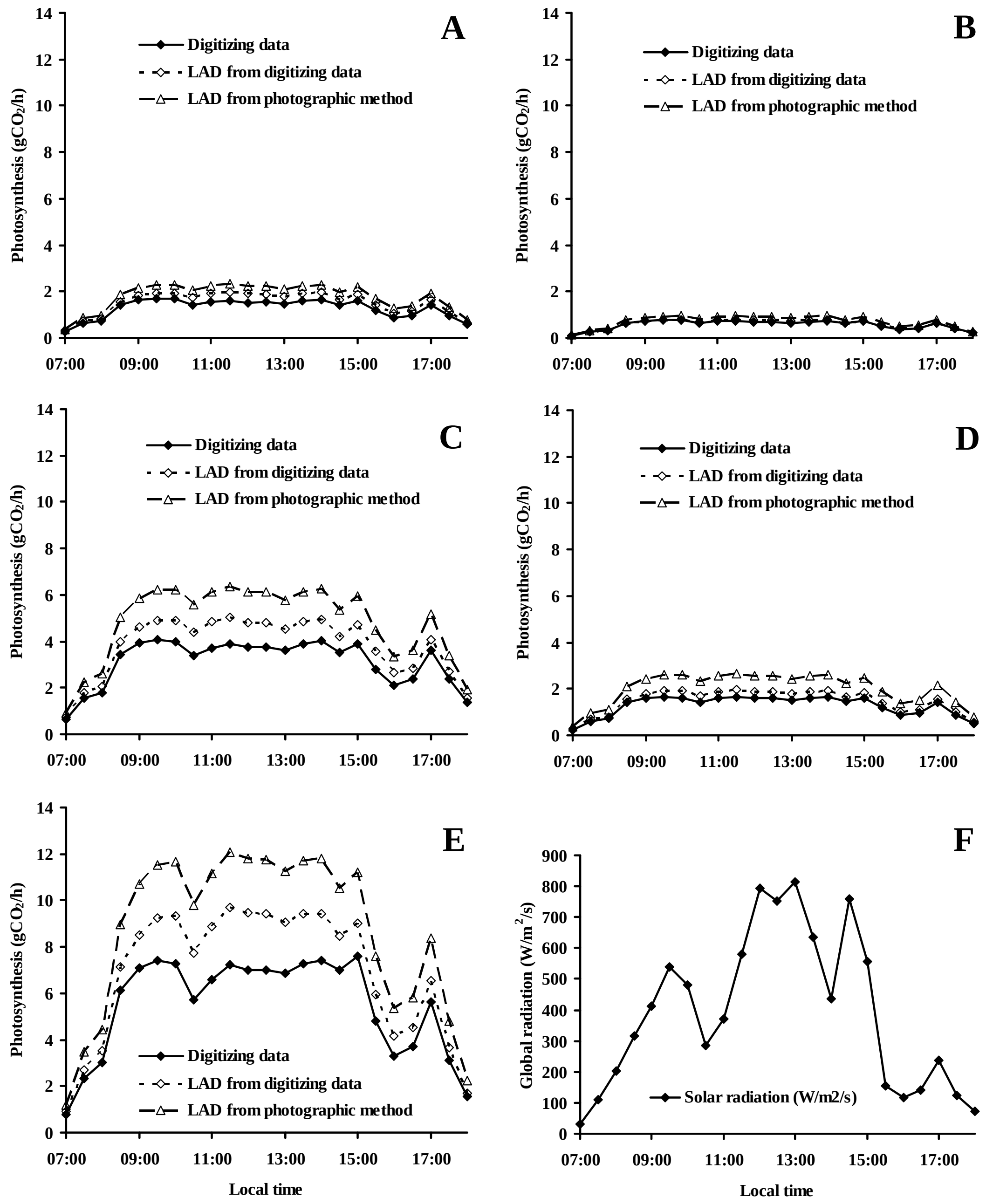

Figure 35 The estimation of diurnal course of photosynthetic rates of canopy during daytime using RATP model as estimated from digitising data (solid line), from LAD calculated from digitising data (dot line), and LAD estimated from photographic method (long dot line), of 2-year-old RRIM600 plant 1 (A) and plant 2 (B), 2-year-old RRIT251 plant 1 (C) and plant 2 (D), and 3-year-old RRIM600 (E). (F) shows the solar radiation those were used in this estimation.

