ความสามารถในการดูดซับคาร์บอนไดออกไซด์ของต้นไม้ในจุฬาลงกรณ์มหาวิทยาลัย

นายชานนท์ สุวรรณมนตรี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาวิทยาศาสตร์สิ่งแวดล้อม (สหสาขาวิชา)
บัณฑิตวิทยาลัย จุฬาลงกรณ์มหาวิทยาลัย
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CARBON DIOXIDE ABSORPTION CAPACITY OF TREES IN CHULALONGKORN UNIVERSITY

Mister Chanon Suwanmontri

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science Program in Environmental Science
(Interdisciplinary Program)
Graduate School
Chulalongkorn University
Academic Year 2012

Thesis Title	CARBON DIOXIDE ABSORPTION CAPACITY OF TREES IN CHULALONGKORN UNIVERSITY
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ชานนท์ สุวรรณมนตรี : ความสามารถในการดูดซับคาร์บอนไดออกไซด์ของต้นไม้ในจุฬาลงกรณ์มหาวิทยาลัย. (CARBON DIOXIDE ABSORPTION CAPACITY OF TREE IN CHULALONGKORN UNIVERSITY) อ.ที่ปรึกษาวิทยานิพนธ์หลัก : ผศ.ดร.ชาญวิทย์ โฆษิตานนท์, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม : รศ.ดร.นพภาพร พานิช, 82 หน้า.

วิทยานิพนธ์ฉบับนี้เป็นการศึกษาเกี่ยวกับอิทธิพลของปัจจัยทางด้านสิ่งแวดล้อมที่มีต่อความสามารถในการดูดซับคาร์บอนไดออกไซด์ของต้นไม้ภายในจุฬาลงกรณ์มหาวิทยาลัยและเปรียบเทียบความสามารถในการดูดซับคาร์บอนไดออกไซด์ของต้นไม้หลักตามขนาดประชากรของต้นไม้ 4 ชนิด ได้แก่ ประดู่ จามจุรี นนทรี และหูกวาง ผู้ศึกษาใช้วิธี Chamber Analysis โดยใช้เครื่อง (Li-6400 Portable Photosynthesis System LI-COR Inc, USA) วิธีวัดแบ่งเป็น 2 แบบ คือ วัดใบไม้ใบเดียวซ้ำในหลายเวลา เพื่อดูการเปลี่ยนแปลงของการดูดซับคาร์บอนไดออกไซด์ในรอบวัน และวัดใบไม้หลายใบในหลายเวลา เพื่อหาความสัมพันธ์ระหว่างปัจจัยภายนอกกับความสามารถในการดูดซับคาร์บอนไดออกไซด์ ผลการศึกษาพบว่าในการวัดแบบใบเดียวซ้ำกัน อัตราการดูดซับคาร์บอนไดออกไซด์ของต้นไม้ทุกชนิดเปลี่ยนแปลงตลอดวันไปตามสภาพอากาศที่ผันผวน เมื่อนำผลการทดลองแบบหลายใบมาสร้างสมการถดถอยแบบไม่ใช่เชิงเส้นทำให้เห็นได้ชัดว่า ความเข้มของแสง (light intensity) เป็นปัจจัยที่มีอิทธิพลมากที่สุดต่อความสามารถในการดูดซับคาร์บอนไดออกไซด์ ของต้นไม้ชนิดหลักทุกชนิด เมื่อเปรียบเทียบกับปัจจัยความเข้มของแสง ปรากฏว่า นนทรี และ จามจุรีมีค่าการดูดซับคาร์บอนไดออกไซด์สูงสุดอยู่ที่ 24.5 CO_2 µnol $m^{-2}s^{-1}$ และ 20.5 µmol $m^{-2}s^{-1}$ ที่ความเข้มแสง 1100 photon µmol $m^{-2}s^{-1}$ และ 1650 µmol $m^{-2}s^{-1}$ ตามลำดับ ในขณะที่ประดู่และหูกวางนั้นไม่พบจุดสูงสุดภายในขอบเขตข้อมูล นอกจากนี้การวิเคราะห์การดูดซับคาร์บอนไดออกไซด์เฉลี่ยด้วยความเข้มแสงเฉลี่ยรายชั่วโมงสามารถสรุปได้ว่า นนทรีเป็นพันธุ์ไม้ที่มีความสามารถ ดูดซับคาร์บอนไดออกไซด์สูงที่สุดในจุฬาลงกรณ์มหาวิทยาลัยในช่วงฤดูฝน

สาขาวิชา ชานนท์ สุวรรณมนตรี ลายมือชื่อนิสิต

ปีการศึกษา 2555 ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก

ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์ร่วม

5487122020 : MAJOR ENVIRONMENTAL SCIENCE
KEYWORDS : CARBON DIOXIDE ABSORPTION / NON-LINEAR REGRESSION / PHOTOSYNTHETICALLY ACTIVE RADIATION

CHANON SUWANMONTRI : CARBON DIOXIDE ABSORPTION CAPACITY OF TREES IN CHULALONGKORN UNIVERSITY. ADVISOR : ASST. PROF. CHARNWIT KOSITANONT, Ph.D., CO-ADVISOR : ASSOC. PROF. NOPPAPORN PANICH, D.Eng., 82pp.

This paper studies how major environmental factors affect carbon dioxide absorption rates of common trees in Chulalongkorn University (Thailand). The carbon dioxide (CO_2) absorption capacity among the 4 most abundant tree species -- *Pterocarpus indicus*, *Samanea Saman*, *Peltophorum pterocarpum*, and *Terminalia Catappa* were compared. Measuring CO_2 absorption was done by chamber analysis approach, using Li-6400 Portable Photosynthesis System (LI-COR Inc., USA). Two kinds of measurements that are 1-leaf measurement, gauging the same leaf many times, and multiple leaf measurement, gauging many leaves many times were carried out. Multiple leaf measurement results were used to form models explaining relations between external factors and CO_2 absorption. Based on all-day 1-leaf data, CO_2 assimilation rates of each species were fluctuated all day in different patterns. The fluctuation was due to unstable weather. According to the models, it is obvious that light intensity (Photosynthetically Active Radiation) is the most influential factor to CO_2 absorption for all studied species. *P. pterocarpum* and *S. saman* reach their maximum CO_2 uptake rate of 24.5 µmol $m^{-2}s^{-1}$ and 20.5 µmol $m^{-2}s^{-1}$ when the photoactive radiation is 1100 µmol $m^{-2}s^{-1}$ and 1650 µmol $m^{-2}s^{-1}$ respectively. The others do not reach their maximum rate within model data range. On account of studied light intensity and plant species, it is concluded that *P. pterocarpum* gave the highest CO_2 absorption in Chulalongkorn University during rainy season.

Field of Study : Environmental Science Student's Signature
Advisor's Signature
Academic Year : 2012 Co-advisor's Signature

ACKNOWLEDGEMENTS

It is a great pleasure to thank persons who made this thesis possible. To begin with, I am cordially grateful to Dr. Uthai Cenpukdee, the external examiner; Assistant Professor Dr. Art-ong Pradatsundarasar, the thesis committee chairman; and Assistant Professor Dr. Naiyanan Ariyakanon, the internal examiner, for sharing their time to review and to give insightful comments in this thesis. I would never have been able to graduate without my advisor -- Assistant Professor Dr. Charnwit Kositanont -- who accepted my research topic with thousands of ideas and helps, who has been caring and being patient than any other professors to instruct me, who are from social science discipline, in doing science research. Likewise, I own my sincere gratitude to my co-advisor, Associate Professor Dr. Noppaporn Panich, who taught me deeply in science modeling, who was always available to give valuable advices and even to cheer me up whenever I faced difficulties. I could not imagine having better advisor and co-advisor at all. Besides, I am deeply grateful to Associate Professor Dr. Charuma Ashakul who taught me excellently in Quantitative Analysis. I am indebted to Assistant Professor Dr. Boonthida Kositsup and Mr. Taveewat Chantavee for teaching me how to use the instrument. I am also indebted with Associate Professor Dr. Boonchai Stitmannaithum for providing me the campus tree map and information. I am particularly thankful to Associate Professor Dr. Somjai Pengpreecha, the program committee chairman, together with Miss Sunantha Chatthaiwathana (program assistant), for supporting me entering the program, and letting me prove that I could accomplish the master degree as the science graduates do.

I would like to thank all of my teachers until now that contributed to my enlightenment, and all of my dear friends for sharing me good times and bad along the whole school life. I would also like to thank my sister, Pichayanun Suwanmontri, and my aunt Vipavee Boonyaprasit, who always take care of me and be my inspiration.

Above all, I would like to devote all benefits deserving this master degree to my mother, Sireemas Suwanmontri, and my father, Dr. Montri Suwanmontri, and dedicate my utmost gratitude to them who gives me a wholesome life with continuous support and encouragement.

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CHAPTER I

Introduction

1.1 Rationale

Environmental problems are such a threat that people all over the world should have been concerned. While high technology keeps on in a fast pace, natural resources have been continuously exploited more and more seriously since industrial revolution. Emitted pollution from human’s daily activities results in environmental impact leading to problems of their own health.

There are many kinds of byproducts released by human, such as sewage, heat, noise, vibration, and toxic chemicals. Though carbon dioxide (CO_2) is a natural component of air, it is considered as a critical factor similar to pollutant as its concentration in the atmosphere has been increased by 39 per cent (from 280 parts per million: ppm, to 388 ppm) comparing to its concentration at the beginning of industrial revolution (Wright and Boorse, 2011: 453). There is possibility of effects to human’s health if a person inhales air with carbon dioxide 426 ppm up for a long term; and the body may immediately effects in difficult breathing, high heart rate, headache, hearing, weariness, or even fainting, when one inhales carbon dioxide at 600 ppm or more (Robertson, 2006: 1607). In addition, carbon dioxide results in excessive greenhouse gases and global warming, scientists put much effort in decreasing carbon dioxide concentration in the air.

Carbon dioxide problem is likely to be more serious in urban area where population and human activities are in dense. In order to reduce concentration of carbon dioxide, CO_2-causing activities must be decreased; however, growing trees is another practical method as trees have capacity in carbon dioxide absorption. For the utmost benefit, it is necessary to do research in many species to find suitable ones for absorbing best in an area. Also, method of measurement should be standardized and reliable. These environmental concerns are the motivation of the author to conduct the research regarding carbon dioxide absorption capacity of trees in an academic leading university, Chulalongkorn University, one of the greenest places in Bangkok.

1.2 Objectives

1. To find relevance between carbon dioxide absorption rates of common tree species in the university and environmental factors, especially light.

2. To compare the carbon dioxide absorption capacity of common trees in the campus under environmental conditions.

1.3 Hypothesis

Light intensity is the most influential environmental factor in carbon dioxide absorption capacity of trees in the university.

1.4 Conceptual Framework

The general objective of this research is to study carbon dioxide absorption capacity of trees in the university; a wide conceptual framework can be illustrated as Figure 1 below. As can be seen from the Figure, carbon dioxide in the air comes from human activities (anthropogenic) and from nature itself. Plants take up and sequester some of that carbon dioxide and let the other remain in the atmosphere. Thus, the concentration of carbon dioxide in the air depends on absorption capacity of trees. Still, the absorption ability depends on species of plants. Due to their own characteristics, they absorb carbon dioxide differently in response to environmental conditions, or even to the same condition. This research, hence, studies how environmental factors affect carbon dioxide absorption of plants in various species, and form mathematical models explaining it.

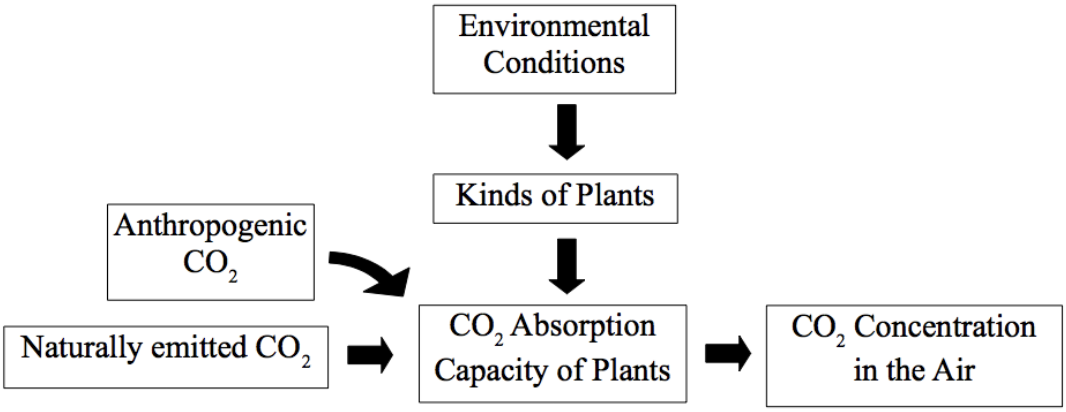

Figure 1 The conceptual framework

1.5 Scope of Research

Since it is not easy to collect all data of carbon dioxide uptaken by and emitted from every single plant, it is so necessary to scope the research and pinpoint some assumptions. Target plants are trees in the university, with at least 130 centimeters height; others such as grasses, epiphytes, mosses, or algae, are not included. The representatives of overall trees in the campus are common tree species found by real survey. The common species, in terms of ecology, refer to species with higher abundance relatively to the others. As for reference time period, the carbon dioxide absorption experiment is held during June and July, 2012, which the weather is unstable in the middle of rainy season. This study assumes that light transmissibility of leaves is near zero. It is also assumed that there are water and nutrients in the soil much enough for plants.

1.6 Anticipated Benefits

1. To be able to develop applicable mathematical models presenting carbon dioxide absorption of trees.

2. To be applied for further research in environmental science, environmental economics, and other studies in solving environmental problems.

CHAPTER II

Literature Review

2.1 Review Introduction

It is commonly known that plants play a major role in sequestering carbon dioxide. Still, there are too many kinds of plants (algae and bacteria are always classified as plant), and each of them has their own capacities. Thus, estimating capacity of all kinds of plants is hard thing. A precise understanding in plant physiology, which will be used in this research, is necessary as well. Therefore in this review of literature, there are 3 parts: photosynthesis and its process, factors affecting photosynthesis rates, and three methods of measuring carbon dioxide absorption.

2.2 Photosynthesis and Its Process

Plants absorb carbon dioxide during their photosynthesis; it is, firstly, essential to know what the photosynthesis and its process are. There are many ways to define the word ‘Photosynthesis’, or 'Photosyntax'. Both words were proposed in 1893 by Charles Barnes (1858-1910), who defined the words as 'a biological process for synthesis of complex carbon compounds out of carbonic acid, in the presence of chlorophyll, under the influence of light' (Gest, 2002: 7). However, the word photosynthesis came into common while the latter one 'photosyntax' was left behind (Gest, 2002: 8). The biological process was accidentally discovered by Joseph Priestley, a renowned British chemist (1733-1804) as the discoverer of oxygen (UNESCO International Bureau of Education, 1994: 343). Priestley described his discovering way as 'a method of restoring air which has been injured by the burning of candles' (Bogorad, 1981: 256s).

There are 4 major components of photosynthesis - - photosynthetic pigments, light, carbon dioxide, and water (Chuanpis Daengsawas, 2001: 207). Photosynthetic pigments are pigments transferring absorbed energy from solar radiation to their electrons that then enter chemical reactions; they could absorb and use very broad types of radiation (Mauseth, 2003: 290). There are several kinds of photosynthetic pigments; to name but a few, Chlorophyll a, Chlorophyll b, and Carotenoids. Chlorophyll a is found in any higher plants; it is the essential pigment since the chemical reaction processes are conducted there (Chau Chinorak and Phannee Chinorak, 1998: 405). The others are regarded as accessory pigments because they absorb light spectra that Chlorophyll a does not and they cannot conduct the chemical reaction itself; in other words, they need to pass the absorbed light energy to Chlorophyll a (Mauseth, 2003: 292). In higher plants, including trees and shrubs, chlorophylls are contained in a cellular organ called Chloroplast. Chloroplast exists in every part of plants, but it is found the most in cells of leaf area named 'Mesophyll' (Chuanpis Daengsawas, 2001: 207). Light, or solar radiation, from 100 per cent, is absorbed by leaves about 80 to 85 per cent; yet it is practically used in photosynthesis just only 0.5 to 3.5 per cent (Chau Chinorak and Phannee Chinorak, 1998: 398). Not all kinds of radiations are absorbed by photosynthetic pigments. Chlorophyll a absorbs red light (especially 660 nm) and blue light (440 nm) very well and the other wavelengths only slightly (Mauseth, 2003: 292).

Photosynthesis can be divided into 2 main processes - - light-dependent reactions (or photochemical reactions) and light-independent reactions (or dark reactions) (Preecha Suwanpinij and Nonglak Suwanpinij, 2003: 134). In light reactions, light energy, absorbed by pigments, is used to form ATP (Adenosine Triphosphate); water molecules are cleaved and the transferred electrons are to change $NADP^+$ to NADPH (Raven, Evert, and Eichhorn, 2005: 121). Oxygen molecules are released at the end of these reactions (Preecha Suwanpinij and Nonglak Suwanpinij, 2003: 140). In dark reactions, the energy of ATP is used to link carbon dioxide covalently to an organic molecule, and the reducing power of NADPH is then used to reduce the newly fixed carbon atoms to a simple sugar (Raven, Evert, and Eichhorn, 2005: 121).

2.3 Factors Effecting Carbon Dioxide Absorption

Plants use carbon dioxide as an ingredient in photosynthesis; there is no doubt that any factor relevant to photosynthesis must impacts carbon dioxide absorption of plants. There are a lot of factors affecting photosynthesis; they can be divided into 2 main kinds : internal factors and external factors.

2.3.1 Internal factors

Internal factors refer to any factor affecting carbon dioxide absorption that is from plant itself. Important ones are: amount of chlorophyll in a leaf, leaf structure, and leaf distribution.

1. Amount of chlorophyll in a leaf: Chlorophyll is a major component of photosynthesis. Leaves with more dense chlorophyll conduct more light reactions. Leaves without chlorophyll, simply those lacking green color, cannot conduct photosynthesis (Chau Chinorak and Phannee Chinorak, 1998: 429).

2. Leaf structure: Leaves with different structure, namely amount of stomata, size of stomata, number and alignment of mesophyll, have different rate of photosynthesis (Chau Chinorak and Phannee Chinorak, 1998: 430). Stomata are cellular organ for gas exchanges; there is more opportunity to conduct photosynthesis with more stomata.

3. Leaf distribution: Trees have their own shading area and leaves are distributed by branches and stem. Plants with high percentage of leaf area per total shading area are implied to have more ability to absorb carbon dioxide, while plants with bad leaf distribution absorb less carbon dioxide. The calculation of leaf area by total shading area is called 'Leaf Area Index' (LAI). At any rate, it also depends on light transmissibility of leaves because the transmissibility directly relates to light absorption (Chuanpis Daengsawas, 2001: 207).

2.3.2 External factors

External factors refer to any factor affecting carbon dioxide absorption that is from the environment, not from the plant. Important ones are: light density, carbon dioxide in the atmosphere, temperature, water, nutrients in soil, and inhibitors.

1. Light intensity: Light is a set of electromagnetic waves, which are composed of extremely small particles, named 'photon' or 'quantum', and it travels at a constant velocity. However, what effects carbon dioxide absorption of trees is the density of light, varied by the time of day and night, the weather, etc. In the time with little or no light, plants need respiration rather than photosynthesis to sustain their lives, so the net carbon dioxide is negative. When light density increases, plants can conduct more photosynthesis, so that plants can absorb more carbon dioxide. The light-compensation point is a state that photosynthesis offsets respiration, meaning the net carbon dioxide becomes zero; the density of light at this point is based on kind of trees. When increasing concentration of photon flux reaches light saturation point, maximum photosynthesis occurs, so that carbon dioxide absorption reaches full capacity and begins leveling off (Taiz and Zeiger, 1991: 254). Respiration should also be considered even around noon. There is a lot of plant physiological research proving that plants use more oxygen and release more carbon dioxide for respiration under high light density than when in the dark. It is known as 'photorespiration', which is different from ordinary respiration since it occurs only in cells with green chloroplast on daytime (Sombun Techapinyoowat, 2005: 119). It is implied that under too much photon flux, there are more respiration, less photosynthesis, and less net carbon dioxide absorption.

There are still only a few pieces of research in Thailand studying about photosynthetic response curve (between Photon flux density and CO_2 assimilation) by using CO_2 analyzer. This paper is expected to result in photosynthetic response curves by dominant kinds of as a profile for future studies.

2. Atmospheric Carbon dioxide: Carbon dioxide, one of 4 main photosynthetic components, are claimed to be causes of the greenhouse effect, so the level of carbon dioxide concentration in the air is being concerned. In general, carbon dioxide concentration in the atmosphere is around 0.03% or 300 ppm of the total air (Sombun Techapinyoowat, 2005: 118). Nevertheless, it is claimed that the concentration level has been rising and has already reached 367 ppm in 1999. Leaves absorb carbon dioxide in 2 phase - - gas phase and liquid phase. In gas phase, carbon dioxide directly diffuses into stomatal pore, sub-stomatal cavity, the intercellular air spaces and into

chloroplast; then in the liquid phase, the remainder diffuses via water layer by wetting cell walls and continues through cytosol and the chloroplast proper (Taiz and Zeiger, 1991: 257). There is a trend of rising photosynthesis when level of carbon dioxide concentration rises; still there is also a CO_2 saturation point, meaning plants do not absorb more carbon dioxide from the point.

3. Temperature: Enzymes in the dark reactions are directly influenced by temperature, so appropriate temperatures are necessary for good carbon dioxide absorption. Temperature is a key to classify plants to C3 or C4. There was a study showing that photosynthesis of C4 plants remains constant with temperature due to low photorespiration, while photosynthesis of C3 plants plunges with temperature because of energy lost by photorespiration (Taiz and Zeiger, 1991: 262). Likewise, temperature influences stomatal conductance; high temperature drives stomata to close; leading to low gas exchanges (Lily Kaveeta et al., 2009: 127).

4. Water: Water, that is H_2O, is the source of electron for ATP and NADPH in light reactions. Without water, plants absolutely cannot photosynthesize and finally die. As mentioned earlier, water also helps leaves for carbon dioxide diffusion in liquid phase. Moreover, when plants do not get enough water, stomatal conductance becomes low so as to decrease transpiration. This implies less gas exchange and less carbon dioxide absorption.

5. Nutrients in soil: Any chemical substances used and utilized to form sugar molecules and cells are impact factors. Excluding carbon, hydrogen, and oxygen, which derive from carbon dioxide and water, essential elements, including without limitation, are nitrogen (for chloroplast), phosphorus (for ATP), potassium (as an enzyme catalyst), magnesium (for chlorophyll, and a cofactor of rubisco), manganese (for chloroplast membrane) (Lily Kaveeta et al., 2009: 128). Lack of nitrogen and magnesium in the soil causes leave colors (normally green) changes to be pale yellow called “chlorosis”, a condition with insufficient chlorophyll (Shaahan, El-Sayed, and Abour El-Nour, 1999: 340).

6. Inhibitors: Some chemicals inhibit functions of enzymes and electron in photosynthesis; to name but a few, triazines, anilides, bipyridylium, and diphenyl ethers (Lily Kaveeta et al., 2009: 129).

2.4 Methods Measuring Carbon Dioxide Absorption Capacity

There are a couple of methods to measure or to estimate carbon dioxide absorption capacity of trees. In this study, 3 methods, which are being widely used, are chosen - - conventional biomass approach, chamber analysis approach, and remote sensing approach. Note that the methods are chosen by interest, not by popularity or any ranking.

2.4.1 Conventional Biomass Approach

Biomass Method is an original method estimating amount of carbon dioxide sequestered in an ecological community. Seeing that plants keep the synthesized carbon into sugar molecules and they become net primary production of the ecosystem, the total weight of carbon dioxide sequestered has to be a portion of the weight of net primary production. Using conventional biomass method results data in term of carbon sequestration, weight of carbon kept in trees. Generally, the method starts with sample plot designs as a proxy of the entire study area. Optimal plot sizes and number depend on wideness and plant diversity of the site. Then the field survey is conducted, collecting information about kinds and dominant species, number and densities, and mensuration of plants in the randomized plots. After getting data, there are two ways to measure the primary productivity; one is to directly extract the plants and weigh the wood, the other is to apply tree allometric equations by using the collected mensuration. Most of the allometric equations come from previous studies using direct weighing; still the equations are usually for big trees, not for little shrubs or understorey.

Sontaya Jampanin and Nantana Gajaseni (2004) studied carbon sequestration assessment in forest ecosystems at Kaeng Krachan national park, Thailand. The main objective of this study was to estimate aboveground carbon sequestration of plants in the national park, which were scoped in mixed deciduous forest, dry evergreen forest, and primary hill evergreen forest. Each forest was randomly plotted and about 40 trees per plot were measured height biannually, then data of height were used to estimate the carbon sequestration of each forest via allometric equations - - equations of Tsutsumi et al (1983) for evergreen forests, and of Ogawa et al (1965) for the mixed deciduous forest (carbon factor is 0.5). The study of Ubonwan Chaiyo et al. (2011) were also to quantify carbon storage in aboveground biomass of mixed deciduous forest and dry dipterocarp forest in Ratchaburi province, Thailand; but trees were classified into 3 groups by level of height, and 4 plots per groups were randomized. The allometric equations used for each groups are different as well (carbon factor is 0.47).

The results of Sontaya Jampanin and Nantana Gajaseni (2004: 50) show that the highest aboveground carbon sequestration was accounted in primary hill evergreen forest as 129 $\pm$ 32.7 ton CO_2 / ha; aboveground carbon sequestration in mixed deciduous forest was 93.15 $\pm$ 4.31 ton CO_2 / ha; and aboveground carbon sequestration in dry evergreen forest was 37.13 $\pm$ 2.63 ton CO_2 / ha. The results of Ubonwan Chaiyo et al. (2011: 640) differs from the first one. The carbon sequestration of mixed deciduous forest in Ratchaburi is 43.22 ton CO_2 / ha with terrain slope 20 to 40 per cent, and 14.55 ton CO_2 / ha with terrain slope 0 to 20 per cent; while that of dry dipterocarp forest (terrain slope 0 to 20 per cent) is 27.94 ton CO_2 / ha. Totally the sequestration of mixed deciduous forest in Ratchaburi (sum of 43.22 ton CO_2 / ha and 14.55 ton CO_2 / ha) is 35.38 $\pm$ 4.31 ton CO_2 / ha less than the sequestration of the national park.

2.4.2 Remote Sensing Approach

Remote sensing, also called electro-optical remote sensing, is an innovation acquiring information about an object or scene without coming into physical contact with that object or scene (Shaw and Burke, 2011: 3). The sensor, which is a satellite, acquires electromagnetic energy from specified objects, so that different reflections are applied to classify kinds of objects. The principle idea of remote sensing approach is converting the sensed data to estimate net primary productivity of the study site and then calculating carbon sequestration similarly to conventional biomass approach. The difference to conventional one is to use satellite images instead of conducting field survey. Not all kinds of electromagnetic energy can be absorbed by plants; among colors of spectrum (or bands), chlorophyll in leaves strongly absorbs radiation in the red and blue wavelengths but reflects green wavelength (Aggarwal, 2003: 33). The reflecting electromagnetic energies are converted into pixels of brightness on a map. In bands of which chlorophyll absorbs, high brightness implies high photosynthesis, and respectively high carbon dioxide absorption. The brightness of pixels is converted to indices, which regression models are formed to estimate net primary productivity. It is necessary to use biomass records of previous studies to run the regression, meaning good estimation of the remotely sensed data requires a lot of conventional biomass studies.

Nuanprang Nuanurai (2004) studies and compares the estimations of aboveground carbon sequestration capacity both from real observation and remote sensing. The main objective was to compare the results of the aboveground biomass in 3 forests of Kaeng Krachan national park, Thailand: evergreen forests, mixed deciduous forest and dipterocarp, form the real observation and from the remote sensing and conclude the aboveground sequestration. The remotely sensed data are acquired from the satellite LANDSAT-5 (TM system) on 26th March 2004 and 1st March 2004, and the observed data are from designated plots in each forest: 30 x 30 m per plot, 60 plots for evergreen forests, 16 plots for mixed deciduous forest, and 10 plots for dipterocarp forest. The other example of papers using remote sensing technology is that of Cheng and Chen (2010). The research is to estimate carbon sequestration in Taipei forestland and its changes between year 1993 to 2000 by applying SPOT images taken on 25th December 1993 and 17th December 2007.

The differences between the two studies are different satellites and vegetation indices as representative of net productivity. (Nuanprang Nuanurai uses R, while Cheng and Chen use NDVI and SR). The study of Nuanprang Nuanurai (2004: 127) results varying carbon sequestration by kinds of forest. For those from real observation, the carbon sequestration was 29.31 ton CO_2 in dry dipterocarp forest, 34.26 ton CO_2 in mixed deciduous forest, and 103.85 ton CO_2 in dry evergreen forest. For those from remote sensing, the carbon sequestration was 29.32 ton CO_2 in dry dipterocarp forest, 34.27 ton CO_2 in mixed deciduous forest, 103.85 ton CO_2 in dry evergreen forest. Overall, there was no significant difference between estimating carbon sequestration by real observation and remote sensing. The results of Cheng and Chen (2010: 6) are that carbon absorption capacity of Taipei forest change 10.68 ton CO_2 / ha in 1993 11.87 ton CO_2 / ha in 2007.

2.4.3 Chamber Analysis Approach

Chamber Analysis is a method measuring absorption ability of trees in a very small spatial scale (units of time and space). A specific area of plants, or a chamber, is measured by using a CO_2 gas analyzer instantaneously. Size of chambers varies from a square meter on a leaf surface to the entire tree. In a minute chamber, there are some adaptive joint for gripping a leaf with a small hole. The small hole is usually covered by a very clear slim piece of plastic, meaning the leaf under measurement could reflect real light density. Real ambient air is pumped into the chamber, so that the leaf could be in the real ambient conditions, then the instrument measure the exchanged carbon dioxide. New models of photosynthesis analyzers, such as Li-6400 Portable Photosynthesis System, CIRAS-2 Portable Photosynthesis System, have many features measuring other parameters in the same time; e.g., temperature, relative humidity, vapor pressure, stomatal conductance. Whereas in a tree covering size chamber, a huge house of clear plastic is used to cover up the tree to control air ventilation (Light density inside depends on the transparency of the plastic). There are 2 opposite channels in the chamber, one for letting the real ambient air in, the other, or the exit, for letting the purified air out. The gas analyzer has to block up the exit to measure how much carbon dioxide is lost. The lost is implied as total carbon dioxide absorbed by the tree.

Sapit Diloksumpun, Phanumard Ladpala, and Jesada Luangjame (2004) studied and compared carbon dioxide uptake ability of 14 species, 6 families of trees in a mixed deciduous forest in Nakhon Ratchasima, Thailand. Using Li-6400 Portable Photosynthesis System (LI-COR Inc., USA), net CO_2 exchange rates of 10 leaves per tree, one tree per species, were measured during rainy season from 7.00 a.m to 6.00 p.m. Issara Pangsee (2009) also experimented carbon dioxide absorption ability of decorative gardens under normal ambient carbon dioxide concentration (370-309 ppm) and high concentration (400-600ppm) by using Li-7000 CO_2 Analyzer (LI-COR lnc., USA). There were 3 types of designated gardens: 100 per cent of lawn, 60 per cent of lawn with 40 per cent of ornamental plants, and 20 per cent of lawn with 80 per cent of ornamental plants and the experiment was conducted in November 2007 from 6.00 a.m to 6.00 p.m.

It can be seen from the study of Sapit Diloksumpun et al. (2004: 7) that there are different diurnal variations in different tree species. Maximum net CO_2 exchange rates ranges from 6.90 to 24.32 µmol $m^{-2}s^{-1}$, and the time of maximum photosynthesis was between 8.30 a.m. and 1.00 p.m. Teak ranks first in the average carbon dioxide absorption around 14.18 µmol $m^{-2}s^{-1}$ and Xylia ranks last around 3.58 µmol $m^{-2}s^{-1}$. It is also concluded that average transpiration and stomatal conductance affects the carbon dioxide absorption ability. While, the experiment of Issara Pangsee (2009: 34) results outstanding outcomes that at normal carbon dioxide concentration, the garden with 100 per cent lawn can absorb carbon dioxide at 32.8 µmol $m^{-2}s^{-1}$ maximum, which is more than the other two types. However, in the dawn at 6am, the 100 per cent lawn garden has negative carbon absorption at -13.6 µmol $m^{-2}s^{-1}$, before reaching the light compensation around 8.30 a.m.

2.5 Strengths and Weakness of Each Approach

In addition to understanding various methods measuring carbon dioxide absorption capacity of the tree, it is also essential to recognize strengths and weakness of the methods. Table 1 below analyzes strength and weakness of each methods concerning 4 points - - environmental friendliness, data precision, limitations, and economic costs.

Table 1 Strength and weakness of each method

Methods Criteria	Conventional Biomass	Remote Sensing	Chamber Analysis
Environmental friendliness	Destructive	Non-destructive (No guarantee)	No damage to leaf
Data precision	Up to size of study area and number of plots	Geographically precise	Real-time measurement
Economic Costs	Timely, cost of employment	Cost of Acquiring data	Instrumentation costs
Limitations	Obstructive terrains	Very dependent to surveys	Fragile instrument

Considering conventional biomass method, it is known as an environmentally bad approach, or destructive, because it requires cutting plants in the ecosystem, at least for understorey. The data precision of the method relies on how much the size of study area and how many sampling plots are. Conducting a field survey is sometimes timely and costs much due to employment. In order to form an allometric equation, it is necessary to cut trees, transporting them, and weighing; therefore it takes time and economic costs. Nonetheless, after decades of conventional biomass method, there have been so many allometric equations practical for various kinds of trees that necessity of cutting trees becomes less and less. There are some limitations on a survey, such as obstructive surveys.

Leaf Chamber Analysis is a very environmentally friendly method; gripping leaves with a joint is proofed that there is no harm to the trees. Moreover, many new models of gas analyzers are claimed to be able to measure parameters on real time. However, cost of the instruments is a big deal for researchers, some cost more than

80,000 USD (US Dollar) to provide. In addition, despite its powerful and complicated technology, gas analyzers are fragile although they are used in field works; for instance, it is not water-repellent.

Remote sensing from a satellite is a non-destructive method, still there is little research supporting that there is no impact to the environment. Strength of the method is that it is geographically precise, meaning that researchers are able to find an exact geographic location. As an investment on building and operating a satellite is very costly and there are many risks, acquiring a sensed data is very expensive. A marked limitation is that using remotely sensed data for estimating carbon sequestration requires adequate records of the study site. Areas without a survey cannot be used with remote sensing.

2.6 Review Conclusion

The carbon dioxide absorption occurs in photosynthesis, which effects environmental factors and internal characteristics itself. Each method is different from the others in concept, advantages and limitations. It depends on researchers' consideration choosing the most appropriate approach. In this thesis, due to readiness of the instrument and other materials, the Chamber Analysis method is applied to estimate carbon dioxide uptake capacity of trees in the campus.

CHAPTER III

Methods and Procedures

3.1 Overview of Methodology

In order to accomplish the objectives of the research, 5 steps below are required in this study.

1. Find secondary data about existing species of trees in the campus. This is done by requesting for a campus map of plant, authorized by the Office of Master Plan, Physical Resources Management, Cham Churi 5 Building, Chulalongkorn University. The map indicates kinds of plants and their locations in the campus.

2. Conduct a real survey to find 4 most common tree species and select as representatives of campus trees. Identifying common species considers number of their populations. (To be extended in Experimental Methods and Procedures part)

3. Prepare necessary equipment and carry out the carbon uptake capacity experiment. This experiment shows rates of carbon dioxide absorption of the common trees, along with data of actual environmental conditions. (To be extended in Experimental Methods and Procedures part)

4. Analyze the experimental results: compare the carbon absorption capacity between species. Applying statistical analysis software, models of carbon dioxide absorption are created. (To be extended in Data Analysis Methods and Procedures part)

5. Conclude the results and the hypothesis, and give policy recommendations.

3.2 Necessary Equipment

The followings are necessary tools and instruments to conduct the survey, and to gauge carbon dioxide uptake:

1) Li-6400 Portable Photosynthesis System, LI-COR Inc.: to measure photosynthetic rate in real time. The unit of measurement of carbon dioxide uptake is CO2 µmol $m^{-2}s^{-1}$

2) Chemical substances; e.g. Desiccant: used for the Li-6400

3) The arranged campus map of plant

4) Stationery: pens, papers for recording data, permanent marker pens

5) Ladder: for climbing up to the canopy

6) Waterproof: for protecting Li-6400 from rain and dust due to the rainy season

7) A compass: for tracking the direction of leaves and light

8) Wooden stick: for holding branches

9) Hot-Air Oven: for regenerating the chemical substances

10) An empty top-closed pail or bucket: to stabilize the

11) A camera: for taking pictures of trees and experiment procedure

12) A binocular: for zooming the canopy

3.3 Experimental Methods and Procedures

There are 2 types of experiment in this study - - the tree species abundance survey, and the carbon dioxide absorption capacity experiment - - conducted respectively.

3.3.1 Tree species abundance survey

The method is to survey trees with more than 130 centimeters height to find 4 most common species found in the campus. The survey is done by several steps:

1. Prepare tools used in the survey, such as the campus map of plant, pens, papers, a compass, and a binocular.

2. Zone the map, making it easier to survey and find the locations by counting the row from 1, 2, 3, and the column from A, B, C respectively. Note that zoning is not a plot random and is not for finding dominant species. As an example, the map below (Figure 2) illustrates how it is zoned.

3. Examine the trees in every single zone. First of all, check whether the trees are in good health or not, that is to say if each tree has complete stem, branches, and leaves. If a tree seems nearly dead, skip it without noting. Classify species of all trees in the zone, and then reckon the location of each tree by sight, based on its distance from a building. After finishing examining a tree, indicate its species name and its location on the map by using the first letter of its name referring to its species, a letter for a tree. Thus, all letters in the map should tell number of trees in every species and their positions. In case it is hard to determine what species they are, skip them without noting.

4. Count numbers all trees in each species, and rank species from the top most abundance. The first 4 species with highest abundance are selected as the common species, which are used in the carbon dioxide absorption experiment.

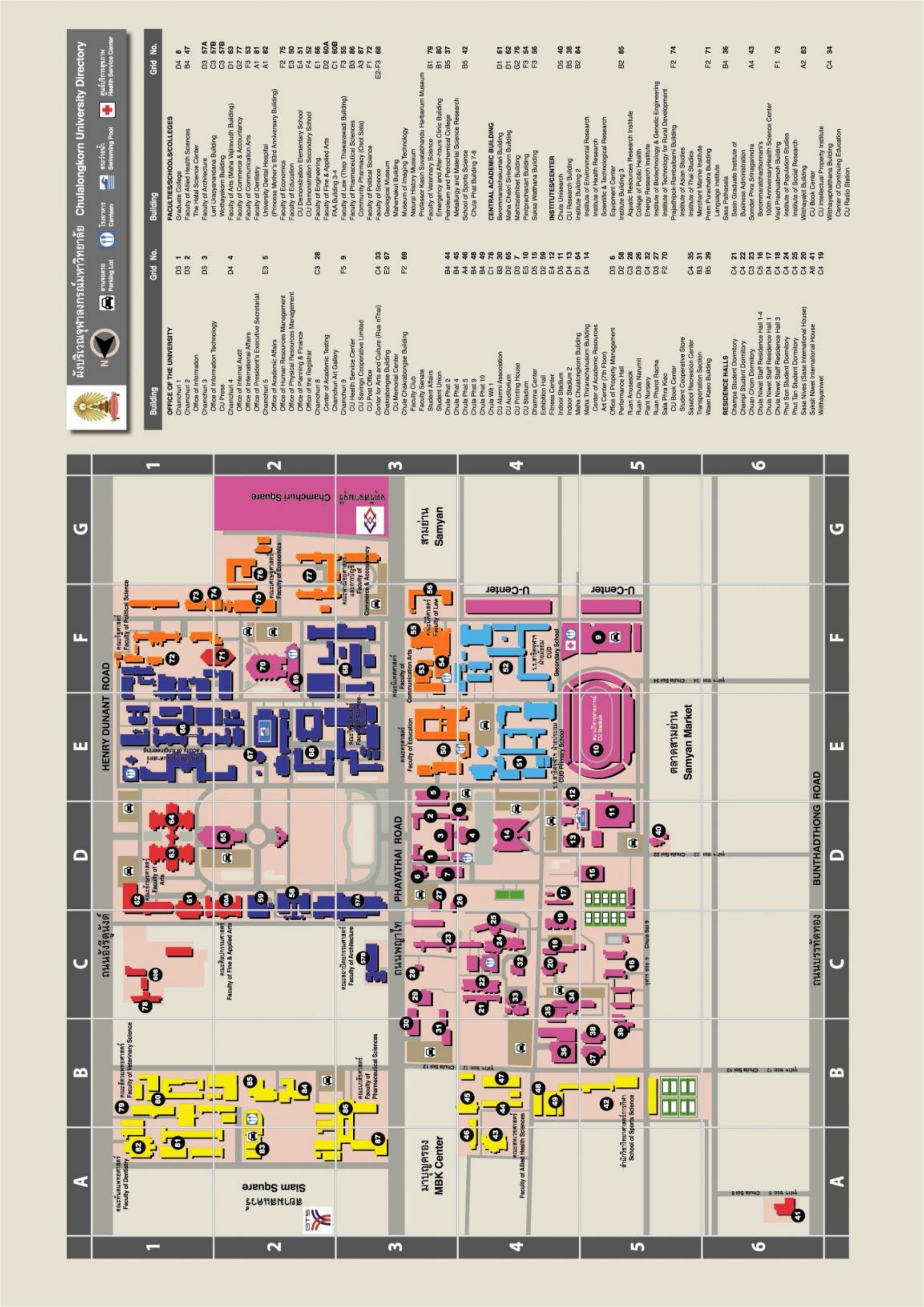

Figure 2 Zoning campus map

3.3.2 Carbon dioxide absorption experiment

There are 2 methods in the carbon dioxide absorption measurement:

1) 1-leaf measurement: is to measure the rate of carbon absorption of the same leaf, in the same tree, many times.

2) Multiple leaf measurement: is to measure the rate of carbon absorption of many leaves, in many trees, and many times.

1-leaf measurement shows how a leaf absorbs carbon dioxide in different time in a day; and the data from multiple leaf measurement should be used to analyze significant of environmental factors. The procedure of this experiment consists of 5 steps, which the two methods are conducted respectively.

1. Assemble the instrument, Li-6400, as follows:

- Sensor head: use 2 x 3 cm size chamber with latching handle.

- Chemical Substances: use soda lime for carbon dioxide absorber, and use drierite (W.A. Hammond Drierite Company) or simple silica gel for desiccant as it is not necessary to use any special function of Li-6400.

- Air supply: use natural air without damping carbon dioxide. Be suggested to use a top-closed bucket in order to let the air get in from time to time and simultaneously prevent over-fluctuation of variables.

- It is necessary to calibrate the Li-6400 every time turning it on. At least 2 things need to be calibrated:

1) Flow meter zero: to adjust the flow rate starting from 0 µmol s^{-1}.

2) IRGA zero: to adjust the sensor head reading concentration of CO_2 and H_2O in empty state. The soda lime tube is full-scrubbed for CO_2 concentration and the desiccant tube is full-scrubbed for H_2O concentration. In case any of the concentration values do not go to 0 µmol $m^{-2}s^{-1}$, zeroing function is needed.