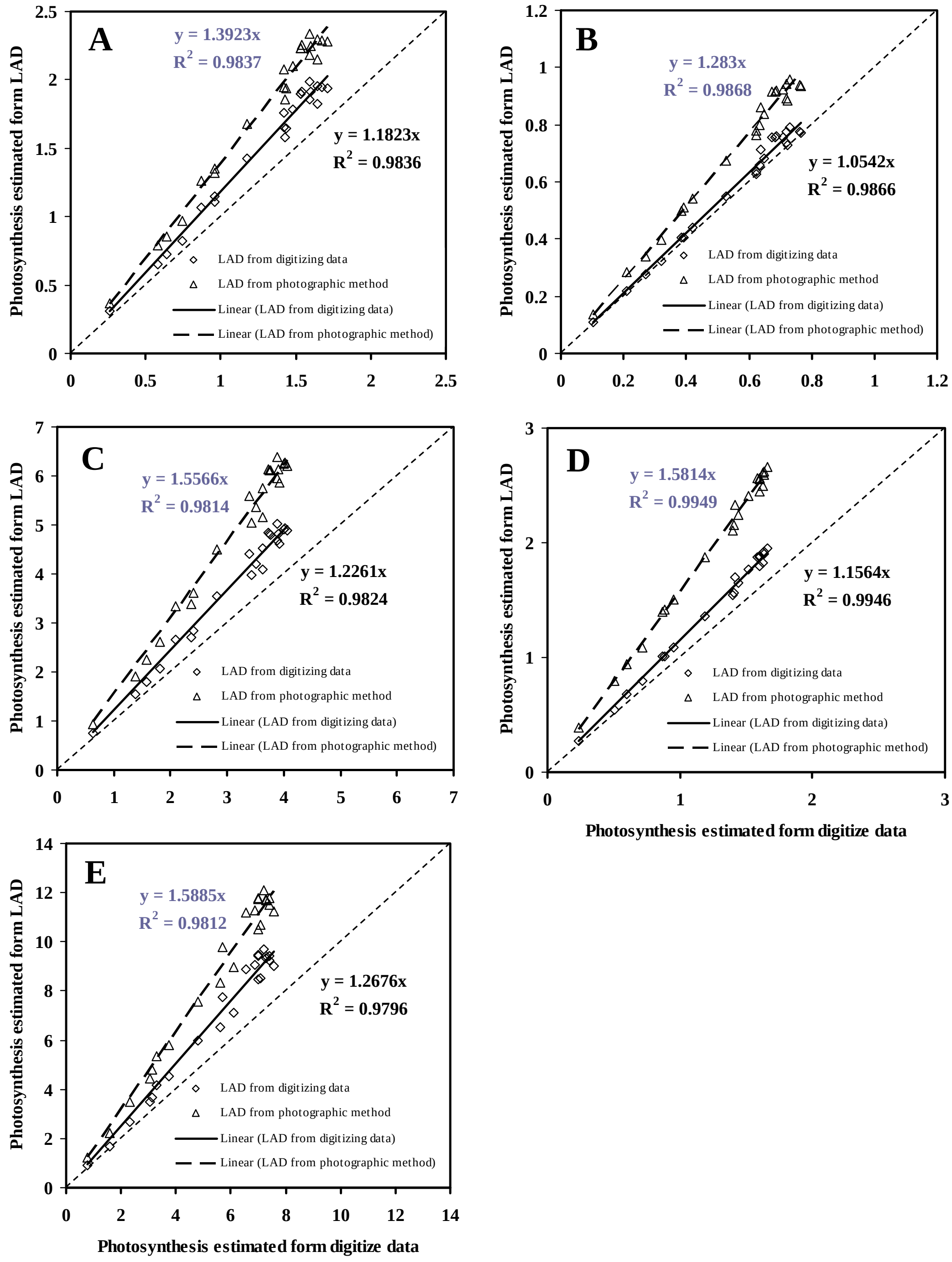

Figure 36 Comparison of photosynthetic rates (gCO_2/h) of canopy during daytime estimated by RATP model using digitising data, LAD calculated from digitising data (square), and LAD estimated from photographic method (triangle), of 2-year-old RRIM600 plant 1 (A) and plant 2 (B), 2-year-old RRIT251 plant 1 (C) and plant 2 (D), and 3-year-old RRIM600 (E).

CONCLUSION AND RECOMMENDATION

Conclusion

Photographic method can be used to estimate canopy structure parameters of rubber tree (i.e. canopy height, diameter, volume, total leaf area, vertical profile of leaf area and spatial distribution of leaf area). The method using digital photographs has been tested with real photographs compared with 3D digitised plants with newly developed equipments. Satisfactory estimation of canopy dimension, canopy volume, total leaf area and spatial distribution of leaf area has been found by using a set of eight photographs taken around the tree from the main horizontal directions (N, S, E, W, NE, NW, SE and SW direction).

Advantage of this method is a fast and non-destructive method which allows following canopy structure of the individual tree canopies under field condition. Spatial distribution of leaf area provided by this method can be used for plant modeling, e.g. RATP model (Sinoquet *et al*., 2001). However, in order to improve calculation of rubber plant geometry, further field experiment may be needed for fine tuning of the algorithms. In addition, for field application, real tree photographs need to be able to separate tree vegetation pixels from picture background (Mizoue, 2001), as in processing fisheye photographs (e.g., Frazer *et al*., 2001).

The RATP model showed a satisfactory simulation of diurnal photosynthetic rate at canopy scale of young rubber tree. The model RATP simulates correctly the maximum transpiration in absence water stress. The global model, the minimal function of both models included together can be used for the best result in any area for rubber tree.

Recommendation

The further study of model RATP comparing with real canopy photosynthesis in several tree ages and durations is needed. The development of photograph method to give a 3 dimensional leaf area density will improved the estimation of photosynthesis.

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CURRICULUM VITAE

NAME : Mr. Jate Sathornkich

BIRTH DATE : February 10th, 1978

BIRTH PLACE : Bangkok Province, Thailand

EDUCATION :

YEAR	INSTITUTION	DEGREE
2002	Mahidol University	B.S. (Plant science)
1999	Kasetsart University	M.S. (Botany)

POSITION : Researcher

WORK PLACE : Department of Horticulture, Faculty of Agriculture, Kasetsart University