- In 'New Measurement' menu, the functions are set as follows:

1) 'Flow': set the flow rate at 500 µmol s^{-1}, but it can be changed by situations.

2) 'Mixer': select MIXER OFF due to using natural air.

3) 'Temp': use the actual air temperature, so select 'OFF' (cooling).

4) 'Lamp': select 'PAROutµm', tracking real light density.

5) 'STOMRT': select 0 if leaf in that species has stomata on one side, select 1 if leaf in that species has stomata on both sides (ordinary).

- Always turn CO_2 scrubber tube and desiccant tube to full-bypass for the real CO_2 and H_2O concentration air-flow.

2. As the first round with 1-leaf measurement, measure the absorption of a leaf for each species from 8.00 a.m. to 5.00 p.m., one day for one species, at the beginning of each hour. Clip leaves by the sensor head, then hold about 2-3 minutes, the console shows variables instantaneously; to name a few, net carbon dioxide exchange rate (Photo: CO2µmol $m^{-2}s^{-1}$), stomatal conductance (Cond: H2O µmol $m^{-2}s^{-1}$), relative humidity (RH_R%: %), air temperature (Tair°C: °C), CO2 concentration in air (CO2R_µml: µml ml^{-1}) , photosynthetically active radiation (ParIn_µm: µmol $m^{-2}s^{-1}$). Save 2 observations per time. Seeing that the 1-leaf measurement focuses on how carbon dioxide absorption in a leaf changes in a day, local time of measurement is considered. The selected leaves as representative of a species should meet 4 qualifications:

1) The leaves are at canopy level.

2) The leaves directly get the sunlight without any shadow from other leaves or branches.

3) The leaves are in good shape and perfect - - no hole on the leaves.

4) The leaf age is not too old and too young; besides, they should be same size

on average to others.

3. As the second round with multiple leaf measurement, measure the absorption of the leaves of each species at the beginning of an hour, 7 hours a day - - 2 days for one species. Now that this measurement focuses on how carbon dioxide absorption of a species and environmental factors are related, local time of measurement is not considered. Measure at least 5 leaves per hour and save 2 observations per leaf. Also, select the leaves by permutation method from various trees and the leaves must meet qualifications as mentioned in step 2. Important variables of this measurement also consist of net CO_2 exchange rate, stomatal conductance, relative humidity, air temperature, CO_2 concentration in air, photosynthetically active radiation. At the end of this round, data of each variable should be collected at least 140 observations.

4. Seeing from the hypothesis that variable PAR is very important in data analysis, PAR data should vary from 50 µmol $m^{-2}s^{-1}$ to 1600 µmol $m^{-2}s^{-1}$. In case PAR data do not vary much enough, another round of measurement is needed. The measurement should be done with many leaves as step 4 (2 observations each) randomly to get various PAR data from 50 µmol $m^{-2}s^{-1}$ to 1600 µmol $m^{-2}s^{-1}$.

3.4 Data Analysis Methods and Procedures

3.4.1 Analysis of data from 1-leaf measurement

Analyze the data by graphical method. Pick up important variables in pairs and plot graphs; for example, plot net carbon dioxide exchange rates by time recorded from 8.00 a.m. to 5.00 p.m., plot environmental conditions e.g. PAR, temperature, CO_2 concentration by time. Then, compare differences of trends between species implying their behavior in response to the environment. Furthermore, determine which variable(s) affects most on carbon dioxide absorption of all species.

3.4.2 Analysis of data from multiple leaf measurement

For the multiple leaf measurement, use statistical techniques to analyze the data as follows:

1. Find a one-way relation between an influential variable (provided from 3.4.1) and the net carbon dioxide assimilation of each species by forming a regression model. According to the literature review, relations between external factors and carbon dioxide absorption are not likely to be linear; therefore non-linear regression models shall be formed. Since estimating coefficients of non-linear regression, especially those have natural number on their base, cannot be calculated manually, using statistical analysis software is the only way to do. This research uses statistical analysis software for estimating 5 non-linear regressions. The followings are 5 choices of regression equations:

a) Three-parameter hill function:

$$\hat{Y} = [\alpha X^{\beta}] / [\gamma^{\beta} + X^{\beta}] \quad ;$$

$\hat{Y}$ = estimated net CO_2 exchange rates

(dependent variable: CO_2 μmol $m^{-2}s^{-1}$)

X = the chosen external factor (independent variable)

α, β, γ = estimated coefficients

b) Three-parameter Logistic function:

$$\hat{Y} = [\alpha] / [\ 1 + (X/X_0)^{\beta}\ ] \quad ;$$

$\hat{Y}$ = estimated net CO_2 exchange rates

X = the chosen external factor

α, β = estimated coefficients

X_0 = X-intercept

c) Three-parameter Sigmoidal function:

$$\hat{Y} = [\alpha] / [\ 1 + e^{-\{(X-X_0) / \beta\}}\ ] \quad ;$$

$\hat{Y}$ = estimated net CO_2 exchange rates (CO_2μmol $m^{-2}s^{-1}$)

X = the chosen external factor

α, β = estimated coefficients

X_0 = x-intercept

e = natural number

d) Two-parameter Exponential Rise to Max function:

$$\hat{Y} = \alpha\,(1 - e^{-\beta X}) \quad ;$$

$\hat{Y}$ = estimated net CO_2 exchange rates (CO_2µmol $m^{-2}s^{-1}$)

X = the chosen external factor

α, β = estimated coefficients

e = natural number

e) Three-parameter Gaussian function:

$$\hat{Y} = \alpha\, e^{[-0.5\{(X-X_0)/\beta\}\{(X-X_0)/\beta\}]} \quad ;$$

$\hat{Y}$ = estimated net CO_2 exchange rates (CO_2µmol $m^{-2}s^{-1}$)

X = the chosen external factor

α, β = estimated coefficients

X_0 = x-intercept

e = natural number

2. Estimate coefficients of all 5 forms and use regression analysis techniques, such as Coefficient of Determination (R^2) to check their validity and to determine the soundest regression form as a model for each species. (The soundest model should be able to explain best about the relation.) Combined in one graph, compare models of all species to find out how much dependent their absorption to the factor is, and how different trends they have.

3.4.3 Analysis of data from 1-leaf and multiple leaf measurement

The data provided from both measurements can be used to determine which species could absorb carbon dioxide best based on an environmental condition. This is done by the following steps:

1. Find hourly average values of the most influential factor and create a graph with error bars.

2. Calculate total CO_2 absorption of each species in one day (from 8 a.m. to 5 p.m.). This is done by using the average value in every hour to estimate CO_2 absorption with the regressed models. Getting the hourly average CO_2 absorption, sum them up and convert the unit of time into 10 hours. The species with highest total 1-day absorption should be the most appropriate on assimilating CO_2 in rainy season.

3. Compare the total 1-day CO_2 absorption of 4 common species to conclude which absorbs carbon dioxide best based on the environmental condition.

CHAPTER IV

Results and Discussion

4.1 Results of Tree Species Abundance Survey

4.1.1 Campus map of trees

The campus map of plant diversity was provided from the Office of Master Plan, Physical Resources Management, Chulalongkorn University. The map presents information, as of September 2011, about 48 species names and their locations, as in Figure 4. Yet, the map do not contain information of all tree species, reported at 172 species (September 2011) by Plants of Thailand Research Unit, Faculty of Science, Chulalongkorn University. Also, tree distribution of the 48 species is not provided. As the reason, it is necessary to conduct a real survey for the information needed. The actual map is provided in the appendix.

4.1.2 The 4 common tree species

After surveying populations and distributions of trees based on the acquired map, it was found that *Pterocarpus indicus* was the trees species with highest abundance, at 399 trees. *Samanea saman* ranked second in population, found 329 trees, which are 70 fewer than *Pterocarpus indicus*. With 172 trees found, *Peltophorum pterocarpum* was the next species that has 157 lower abundance compared to *Samanea saman*. The other species surely had their own population less than 100 based on the survey. *Terminalia Catappa* was the only species with population near 100, namely 88, around 22 per cent of *Pterocarpus indicus*. Rank-abundance chart from the survey is shown in Figure 3.

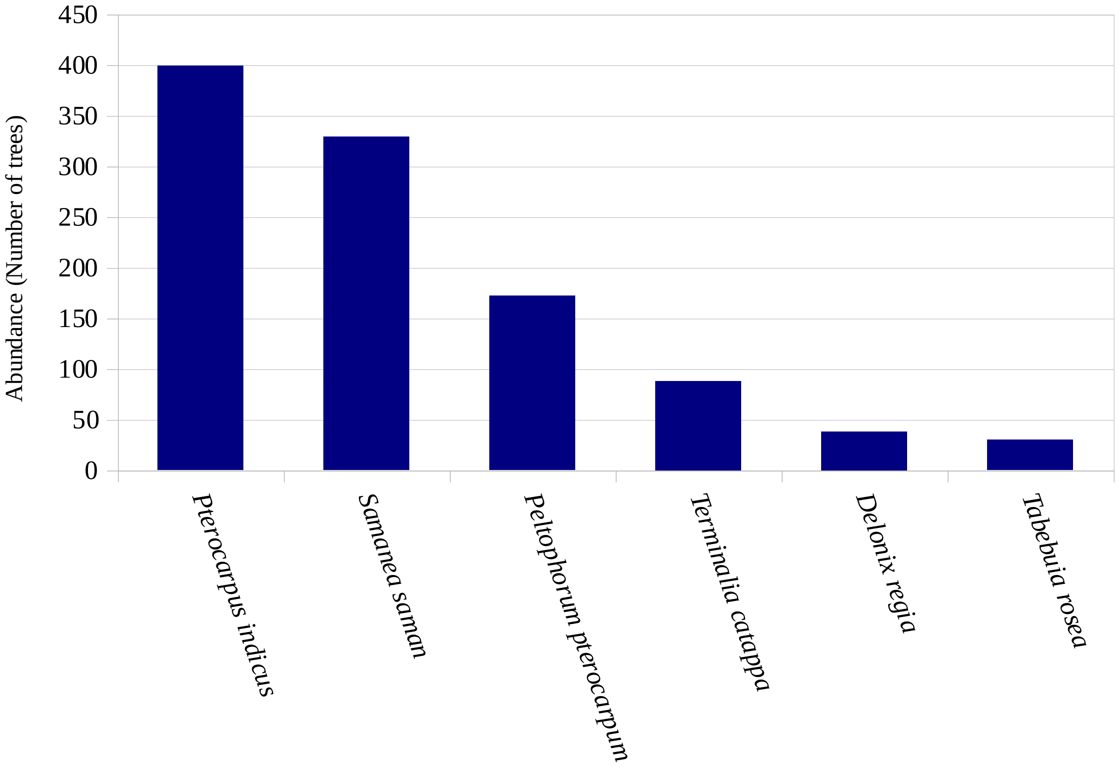

Figure 3 Tree species ranked by abundance

Figure 4 below illustrates how trees in each species were located using blue texts (Note that it does not present the locations of every single tree; otherwise, many of the marks would overlap each other). It can be seen that *Pterocarpus indicus, Samanea saman, Peltophorum pterocarpum,* and *Terminalia Catappa* can be found throughout campus. It was also found that many trees in the same species were located in group; for example, *Tabebuia rosea* gathered around the main pond, and *Lagerstroemia loudonii* were in a line along with the fence near the tennis courts. Thus, it is implied that the green area of the campus is a built-environment designed by human, not formed naturally. In short, *Pterocarpus indicus, Samanea saman, Peltophorum pterocarpum,* and *Terminalia Catappa* were selected as representatives of trees in the university, thanks to the 4 most common species.

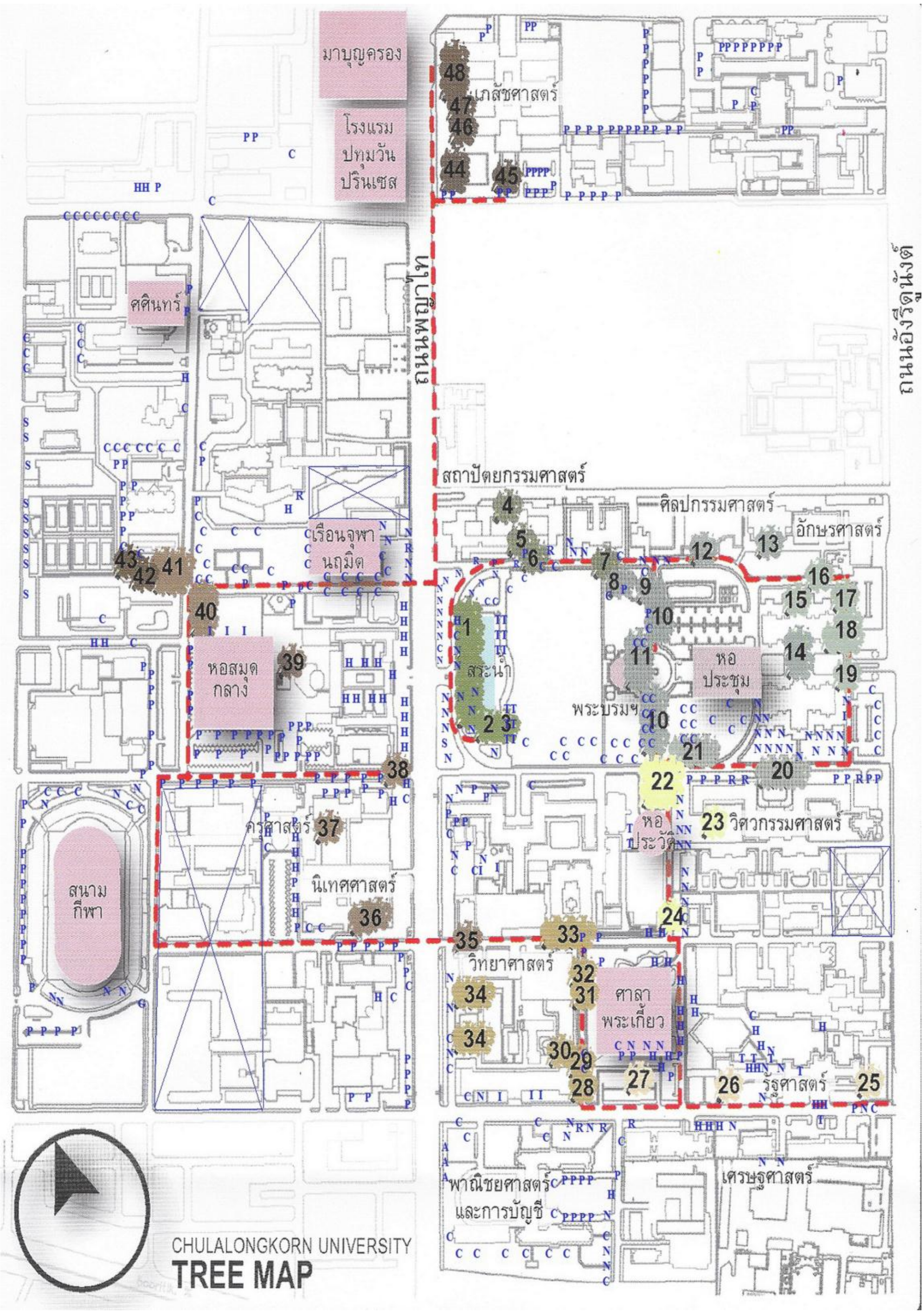

Figure 4 Detailed campus tree map

Note: C = *Samanea saman*, H = *Terminalia Catappa*, I = *Lagerstroemia speciosa*, N = *Peltophorum pterocarpum*, P = *Pterocarpus indicus*, R = *Delonix regia*, S =

Lagerstroemia loudonii, T = *Tabebuia rosea*

4.2 Results of 1-leaf Measurement

4.2.1 Carbon dioxide absorption rate of common trees

Gauged at the beginning of hour from 8.00 a.m. to 5.00 p.m., the carbon dioxide assimilation rates of the 4 species were as in Figure 5. According to the graph, *Peltophorum pterocarpum* had a maximum carbon absorption rate, higher than the others, at 24.25 µmol $m^{-2}s^{-1}$, as *Samanea saman* had 19.45 µmol $m^{-2}s^{-1}$ at 9 a.m. On the other hand, *Pterocarpus indicus* and *Terminalia Catappa* reached their peaks at much lower rates that were 12.35 µmol $m^{-2}s^{-1}$ and 11.55 µmol $m^{-2}s^{-1}$ respectively.

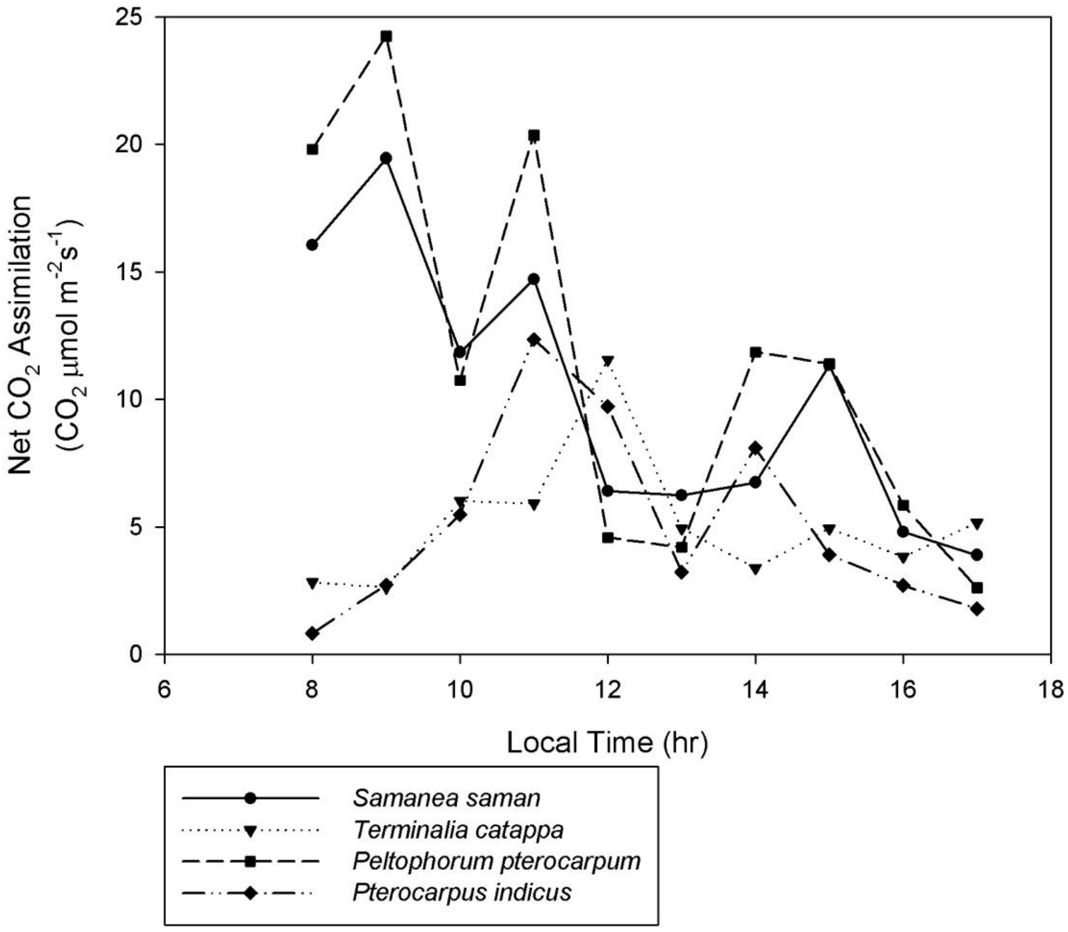

Figure 5 Diurnal CO_2 absorption of common species

Most of the common species had minimum absorption rates in late afternoon (5 p.m.). In addition to the maximum rates, there were fluctuations all day on carbon dioxide assimilation of every species in different patterns due to unstable weather in the rainy season. As the 4 species were measured on different days, there were several environmental factors such as light intensity, air temperature, and leaf temperature causing the fluctuations and different patterns.

4.2.2 Light intensity

Moving to the next Figure below (figure 6), it shows how light intensity, or photoactive radiation, changed from 8 a.m. to 5 p.m. The light intensity was very low from 8 to 10 a.m. on the day that *Peltophorum pterocarpum* and *Terminalia catappa* were collected, whereas there were much more light on the day of *Pterocarpus indicus* and *Samanea saman*. Highest light intensity was 1692 µmol $m^{-2}s^{-1}$ in a clear sky at 11 a.m. when *Pterocarpus* indicus was measured. Very low light intensity, about 10-200 µmol $m^{-2}s^{-1}$, refers to a complete overcast sky; this implies the reason why the two pairs absorb CO_2 differently more than 3 times in the morning. The sky was overcast all day long when *Terminalia catappa* was measured.

Mentioned above that the net CO_2 assimilation of the 4 species at 1, 4, and 5 p.m. were in same level, it is because the actual photoactive radiation was in the same range. In addition, it can be inferred from Figure 5 and 6 that light intensity should be an outstanding influential external factor.

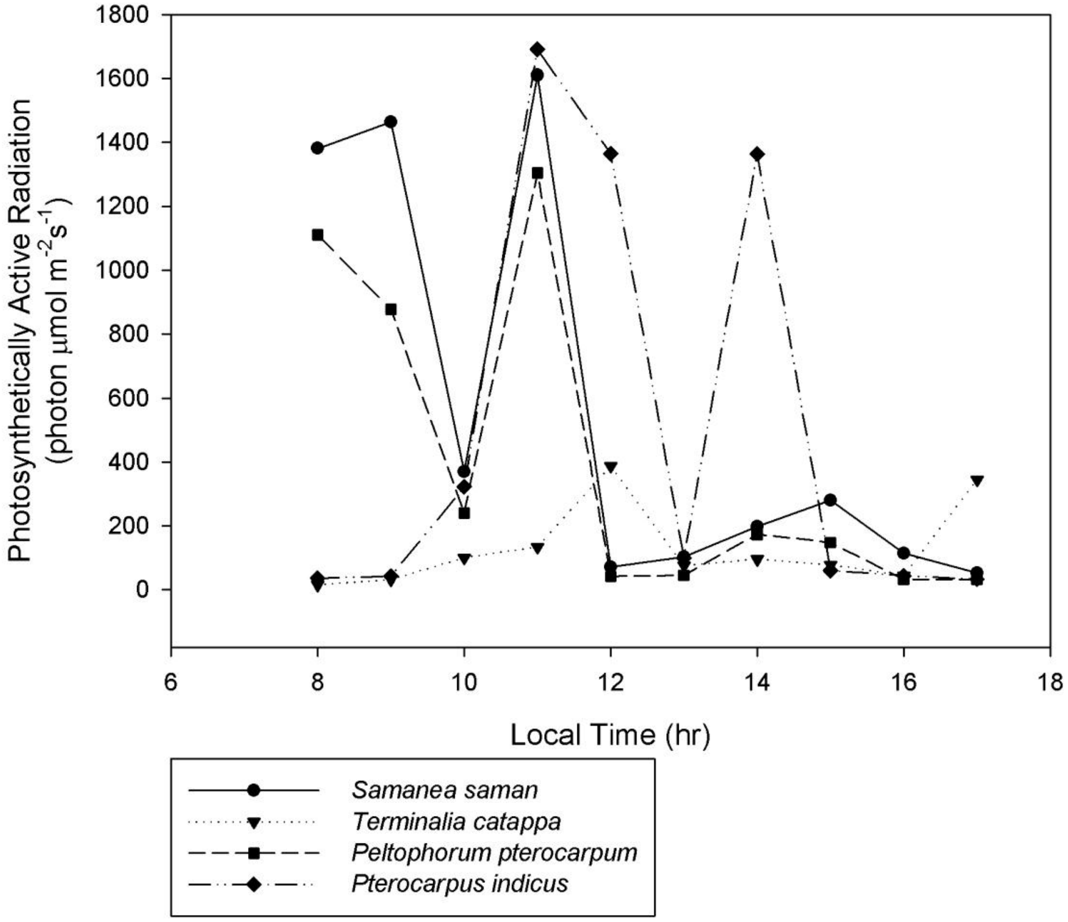

Figure 6 Actual light density on 1-leaf measurement

4.2.3 Carbon dioxide concentration in air

Considering CO_2 concentration in air, Figure 7 shows how the variable varies during daytime. It is clear that all 4 graphs had the same trends. The concentration was high, 403 ppm in average, in the morning (8 a.m.); then, it slightly decreased until around 2 p.m. After that, it increased again and reached its peak at 4 p.m., 414.5 ppm in average

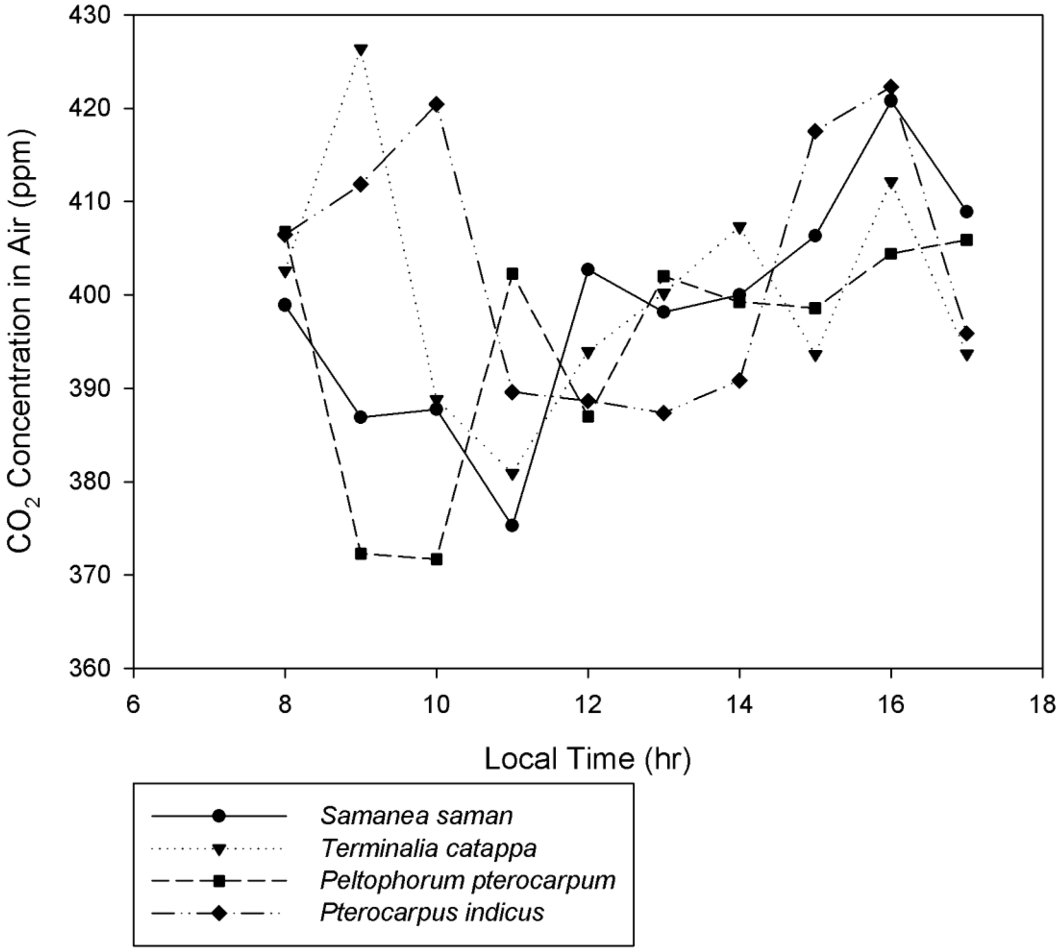

Figure 7 Actual ambient CO_2 concentration on 1-leaf measurement

The amount of carbon dioxide in the atmosphere partly comes from human respiration and human activities; hence, number of people walking in the campus and running automobiles should be a reason of the trend. Most of the students and staffs go inside the campus by walk and cars in the morning around 7 - 8 a.m., and leave the campus around 3 - 4 p.m. after classes finish. Another reason is that plants respire, taking oxygen and emitting carbon dioxide, during night due to no light, so the carbon dioxide concentration in the air would be higher early in the morning. Then, it would decrease around noon, along with photosynthesis, before increasing again at the time of sunset.

4.2.4 Air Temperature

Ambient air temperature is another environmental factor collected in the experiment. According to Figure 8, the air temperature at 8 a.m., 30.8°C – 31.9°C, was relatively low to other times of the day. The temperature tended to be higher in late morning, but it fluctuated after 11 a.m. Since it was in the rainy season, temperature did not go above 40°C and below 29°C. The highest one was 36.6°C at 2 p.m., while the lowest one was 29.9°C at 9 a.m. on *Pterocarpus indicus* measurement. *Samanea saman* and *Peltophorum pterocarpum* were collected on the same day, so their temperatures were in the same trend.

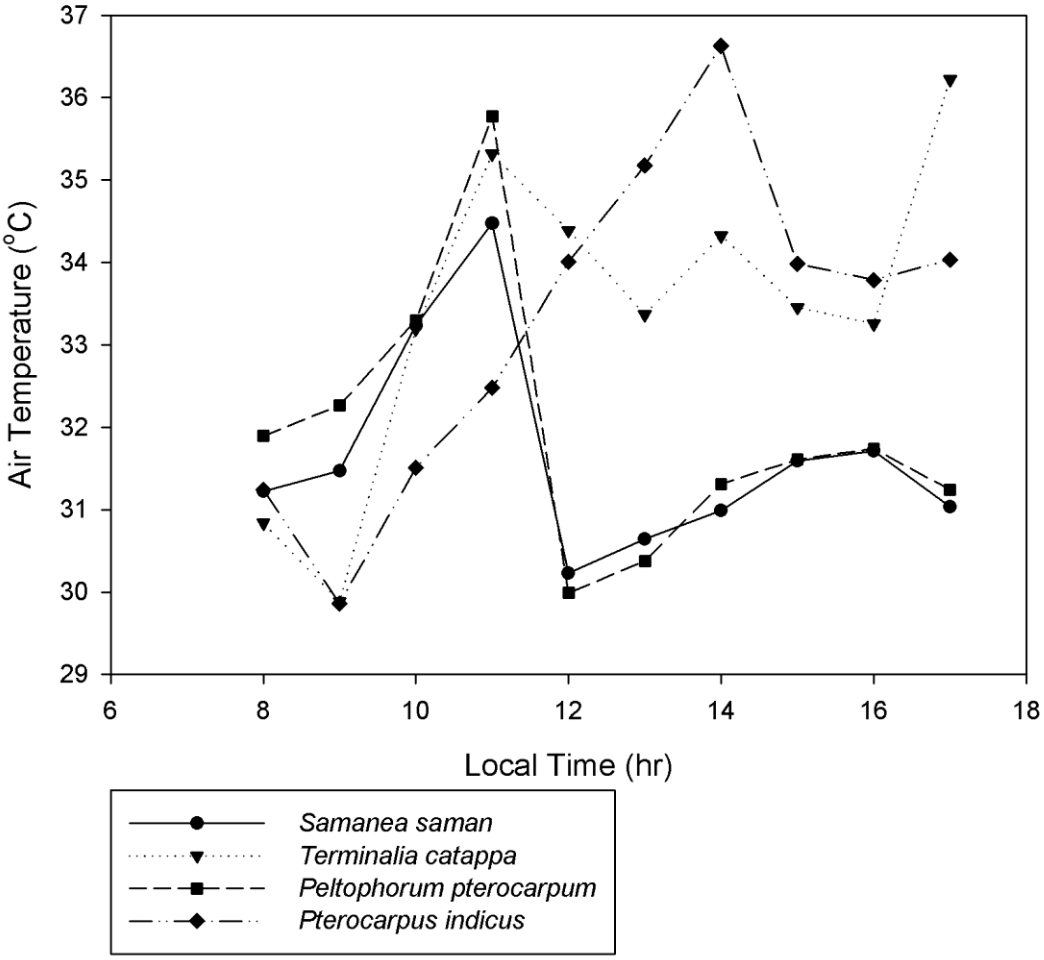

Figure 8 Actual air temperature on 1-leaf measurement

4.2.5 Leaf Temperature

In addition to temperature in the air, temperature on leaf surface should also be considered. As shown in Figure 9, leaf temperature varied from 29.6°C to 36.6°C as the same range as air temperature. Not only for the range, but leaf temperature of each species was also in the same trend as air temperature. Thus, the two variables should be dependent to sky conditions and kinds of air mass. Despite measuring at 12 a.m., the leaf temperature of *Samanea saman* and *Peltophorum pterocarpum* were below 30°C because the weather was completely overcast with moderately strong wind.

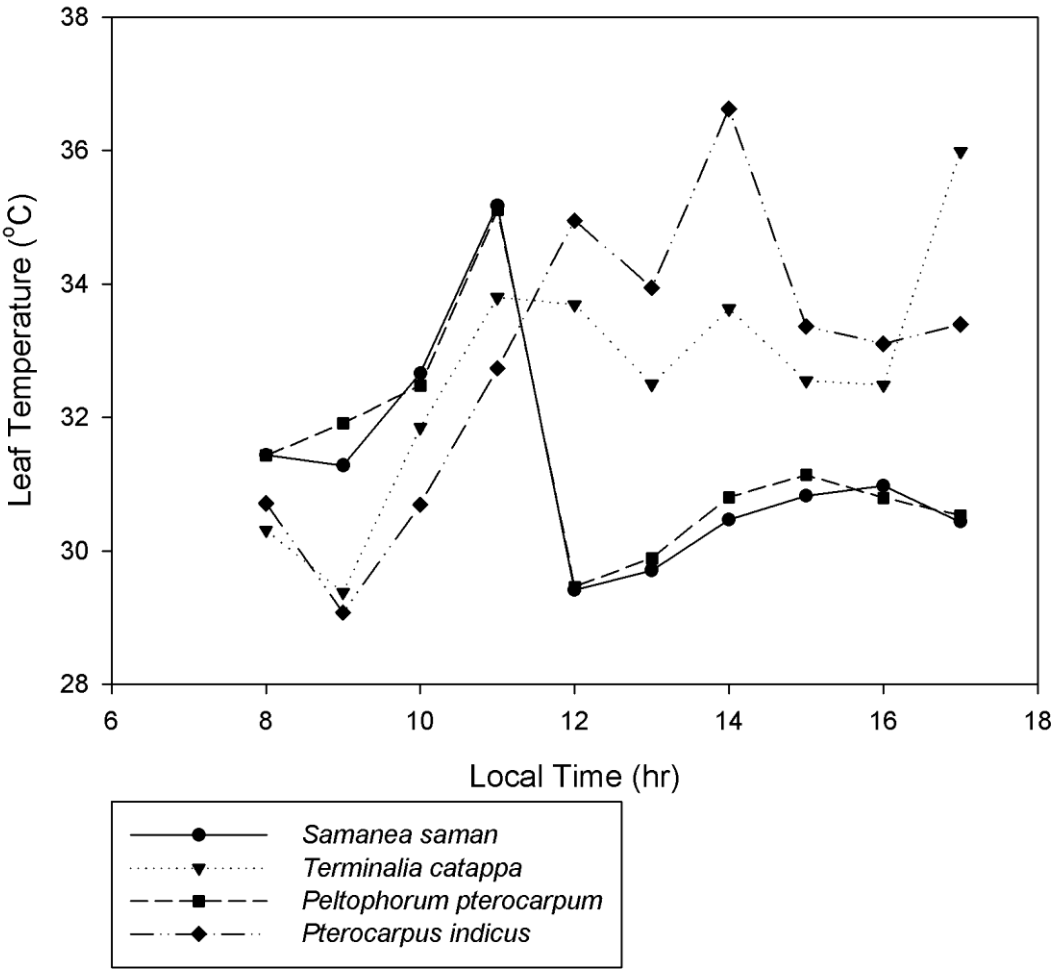

Figure 9 Actual leaf temperature on 1-leaf measurement

4.2.6 Relative humidity

The other environmental factor – relative humidity – is presented in Figure 10. At 8 a.m., the average relative humidity of all days of 1-leaf measurement was 60.2 per cent, which was higher than any other time of the day. The humidity sharply decreased after 8 a.m. until 11 a.m., before leveling off to around 45 per cent at the end of the day. Highest relative humidity from the 1-leaf measurement was 63.06 per cent, and the lowest one was 33.28 per cent. It can be seen that relative humidity changed in same direction most of the time.

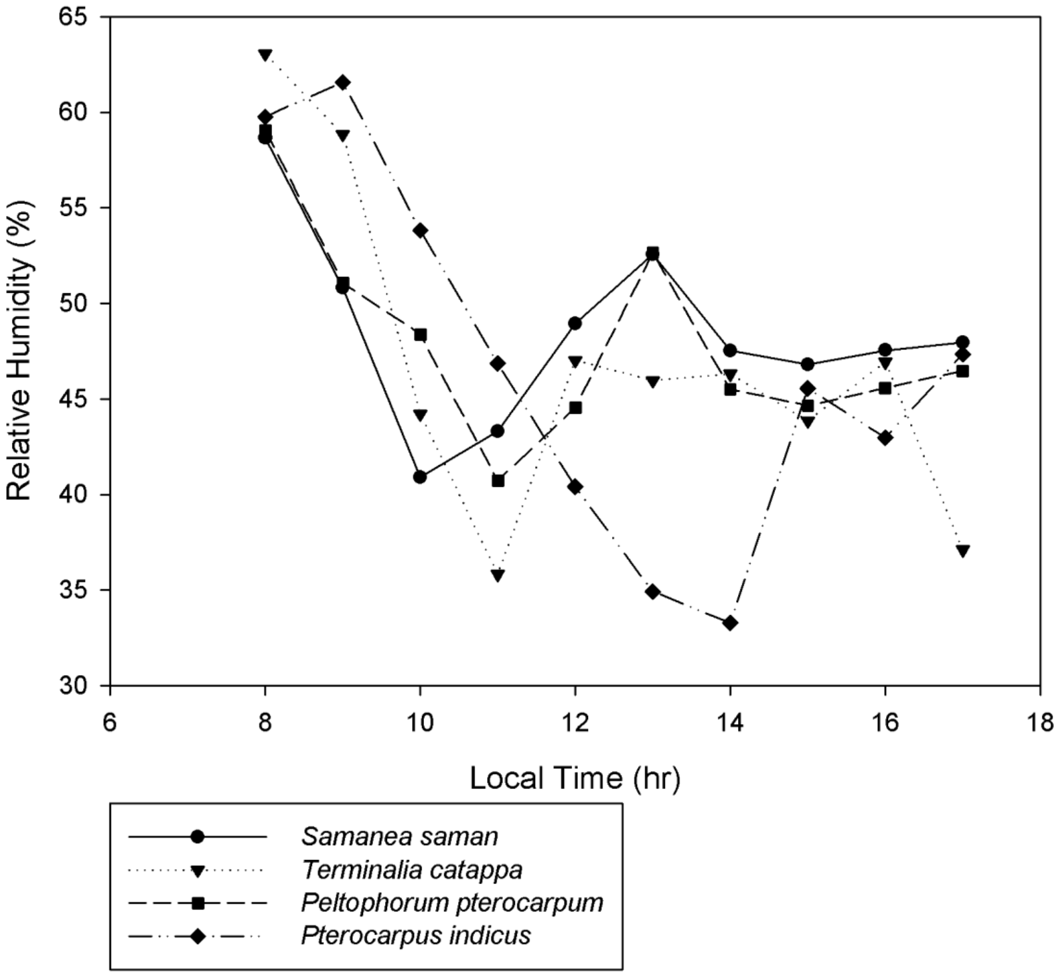

Figure 10 Actual relative humidity on 1-leaf measurement

All of the 1-leaf measurement data illustrate how the variables changed during the day and can be guessed which the significant environmental factors are. Still, comparing carbon dioxide absorption capacity between species and judging which one absorbs best needs many more observations with wide ranges of data from various leaves and trees. Multiple leaf data better deal with this comparison.

4.3 Results of Multiple Leaf Measurement

Data from the multiple leaf measurement were used to form non-linear regressions, in order to find relevance between each environmental factor and carbon dioxide absorption rates in a single species. Collected leaf measurement 7 hours a day and at least 5 leaves per hour, there were total 218 observations of *Samanea saman*, 252 of *Terminalia catappa*, 264 of *Peltophorum pterocarpum*, and 242 observations of *Pterocarpus indicus*. Among 5 choice functions, only 3-parameter gaussian and 3-parameter sigmoidal were chosen as most appropriate regression forms. The followings are results of forming regressions together with graphs.

4.3.1 Light intensity and carbon dioxide absorption

The photosynthetically active radiation (PAR) data, as independent variable, and carbon dioxide absorption rate, as dependent variable, were regressed using 5 functions – hill function, logistic function, Sigmoidal function, exponential rise to max function, and Gaussian function. The best fitted regression, one with highest R^2, for each tree species is shown in Table 2. According to the table, Sigmoidal function was chosen for *Samanea saman,* while Gaussian was chosen for the others. PAR data of *Peltophorum pterocarpum* was fitted with carbon dioxide absorption better than any other, seeing that the R^2 was 0.8926.

Table 2 Estimated coefficients and analysis of CO_2 absorption subject to PAR

Estimated Regression	*Samanea saman*	*Terminalia catappa*	*Peltophorum pterocarpum*	*Pterocarpus indicus*
Function	Sigmoidal	Gaussian	Gaussian	Gaussian
α	24.4604	23.5040	24.4406	24.1045
β	274.2606	1477.9279	623.9510	2133.7638
X_0	336.7547	2767.4333	1096.5999	4284.7937
r (correlation coefficient)	0.9210	0.8913	0.9448	0.9126
R^2	0.8482	0.7944	0.8926	0.8328
F statistic	600.9014	482.8708	1084.8112	597.72

F statistic measures how much the independent variable can explain the variation of dependent one. The 4 regressions above were done testing hypothesis as follows:

H_0: $\alpha = \beta = X_0 = 0$ (null hypothesis)

H_A: not all coefficients are zero (alternative hypothesis)

Determined Significant level (α) = 0.001

$F_{0.001} = 11.6$ when residual degree of freedom is around 200

The null hypothesis is rejected if calculated F > $F_{0.001}$

Now that none of the calculated F values was less than or equal to 11.6, the null hypothesis is rejected. It was concluded that photoactive radiation could explain the variation of carbon dioxide absorption. To clarify the estimation, a scatter diagram with fitted non-linear regression of *Samanea saman*, *Terminalia catappa*, *Peltophorum pterocarpum*, and *Pterocarpus indicus* are presented in Figure 11, 12, 13, and 14 respectively.

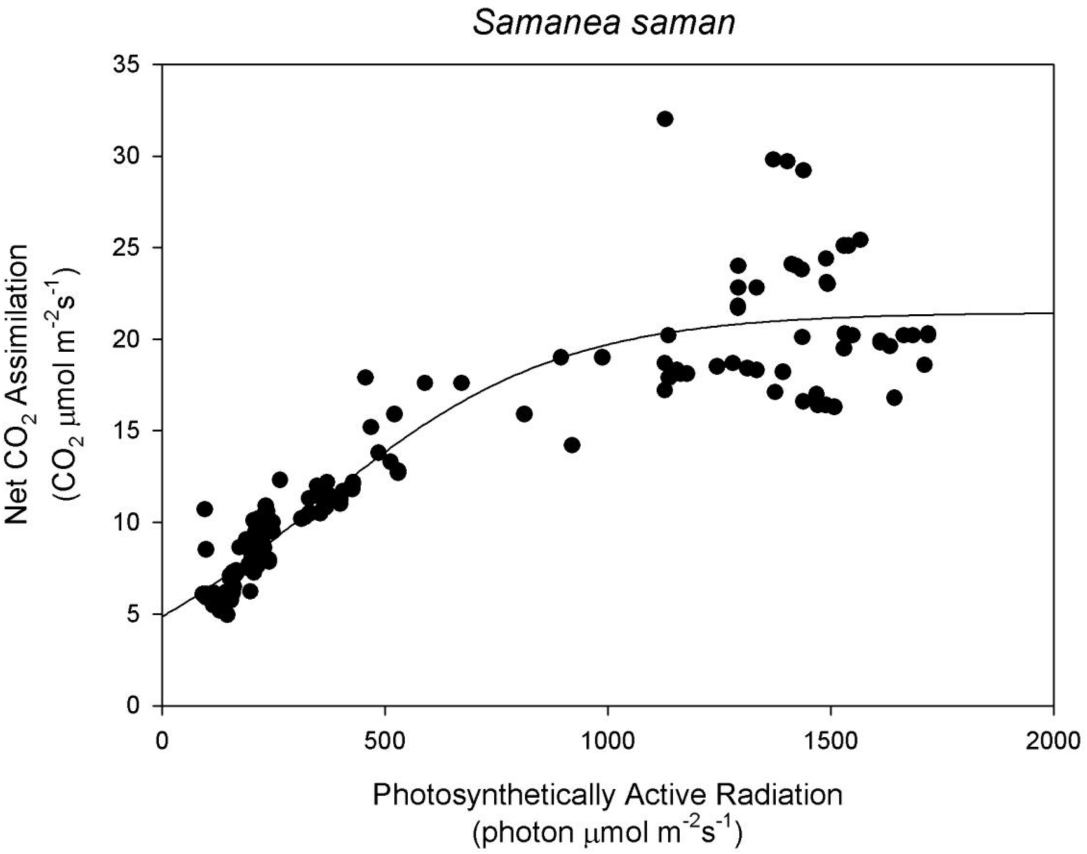

Figure 11 Scatter diagram with regression of PAR and CO_2 absorption of *Samanea saman*

Samanea saman constantly absorbs more carbon dioxide from 30 µmol $m^{-2}s^{-1}$ to around µmol $m^{-2}s^{-1}$. After 100 µmol $m^{-2}s^{-1}$, the absorption levels off to around 20 µmol $m^{-2}s^{-1}$.

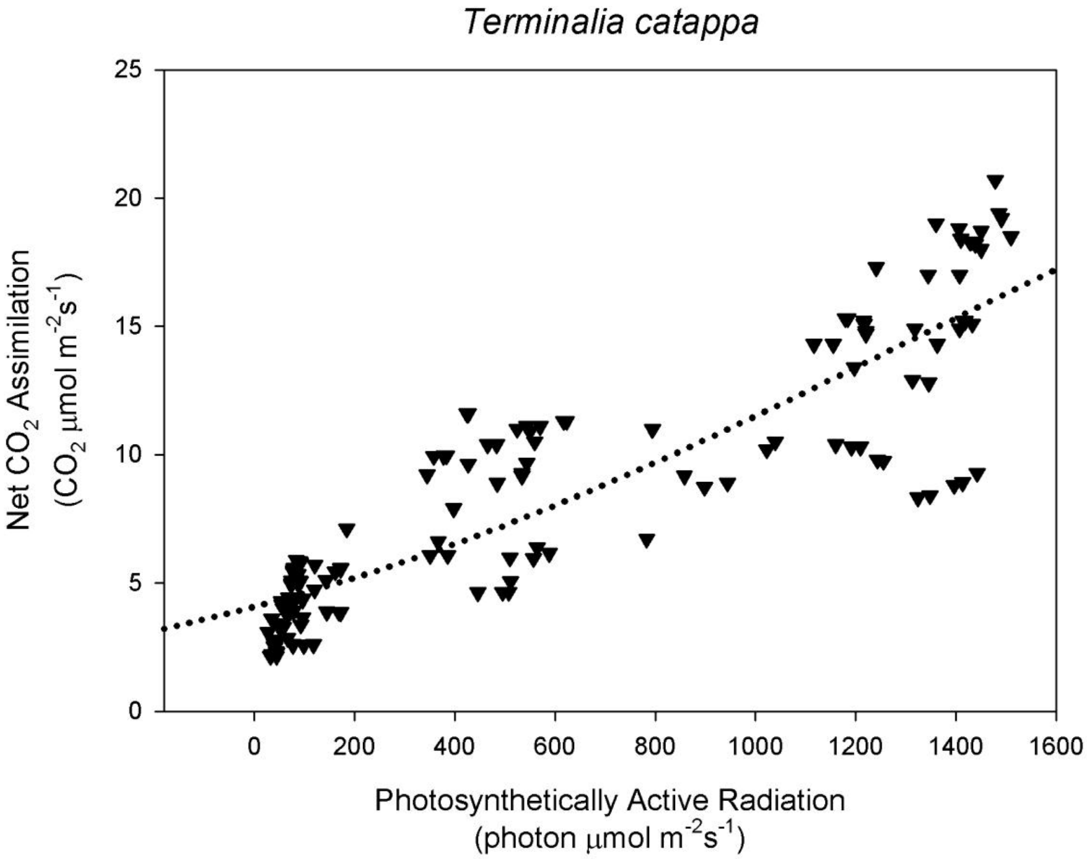

Figure 12 Scatter diagram with regression of PAR and CO_2 absorption of *Terminalia catappa*

The carbon dioxide absorption rate of *Terminalia catappa* when photoactive radiation is between 30 and 1500 µmol $m^{-2}s^{-1}$ has a moderately increasing trend. The estimated absorption rate is 4.2 µmol $m^{-2}s^{-1}$ at the beginning (PAR = 30 µmol $m^{-2}s^{-1}$) and is 15.9 µmol $m^{-2}s^{-1}$ under 1500 µmol $m^{-2}s^{-1}$ photoactive radiation.

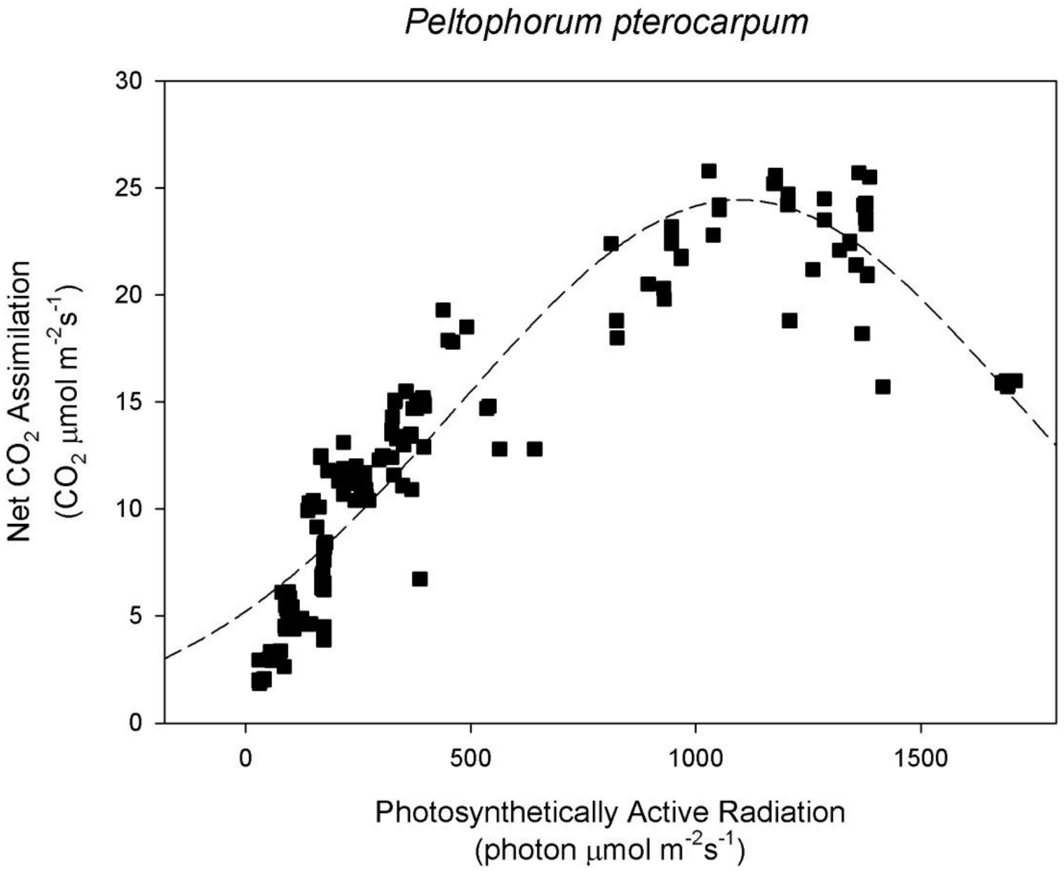

Figure 13 Scatter diagram with regression of PAR and CO_2 absorption of *Peltophorum pterocarpum*

The carbon dioxide absorption of *Peltophorum pterocarpum* sharply increases from below 5 µmol $m^{-2}s^{-1}$ to over 20 µmol $m^{-2}s^{-1}$ until photoactive radiation is around 800 µmol $m^{-2}s^{-1}$. After 800 µmol $m^{-2}s^{-1}$ PAR, the abosorption rate slightly increase before reaching its peak at 24.5 µmol $m^{-2}s^{-1}$ under 1100 µmol $m^{-2}s^{-1}$ PAR. There is a decline in carbon dioxide absorption when PAR is higher than 1500 µmol $m^{-2}s^{-1}$.

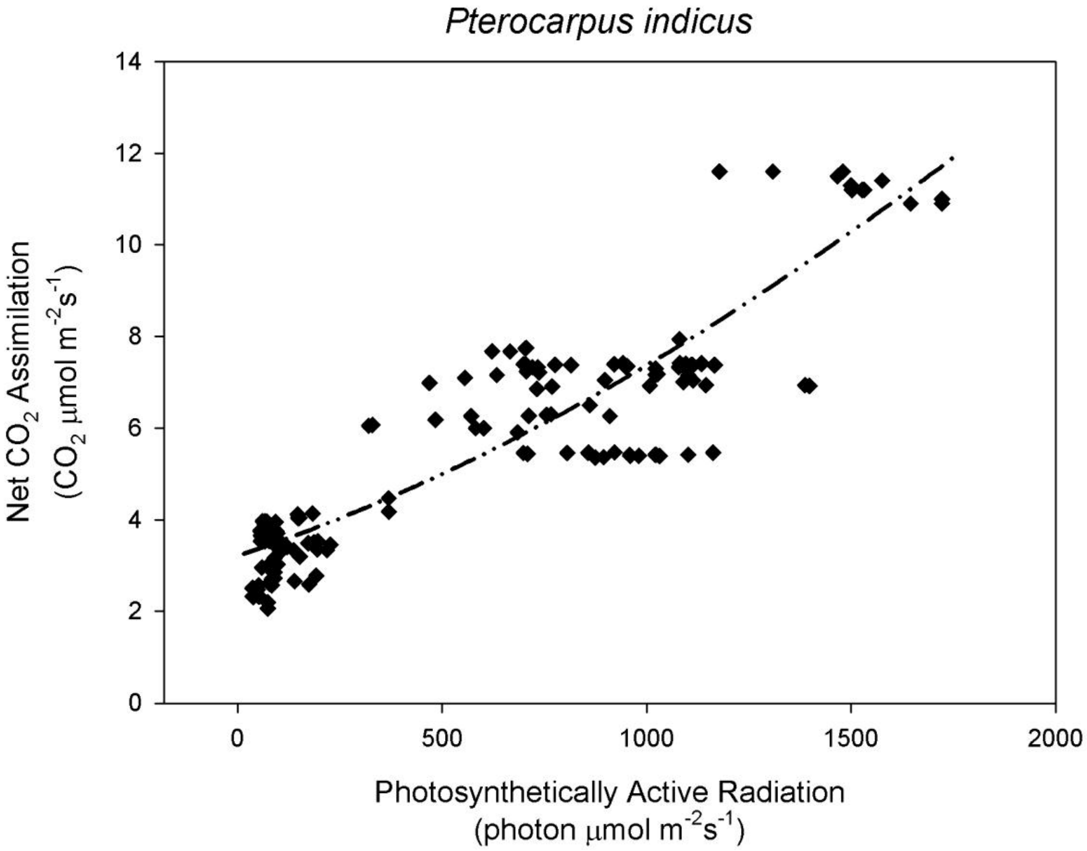

Figure 14 Scatter diagram with regression of PAR and CO_2 absorption of *Pterocarpus indicus*

Pterocarpus indicus has a similar trends in absorbing carbon dioxide to *Terminalia catappa* given light intensity is the cause. Starting from 30 µmol $m^{-2}s^{-1}$ photoactive radiation, the assimilation rate moderately increases 9 CO_2 µmol $m^{-2}s^{-1}$ until 1600 µmol $m^{-2}s^{-1}$ PAR.

4.3.2 Carbon dioxide concentration in air and carbon dioxide absorption

Considering effects of carbon dioxide concentration in the air on carbon dioxide absorption of common trees, ambient air carbon dioxide concentration was put as independent variable (X), while carbon dioxide assimilation rate was put as dependent variable. The results of running regressions are shown in Table 3. The results shown were unexpected. In spite of fitting data, there were only 2 species whose data could be fitted with regression. *Samanea saman,* with gaussian function, had R^2 at only

0.35. The data of was *Pterocarpus indicus* badly regressed with 0.4 R^2 value. The others, *Terminalia catappa* and *Peltophorum pterocarpum*, were not applicable with any of the function.

Table 3 Estimated coefficients and analysis of CO_2 absorption subject to ambient CO_2 concentration

Estimated Regression	*Samanea saman*	*Terminalia catappa*	*Peltophorum pterocarpum*	*Pterocarpus indicus*
Function	Gaussian	NA*	NA	Gaussian
α	18.2947	-	-	6.1703
β	10.9176	-	-	10.4962
X_0	379.6385	-	-	390.5393
r	0.5984	-	-	0.2109
R^2	0.3581	-	-	0.0445
F statistic	59.9691	-	-	5.5852

* NA = Not applicable with any function

Testing analysis of variance, the survived 2 regressions were tested as follows:

H_0: $\alpha = \beta = X_0 = 0$ (null hypothesis)

H_A: not all coefficients are zero (alternative hypothesis)

Determined Significant level (α) = 0.001

$F_{0.001}$ = 11.6 when residual degree of freedom is around 200

The null hypothesis is rejected if calculated F > $F_{0.001}$

Since calculated F value of *Samanea saman* was 59.9691, null hypothesis was rejected. It was accepted that not all coefficients are zero. Gaussian regression of *Pterocarpus indicus*, in opposite, its little F-value 5.5852 caused acceptance of null hypothesis, meaning the carbon dioxide concentration cannot explain their carbon dioxide absorption. The reason why most of the regressions failed the test should be seen in the scatter diagrams in Figure 15.

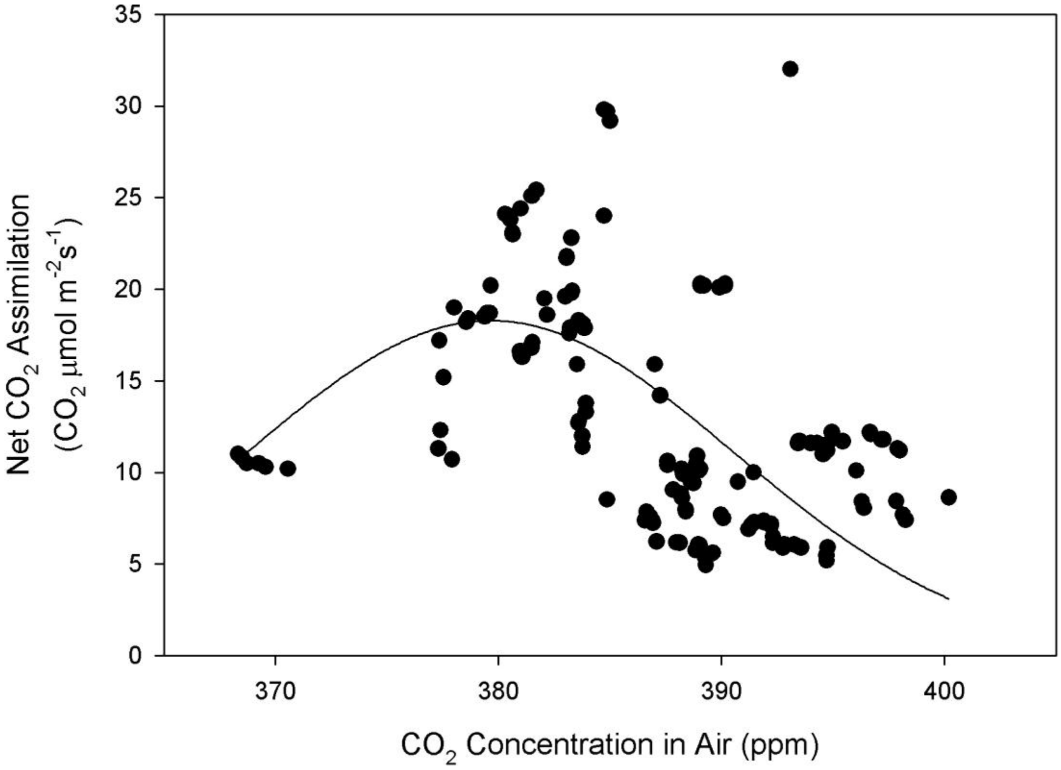

Figure 15 Scatter diagram with regression of air CO_2 concentration and CO_2 absorption of *Samanea saman*

For the only one survived, the curve of *Samanea saman* has a peak when the carbon dioxide concentration in air is 380 ppm. Too much high concentration may relate to plunge of the carbon dioxide absorption.

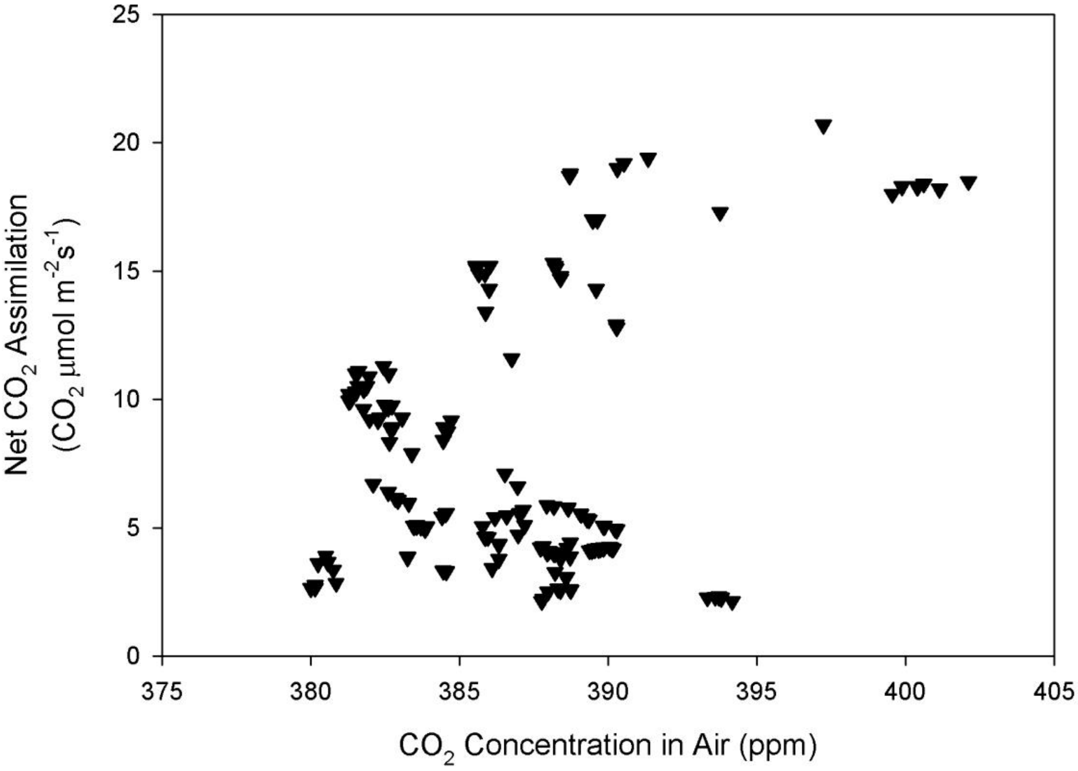

Figure 16 Scatter diagram of air CO_2 concentration and CO_2 absorption of *Terminalia catappa*

The data of *Terminalia catappa*, which model cannot be formed, had too much variation when the carbon dioxide concentration was higher than 385 ppm. For instance, under 395 ppm, the carbon dioxide absorption rate may be over 15 µmol $m^{-2}s^{-1}$ or only 2 µmol $m^{-2}s^{-1}$.

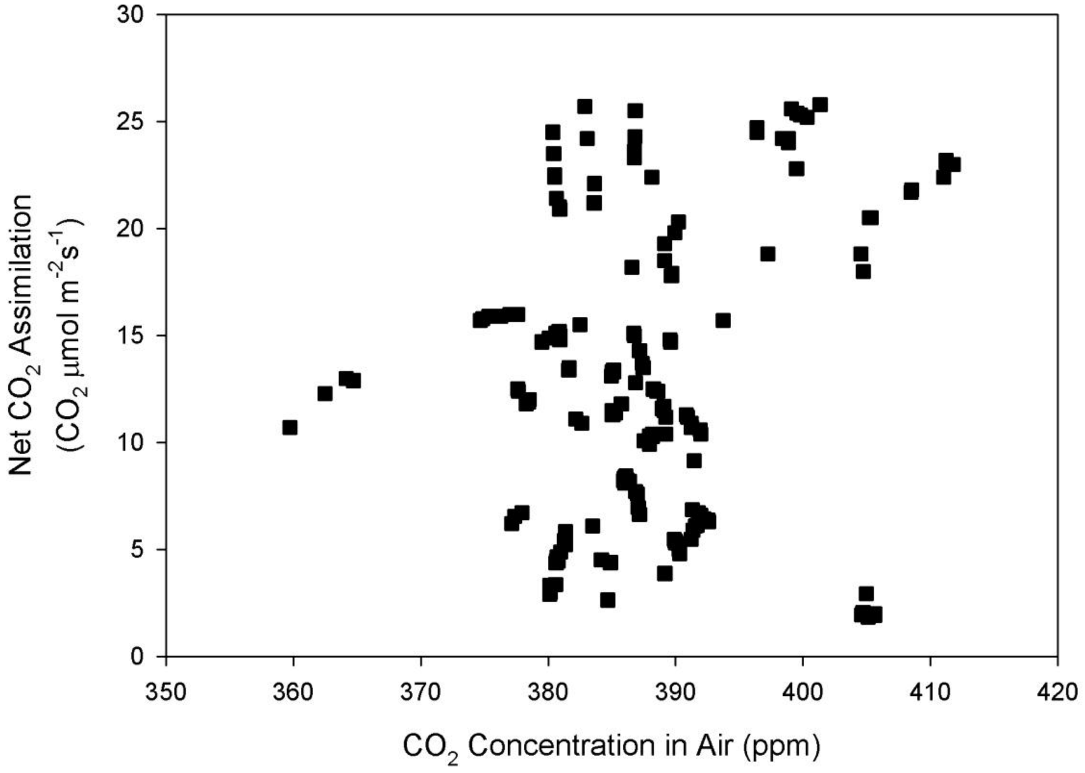

Figure 17 Scatter diagram of air CO_2 concentration and CO_2 absorption of *Peltophorum pterocarpum*

The scatter plot of *Peltophorum pterocarpum* was somewhat gathered in circle shape, with the center was between 380 and 290 ppm. This condition means relation between carbon dioxide concentration and carbon dioxide absorption cannot be explained.

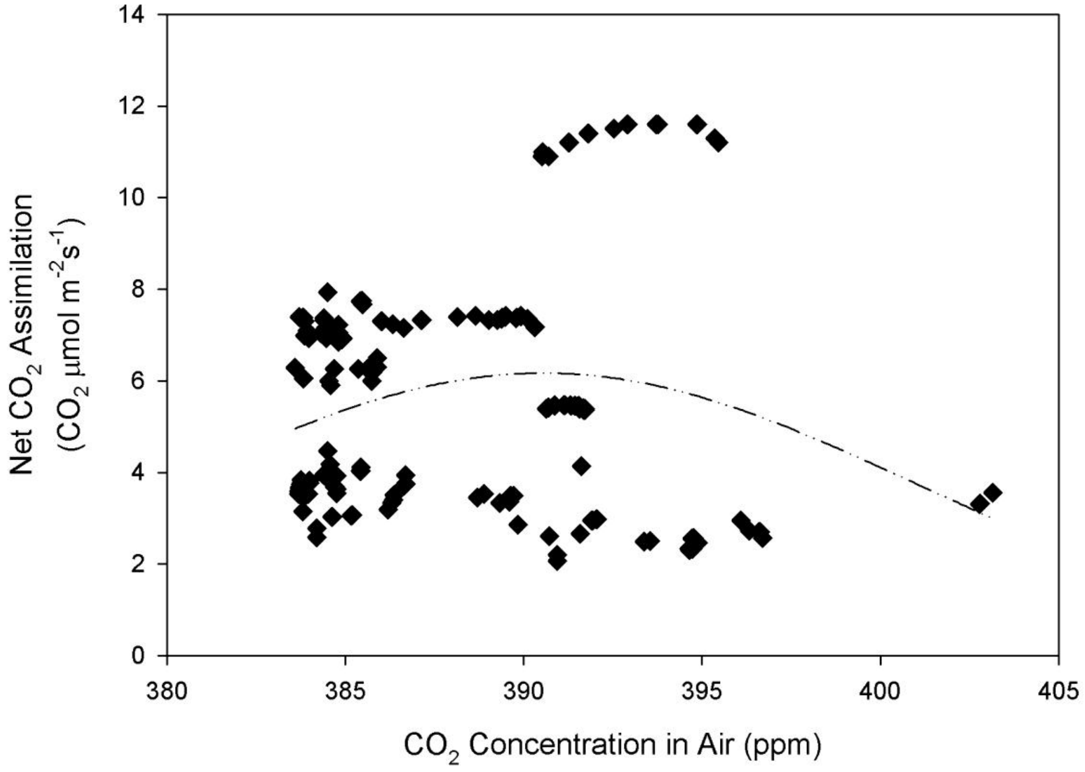

Figure 18 Scatter diagram with regression of air CO_2 concentration and CO_2 absorption of *Pterocarpus indicus*

Pterocarpus indicus, likewise *Terminalia catappa*, had so high variance of its data that the previously estimated regression did not overlay on any point of data point. At 395 ppm concentration, the carbon dioxide absorption varied by 10 µmol $m^{-2}s^{-1}$, not letting any curve possible to overlay.

4.3.3 Air temperature and carbon dioxide absorption

The air temperature data from multiple leaf measurement were also used to find relations to carbon dioxide absorption. Fitting data, air temperature as independent variable and CO_2 absorption as dependent variable, was with 5 forms of regressions. The estimated coefficients and analysis are shown in Table 4. Sigmoidal function was chosen as best fitting function for *Samanea saman*, *Terminalia catappa* and *Peltophorum pterocarpum*; while gaussian function was chosen for *Pterocarpus indicus*. R^2 of *Pterocarpus indicus* was low (0.17), so the regression was not so explainable to collected data.

Table 4 Estimated coefficients and analysis of CO_2 absorption subject to air temperature

Estimated Regression	*Samanea saman*	*Terminalia catappa*	*Peltophorum pterocarpum*	*Pterocarpus indicus*
Function	Sigmoidal	Sigmoidal	Sigmoidal	Gaussian
α	18.9615	7.45×10^9	15.5767	6.6127
β	0.8653	3.0146	0.445	2.3237
X_0	32.8305	96.8171	32.9541	33.8419
r	0.7267	0.7328	0.5328	0.4219
R^2	0.5280	0.2830	0.2830	0.1780
F statistic	120.3107	145.0076	51.7297	25.9918

Considering F-test, the same null hypothesis and alternative hypothesis as in previous ones were set. Also, significant level was 0.01, meaning critical F value was 11.6 as well. All calculated F value of 4 regressions passed the critical F value and accepted the alternative hypothesis. It was concluded that air temperature could explain the variation of CO_2 absorption data.

Figure 19, 20, 21, and 22 present scatter diagram of *Samanea saman*, *Terminalia catappa*, *Peltophorum pterocarpum* and *Pterocarpus indicus* with their best fitting regression respectively.

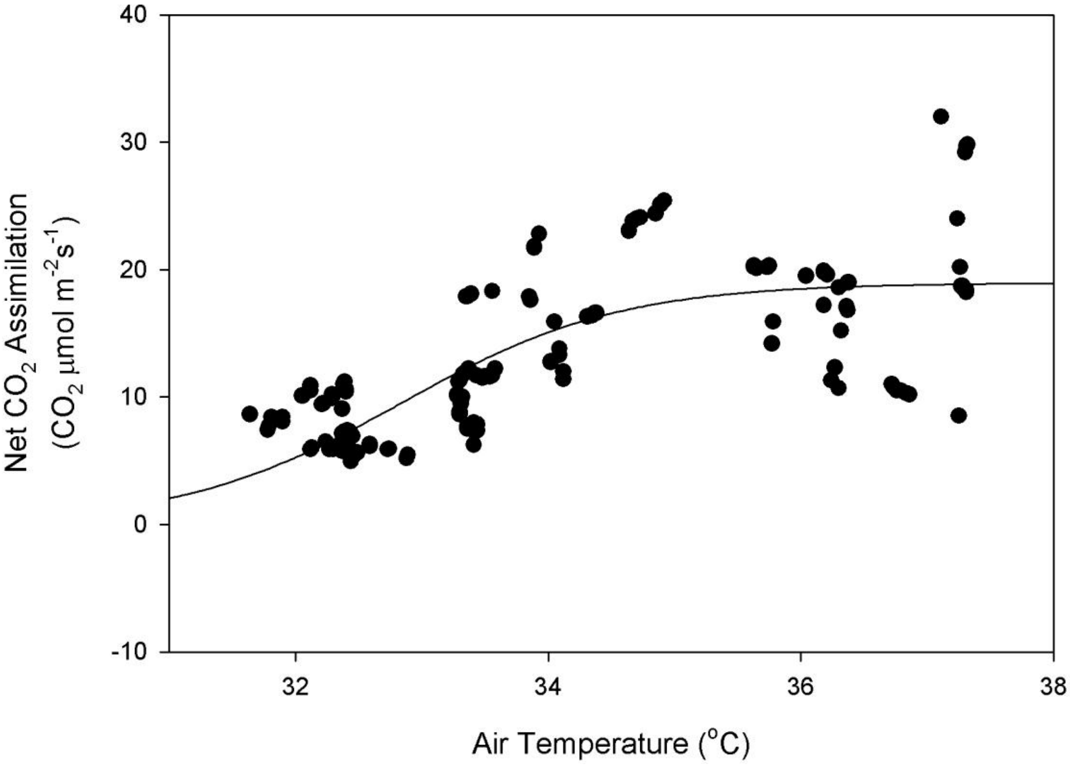

Figure 19 Scatter diagram with regression of air temperature and CO_2 absorption of *Samanea saman*

Samanea saman had a variation of air temperature between 31.6°C and 37.7°C. The regression predicts that the carbon dioxide absorption could be around 5 μmol $m^{-2}s^{-1}$ when the temperature in air is around 32°C, and would be near 20 μmol $m^{-2}s^{-1}$ when the temperature is around 36°C. There would not be an increase in carbon dioxide absorption when it is hotter than 36°C.

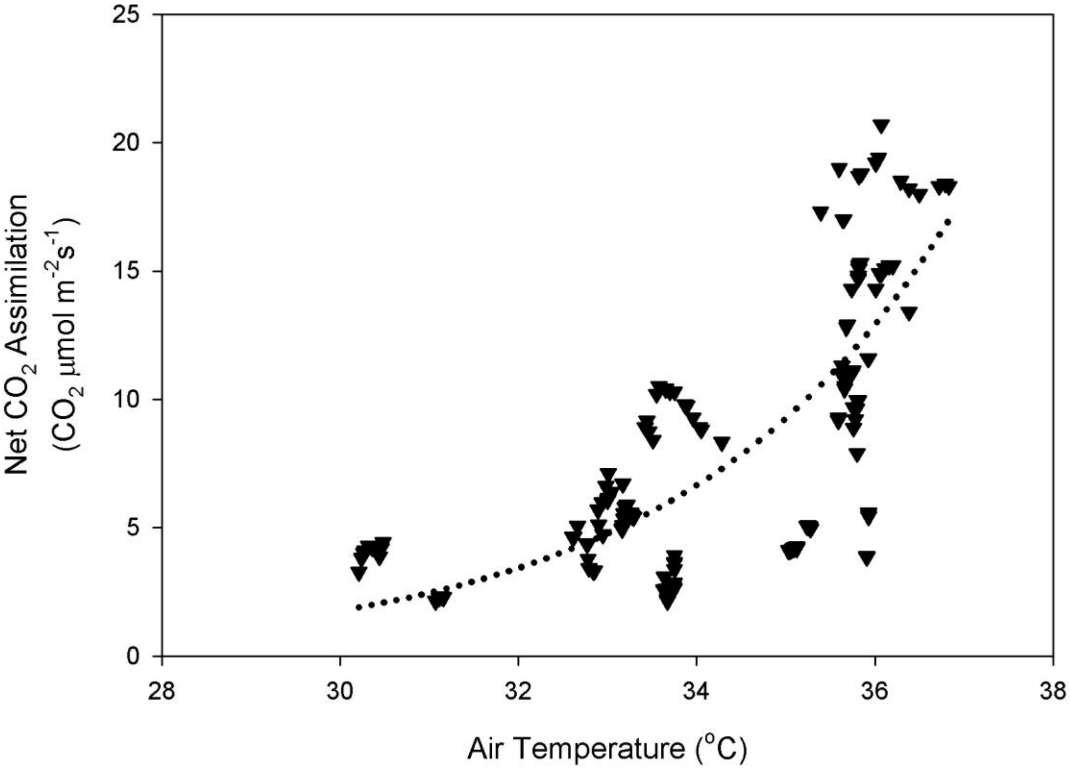

Figure 20 Scatter diagram with regression of air temperature and CO_2 absorption of *Terminalia catappa*

Although Figure 20 shows that there is a steep slope in the regression from 32°C to 37°C, it cannot be concluded that *Terminalia catappa* responds to air temperature sensitively. The variance of net Carbon dioxide assimilation was not constant as the absorption varied from 4 µmol $m^{-2}s^{-1}$ to 20 µmol $m^{-2}s^{-1}$ at 36°C temperature.

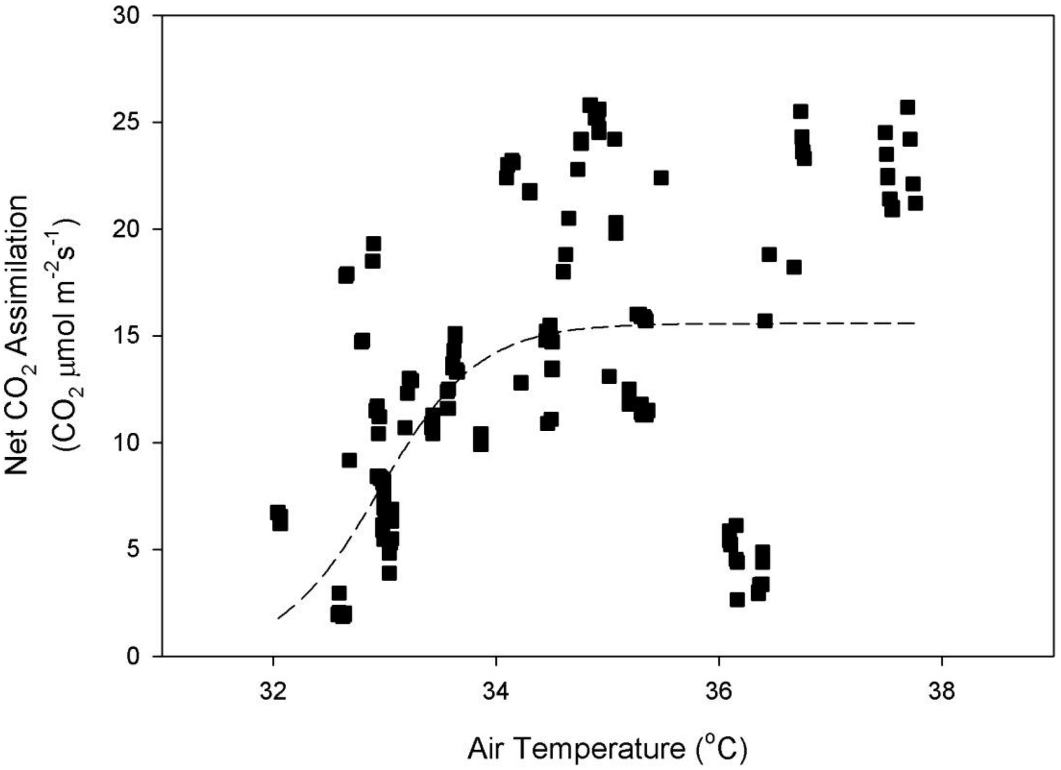

Figure 21 Scatter diagram with regression of air temperature and CO_2 absorption of *Peltophorum pterocarpum*

Peltophorum pterocarpum also had a sigmoidal curve estimating the data. The graph in Figure 21 indicates that the carbon dioxide absorption reaches maximum at 15 μmol $m^{-2}s^{-1}$ when it is 35°C in the air. However, a group of data around 36°C (net CO_2 assimilation is around 5 μmol $m^{-2}s^{-1}$) refers to high standard error of the regression.

The data of *Pterocarpus indicus* was the only one explained by gaussian function, shown in figure 22 below. According to the graph, the carbon dioxide absorption would reach the peak of 6.5 μmol $m^{-2}s^{-1}$ under 34°C ambient temperature. Nonetheless, the regression overlays a few points of data causing R^2 value to be only 0.178.

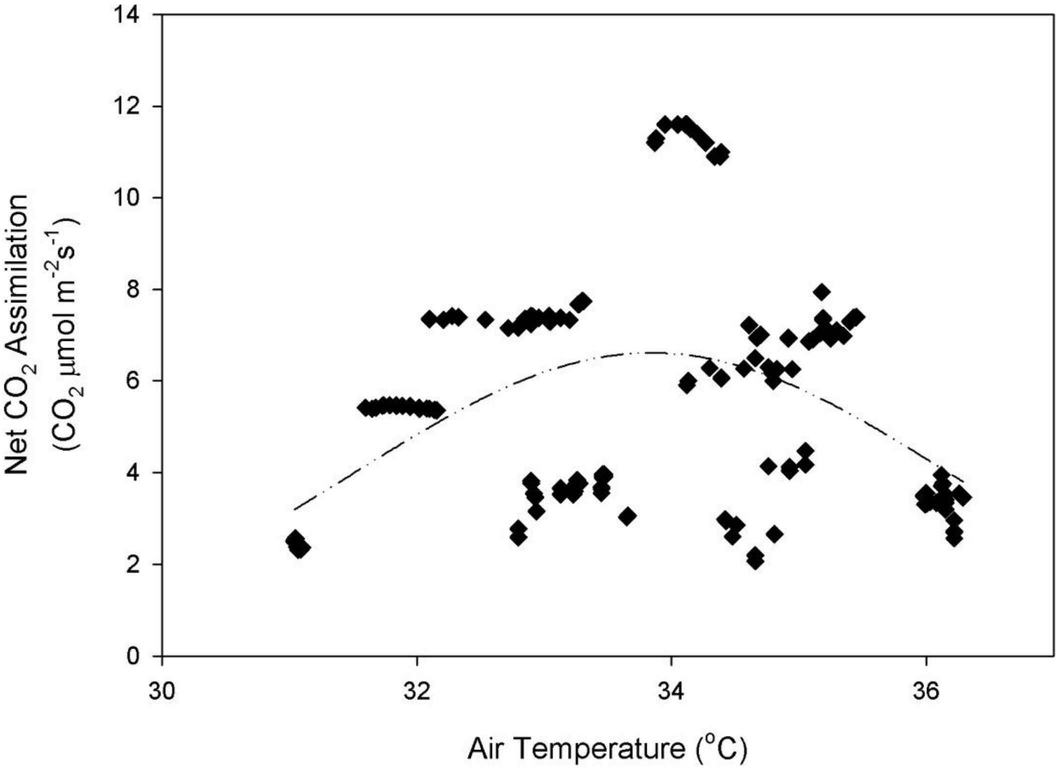

Figure 22 Scatter diagram with regression of air temperature and CO_2 absorption of *Pterocarpus indicus*

4.3.4 Leaf temperature and carbon dioxide absorption

Similarly to the other environmental factor, leaf temperature was put as independent variable, while the dependent variable was the net carbon dioxide assimilation. Table 5 provides results of regressing data with the 5 functions. According to the table, sigmoidal regression of *Terminalia catappa* had the highest R^2 (0.692), while *Samanea saman* had a little less R^2, 0.55. The others had much lower R^2, only around 0.2, meaning the regressions could represent data in some level.

F-value of these 4 regressions was also tested in the same condition as previous ones.

H_0: $\alpha = \beta = X_0 = 0$ (null hypothesis)

H_A: not all coefficients are zero (alternative hypothesis)

Given significant level (α) = 0.001

The critical $F_{0.001}$ = 11.6 when residual degree of freedom is around 200

The null hypothesis is rejected if calculated F > $F_{0.001}$

Table 5 Estimated coefficients and analysis of CO_2 absorption subject to leaf temperature

Estimated Regression	*Samanea saman*	*Terminalia catappa*	*Peltophorum pterocarpum*	*Pterocarpus indicus*
Function	Sigmoidal	Sigmoidal	Sigmoidal	Gaussian
α	18.9405	12567.2	15.7218	6.9354
β	0.9274	2.8959	0.612	1.9808
X_0	31.6194	55.3235	32.0604	34.0535
r	0.748	0.8323	0.5323	0.4512
R^2	0.5595	0.6927	0.2833	0.2036
F statistic	136.5405	281.7745	51.5841	30.6783

All of the calculated F values (136, 281, 51.5, and 30.6) provided in the table were much higher than 11.6. Null hypothesis of every regression was rejected, so the alternative hypothesis was accepted. It is implied that the temperature on the leaf surface also affects carbon dioxide absorption of the common tree species. Scatter diagrams with non-linear regressions based on the table are shown in Figure 23, 24, 25, and 26. Leaf temperature directly affects enzymes in the photosynthesis; it should be more explainable than temperature in the air.

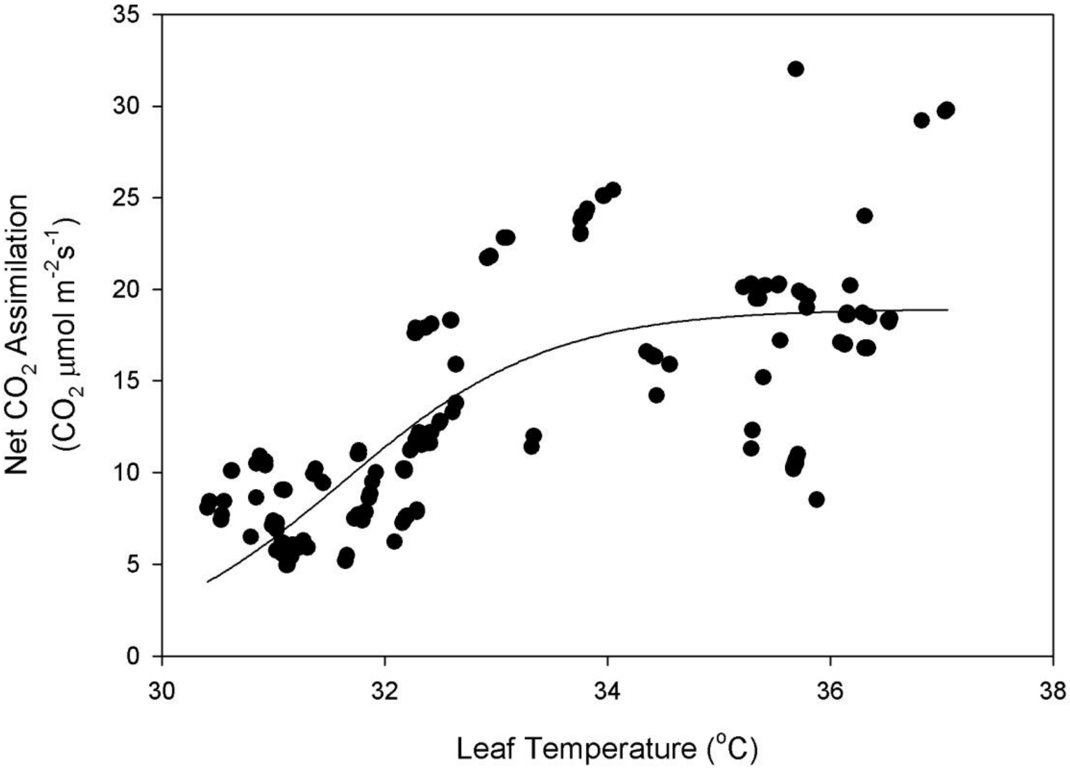

Figure 23 Scatter diagram with regression of leaf temperature and CO_2 absorption of *Samanea saman*

The trend of *Samanea saman* in figure 23 indicates that when leaf temperature is 36°C, the carbon dioxide absorption rate would rise to maximum around 19 µmol $m^{-2}s^{-1}$. It is seen that variance of carbon dioxide assimilation under 30 to 32°C leaf temperature was lower than those in 34 to 37°C.

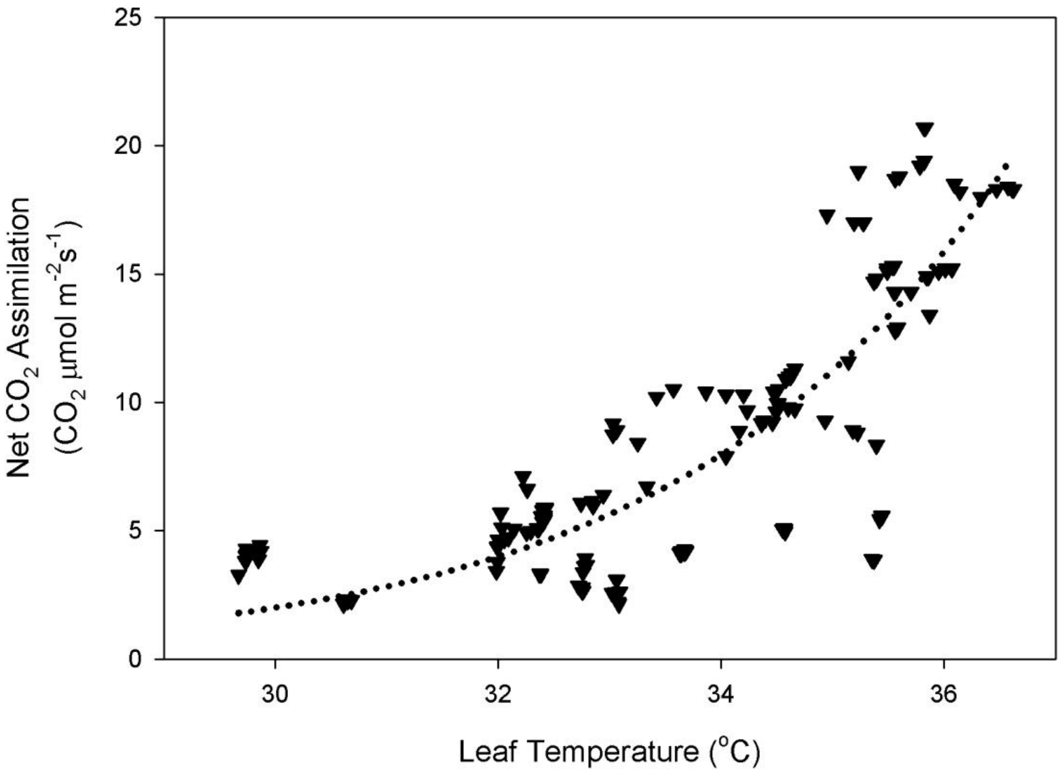

Figure 24 Scatter diagram with regression of leaf temperature and CO_2 absorption of *Terminalia catappa*

The regression of *Terminalia catappa* (Figure 24) has a sharp increase from 30°C to over 36°C. However, there was no maximum point within the data range. There was no significant difference in variance of data between 32°C and 36°C as well.

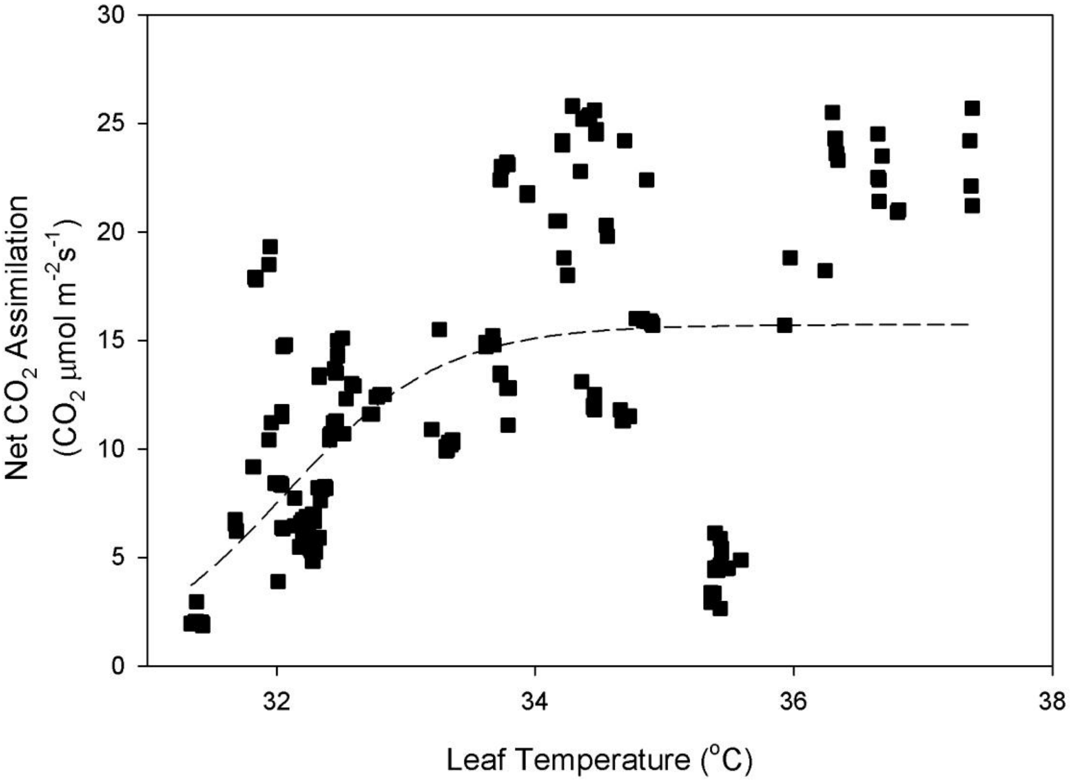

Figure 25 Scatter diagram with regression of leaf temperature and CO_2 absorption of *Peltophorum pterocarpum*

The trend of *Peltophorum pterocarpum* subject to leaf temperature in Figure 25 is similar to the trend in Figure 21 (subject to air temperature). The carbon dioxide assimilation rises from 5 µmol $m^{-2}s^{-1}$ (with 32^oC on leaf surface) to around 15 µmol $m^{-2}s^{-1}$ before leveling off at 34^oC leaf temperature.

The leaf temperature data of *Pterocarpus indicus*, regressed with gaussian function, has the peak at around 7 µmol $m^{-2}s^{-1}$ under 34^oC on leaf, similarly to that of air temperature in Figure 22. Again, there was a huge variation around the peak, despite more R^2 value than that of air temperature.

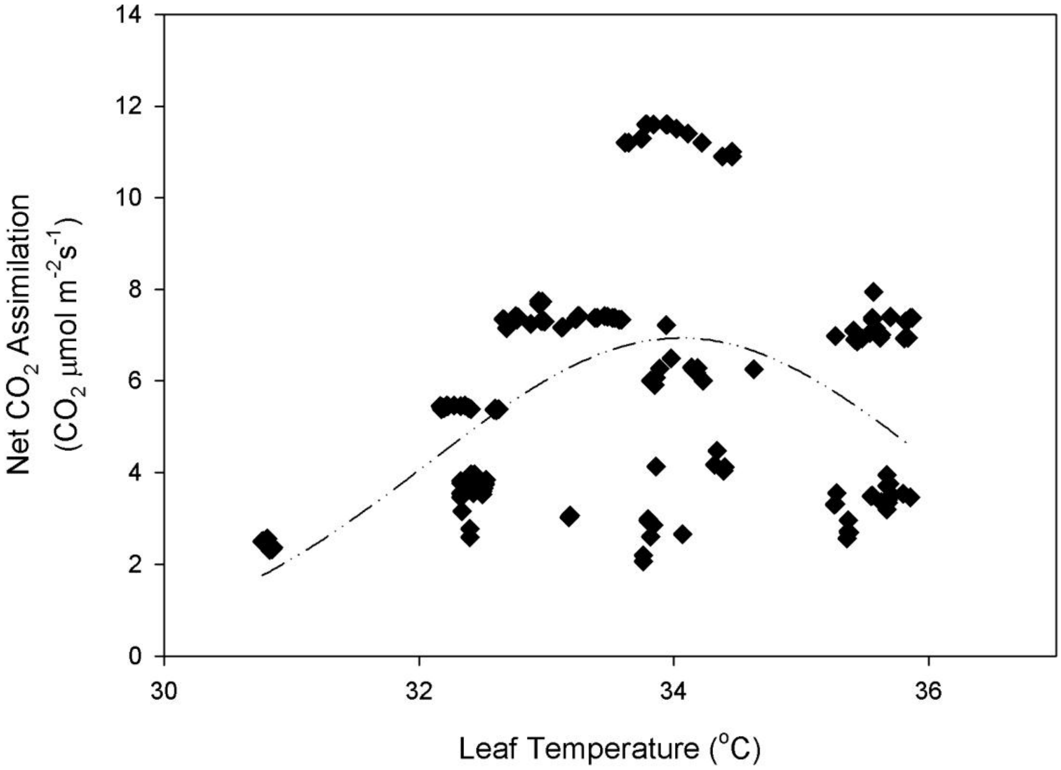

Figure 26 Scatter diagram with regression of leaf temperature and CO_2 absorption of *Pterocarpus indicus*

4.3.5 Relative humidity and carbon dioxide absorption

Relative humidity is the other environmental factor considered in the research. The effect of it to carbon dioxide absorption of each species was also judged by forming 5 regressions from the 5 functions. The results were that none of the common species data could be applicable to any regression function. As a result of the regression unfeasibility, R^2 value was not provided; particularly, the F-statistic measuring relevance between the two variables was not able to be calculated. Nevertheless, it is necessary to show how the data of the species were distributed, as shown in Figure 27, 28, 29, and 30, to find the reason behind that.

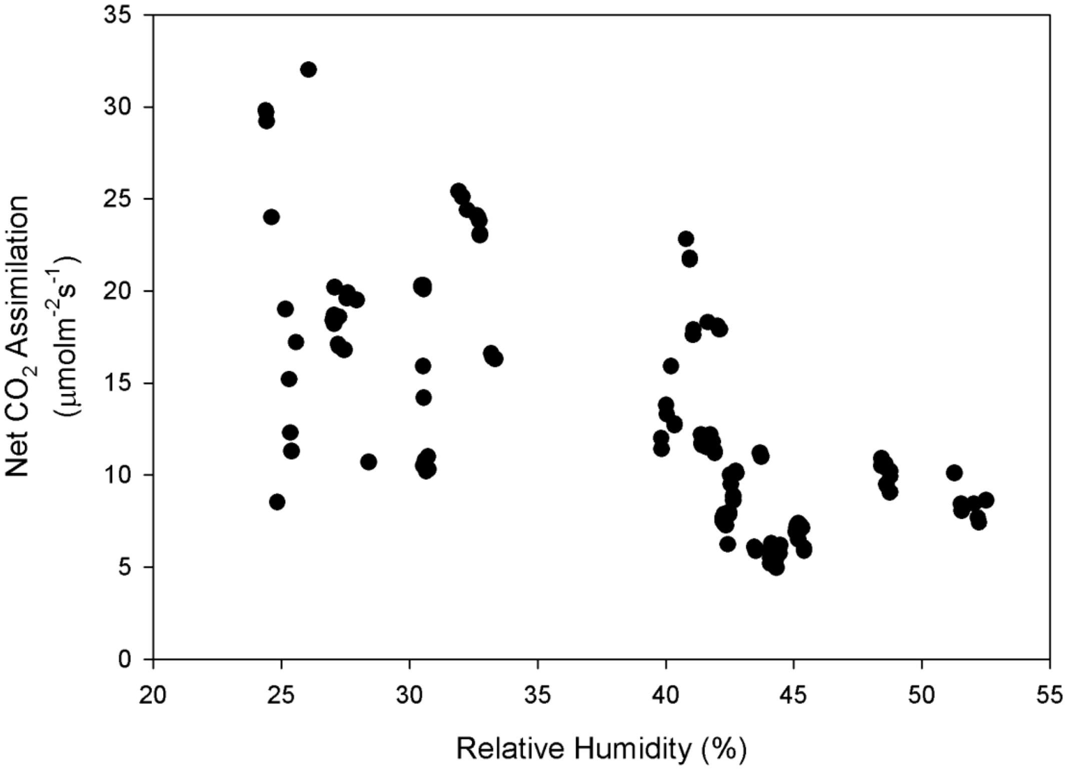

Figure 27 Scatter diagram of relative humidity and CO_2 absorption of *Samanea saman*

In Figure 27 of *Samanea saman*, the relative humidity ranged between 25 per cent to around 53 per cent. The data between 34 per cent and 40 per cent was lack, dividing the plot into 2 sections. That was the reason why regression was not applicable.

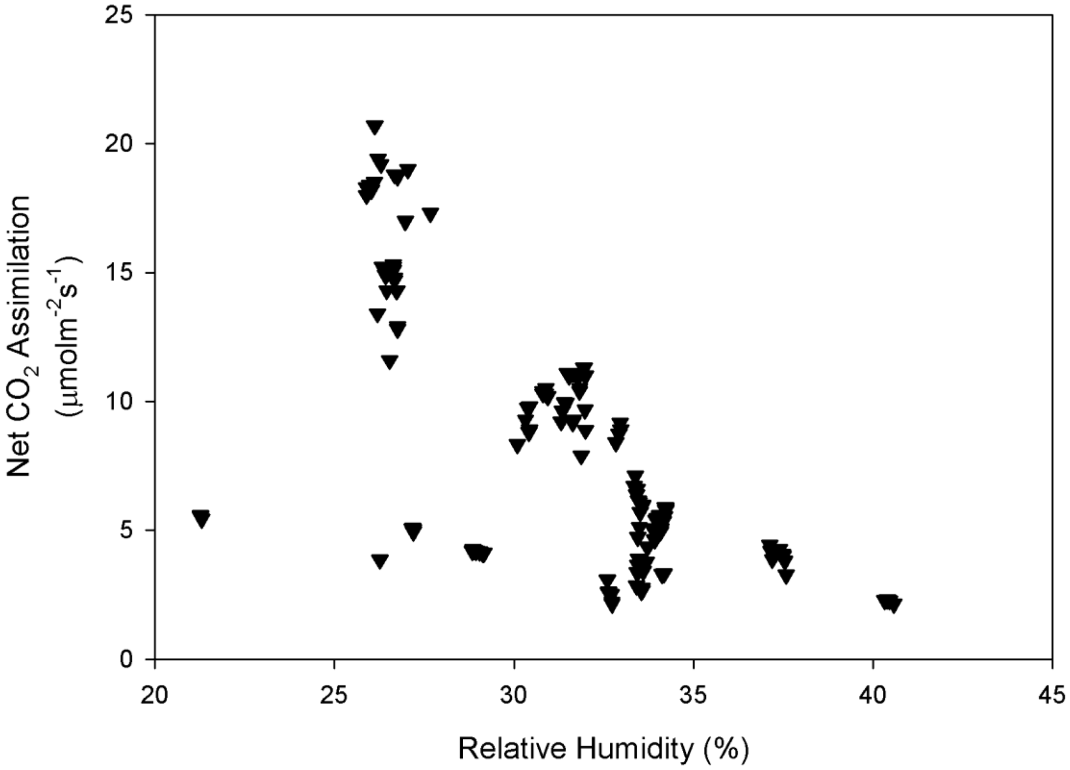

Figure 28 Scatter diagram of relative humidity and CO_2 absorption of *Terminalia catappa*

The data of *Terminalia catappa* in Figure 28 shows that carbon dioxide absorption rates were in group only when the relative humidity was around 36 per cent to 40 per cent. The absorption rates at the other humidity had so high variance, especially at 26 per cent, that it was difficult to form a model.

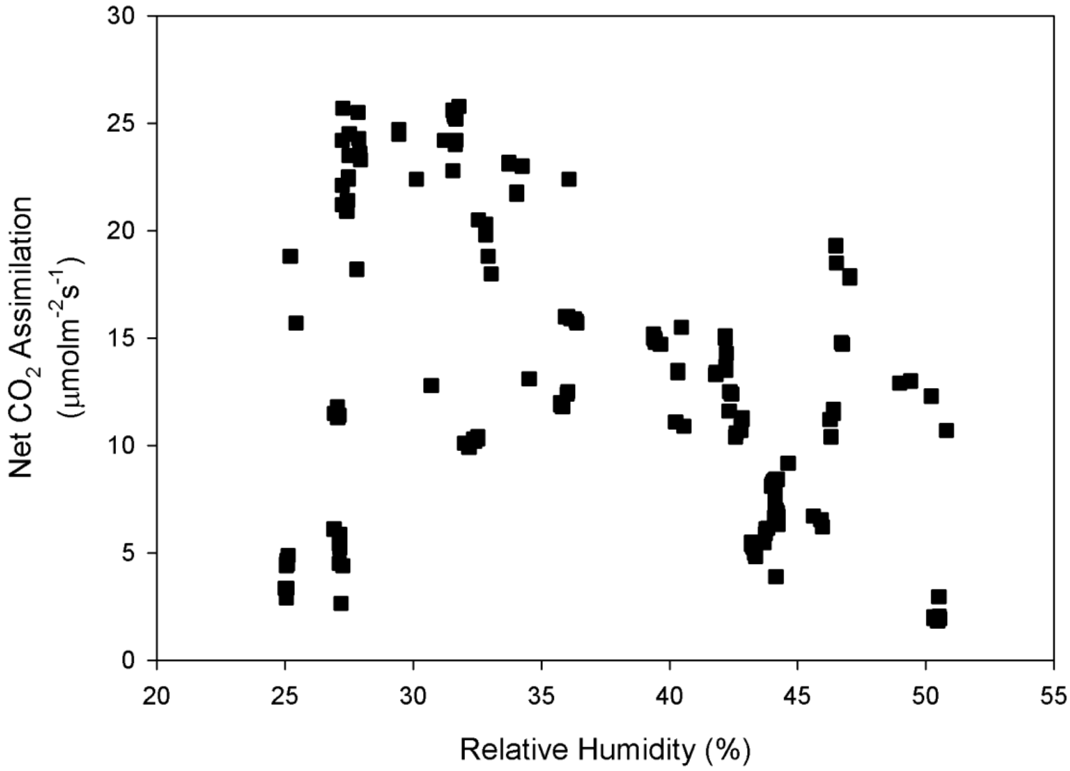

Figure 29 Scatter diagram of relative humidity and CO_2 absorption of *Peltophorum pterocarpum*

Figure 29 gives information on relation between relative humidity and the carbon dioxide absorption of *Peltophorum pterocarpum*. Starting with 25 - 35 per cent relative humidity, there was a large variance went less when the relative humidity was around 35 - 40 per cent, before getting higher again in higher humidity. This could be regarded as heteroscedasticity, violating regression estimation.

The data of *Pterocarpus indicus* in Figure 30 lied in pyramid shape. Seeing them more deeply, the data could be divided into 3 groups based on net carbon dioxide assimilation – a group lying around 2 - 4 µmol m^{-2}s^{-1}, another group on 6 - 8 µmol m^{-2}s^{-1}, and the other group with over 10 µmol m^{-2}s^{-1}. Iterating curve over them was not feasible.

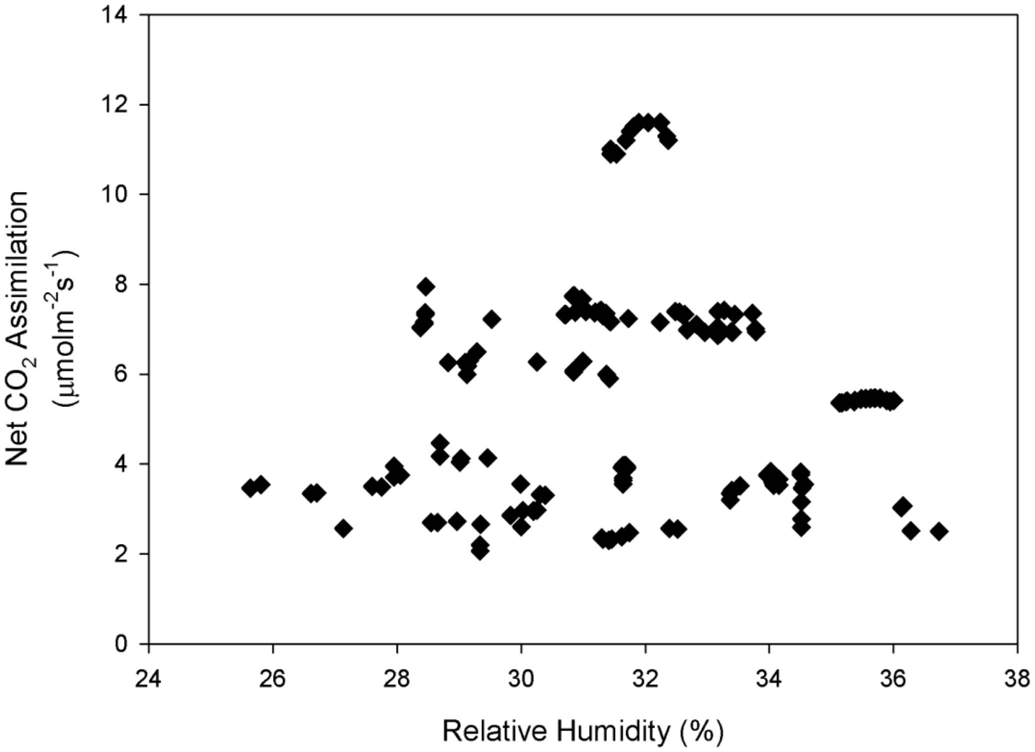

Figure 30 Scatter diagram of relative humidity and CO_2 absorption of *Pterocarpus indicus*

4.3.6 Comparing influences between the environmental factors

Taking F values into account, light intensity (PAR variable) was the most influential factor for all species, leaving the other variables far behind. The R^2 values, 0.79 to 0.89, were very high despite the experiment with uncontrolled environment. Another factor affecting CO_2 assimilation next to PAR is leaf temperature, seeing that the F and R^2 values were at least acceptable. Air temperature was also an explainable factor at some level, but worse than leaf temperature. The reason is that temperature at the leaf surface directly affects enzyme activities in photosynthesis, while air temperature does not. Air CO_2 concentration and relative humidity have no significant influence on the CO_2 absorption. Determined that PAR was the most important environmental factors affecting CO_2 absorption, it was used to compare the absorption capacity.

4.3.7 Comparing to other related studies

There are few other pieces of research conducted in Bangkok that gauge carbon dioxide absorption of the 4 studied species. Table 6 presents maximum CO_2 absorption of *Pterocarpus indicus* from 2 previous studies compared with this paper's estimation.

Table 6 Comparing CO_2 absorption of *Pterocarpus indicus* from other studies and this paper

Previous study	PAR from the study (photon µmol $m^{-2}s^{-1}$)	CO_2 absorption from the study (CO_2 µmol $m^{-2}s^{-1}$)	CO_2 absorption estimated by this paper's model (CO_2 µmol $m^{-2}s^{-1}$)
By Puangchit & Royampaeng (1994)			
At Lumpini park	800	6.51	6.35
At Jatujak park	1050	9.46	7.51
By Samphantharak (2005)	800	4.1	6.35

It can be seen that at PAR 800 µmol $m^{-2}s^{-1}$, the CO_2 absorption rate in the study of Ladawan Puangchit and Sapit Royampaeng (1994) was 6.51, while the absorption rate by Samphantharak (2005) was around 4.1. Applying the same PAR (800 µmol $m^{-2}s^{-1}$) to the Gaussian model of *Pterocarpus indicus* in this study, the estimated absorption rate was 6.35 µmol $m^{-2}s^{-1}$. It can be seen that the estimated CO_2 absorption from this research were comparable to the other studies.

4.4 Comparing CO_2 absorption capacity of the common trees

Figure 31 below illustrates how the common species in the campus assimilate CO_2 in response to light intensity, plotting estimated coefficients provided from Table 3. They respond differently under light intensity from 30 photon µmol $m^{-2}s^{-1}$ to around 1600 µmol $m^{-2}s^{-1}$.

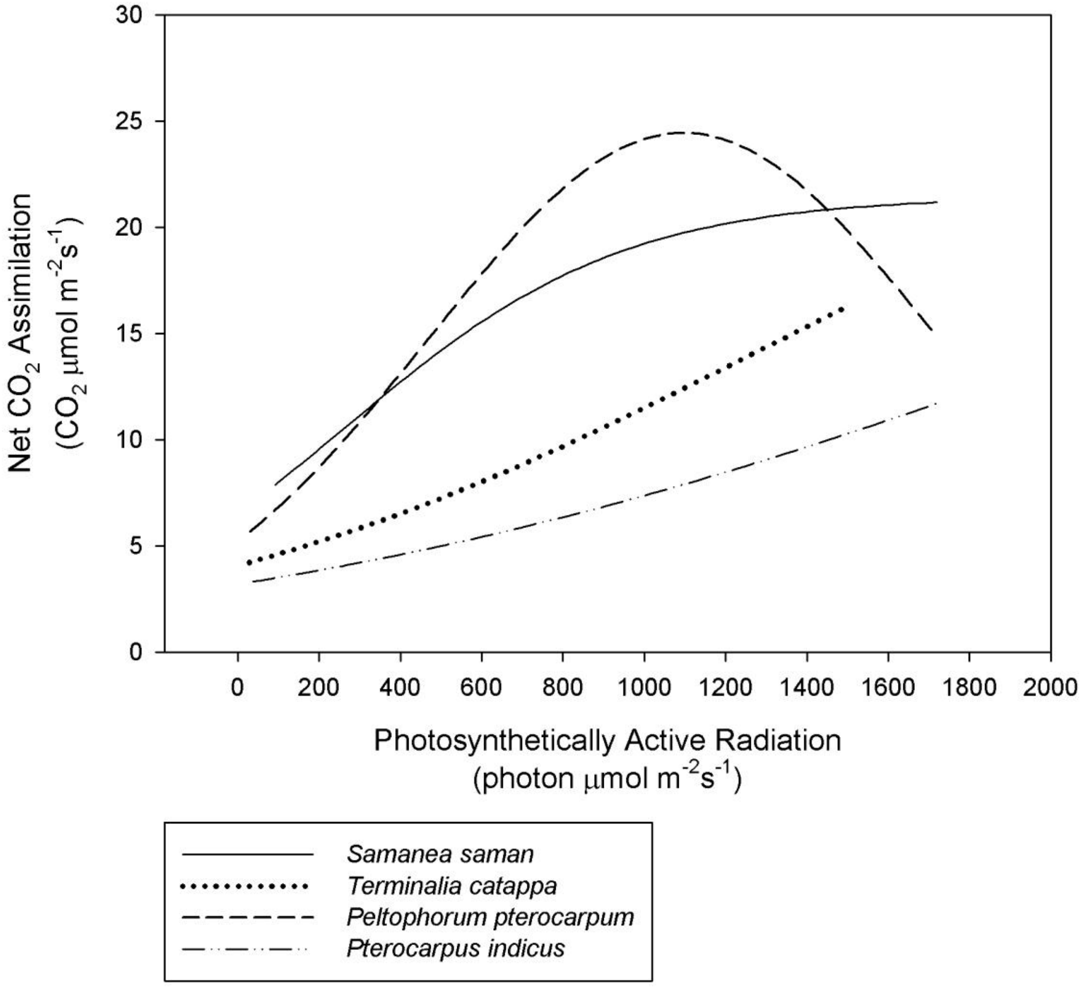

Figure 31 CO_2 assimilation curves of common species subject to Photosynthetically Active Radiation

According to the graph, *Samanea saman* has highest absorption rates under low light intensity to around 380 µmol $m^{-2}s^{-1}$. Nevertheless, *Peltophorum pterocarpum*'s becomes higher from about 350 µmol $m^{-2}s^{-1}$ to 1450 µmol $m^{-2}s^{-1}$ before *Samanea saman*'s absorption is highest again in higher light intensity. As a result, *Peltophorum pterocarpum* and *Samanea saman* reach their maximum CO_2 uptake rate, at 24.5 µmol $m^{-2}s^{-1}$ and 20.5 µmol $m^{-2}s^{-1}$ when the photosynthetically active radiation was 1100 µmol $m^{-2}s^{-1}$ and 1650 µmol $m^{-2}s^{-1}$ respectively. The others, *Pterocarpus indicus* and *Terminalia Catappa*, do not reach their peaks within collected PAR data range. In addition, their absorption rates are much less than *Peltophorum pterocarpum* and *Samanea saman*.

Grouping PAR data from 1-leaf measurement and multiple leaf measurement by actual time from 8 a.m. to 5 p.m., the average PAR value for each hour is found in Figure 32. There were total 1056 observations of PAR. As shown in the Figure, the average light intensity was fluctuated within 822.35 photon µmol $m^{-2}s^{-1}$ (at 10 a.m.) and 59.5 µmol $m^{-2}s^{-1}$ (at 4 p.m.). While the average PAR at 8 a.m. could have 200 µmol $m^{-2}s^{-1}$ mean error, the others could have low or little error in mean.

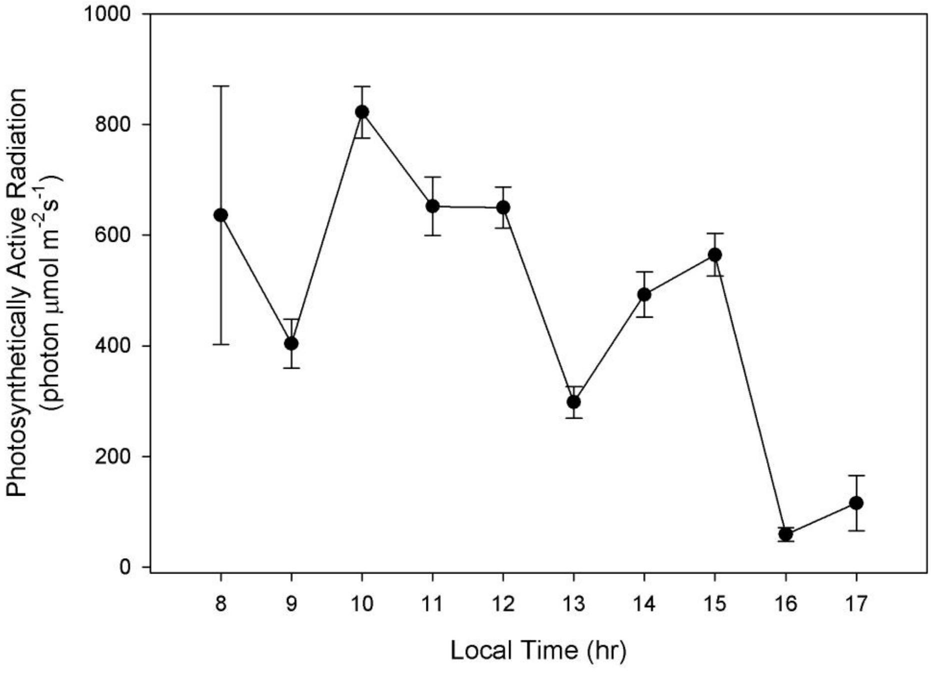

Figure 32 Average photosynthetically active radiation from 8 a.m. to 5 p.m.

Assumed that the hourly average PAR values are good representative light intensity in the rainy season, the carbon dioxide absorption capacity of the 4 common trees can be compared as in Figure 33. Figure 33 shows the estimated carbon dioxide absorption by the derived models of all species using the average PAR value in figure 32. It was found that *Samanea saman* and *Peltophorum pterocarpum* have similar average carbon dioxide absorption every hour. *Samanea saman* has highest absorption of 17.94 CO_2 µmol $m^{-2}s^{-1}$ and lowest absorption of 7.42 µmol $m^{-2}s^{-1}$. *Peltophorum pterocarpum* have highest absorption of 22.2 CO_2 µmol $m^{-2}s^{-1}$ and lowest absorption of 6.14 µmol $m^{-2}s^{-1}$. On the other hand, *Terminalia catappa* and *Pterocarpus indicus* had much lower absorption all day than the first two. The maximum average carbon dioxide absorption of *Terminalia catappa* and *Pterocarpus indicus* were only 9.88 CO_2 µmol $m^{-2}s^{-1}$ and 6.46 µmol $m^{-2}s^{-1}$.

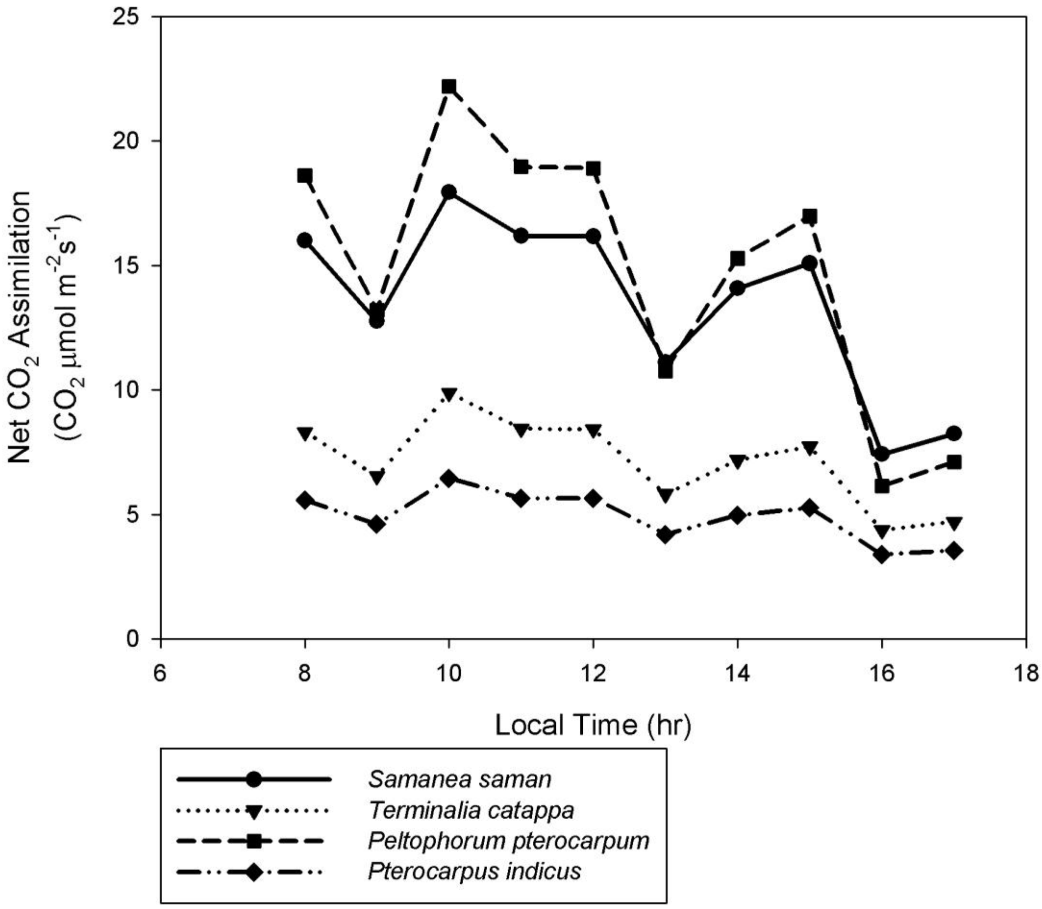

Figure 33 The average CO_2 absorption from 8 a.m. to 5 p.m. estimated by this paper models

Another way to compare absorption capacity is to calculate 1-day total carbon dioxide absorption. Finding areas under the graphs of all species, it was found that from 8 a.m. to 5 p.m., the total carbon dioxide absorption (per m^2 of leaf area) of *Samanea saman*, *Peltophorum pterocarpum*, *Terminalia catappa*, and *Pterocarpus indicus* were 0.486 mol, 0.257 mol, 0.533 mol, and 0.177 mol respectively. It should be determined that *Peltophorum pterocarpum* absorbs carbon dioxide best in rainy season, while *Pterocarpus indicus* is not a good CO_2 sink compared to others.

It cannot be predicted outside model's data range; perhaps *Pterocarpus indicus*, as well as *Terminalia Catappa*, would absorb better in higher light intensity, such as around 1900-2000 µmol $m^{-2}s^{-1}$. Serm Janjai and Rungrat Wattan (2011: 1690), however, found that light intensities higher than 1800 µmol $m^{-2}s^{-1}$ occurred only around 11 a.m. to 1 p.m. in March and April. This means there is just a little possibility that *Samanea saman* and *Peltophorum pterocarpum* absorb CO_2 less than *Pterocarpus indicus* and *Terminalia Catappa*. Hence, *Samanea saman* and *Peltophorum pterocarpum* are good carbon sinks.

4.5 Discussion on experimental methods

Since there are two kinds of measurement in this study, the results of them can be used to find out if the two measurement gave similar results or not. Figure 34, 35, 36, and 37 shows the comparison between data from 1-leaf measurement and regression from multiple leaf measurement using photosynthetically active radiation as the external factor.

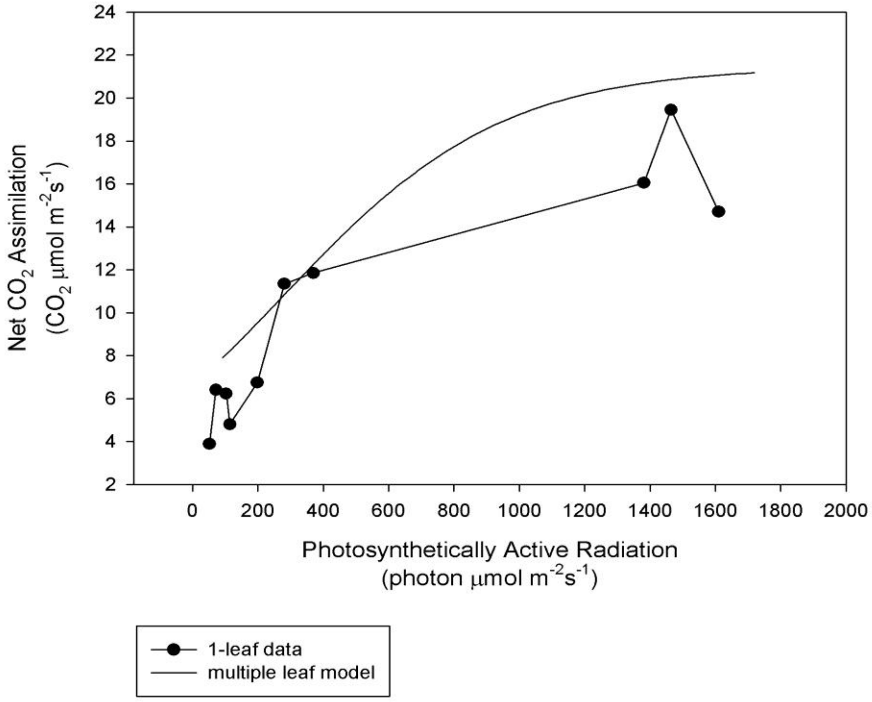

Figure 34 Comparison between data from 1-leaf measurement and regression from multiple leaf measurement in *Samanea saman*

The 1-leaf data of *Samanea saman* in Figure 34 had the same trend with multiple leaf regression, but there was moderate to large gap between them from 1000 μmol m^{-2}s^{-1} PAR. *Terminalia catappa* (Figure 35) had a totally difference between its 1-leaf data and multiple data. The gap was acceptable at PAR around 0 to 100 μmol m^{-2}s^{-1} before the dramatic increase of the 1-leaf data around 400 μmol m^{-2}s^{-1} PAR.

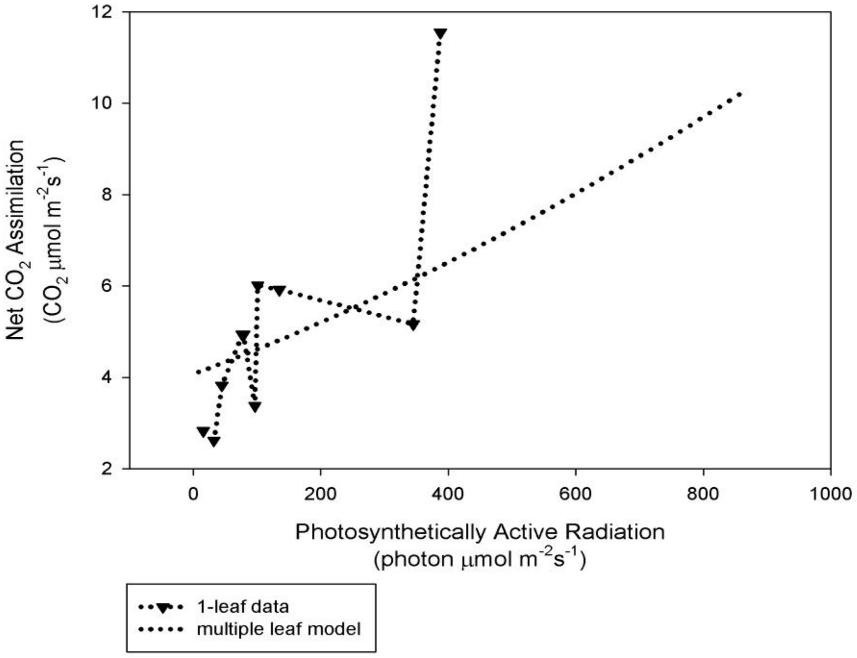

Figure 35 Comparison between data from 1-leaf measurement and regression from multiple leaf measurement in *Terminalia catappa*

The 1-leaf data of *Peltophorum pterocarpum*, as well as of *Pterocarpus indicus*, had a very low gap to its regression, meaning the result of 1-leaf measurement had no significant difference to multiple leaf result for *Peltophorum pterocarpum* and *Pterocarpus indicus*. It has be seen that there were only the 1-leaf data of *Peltophorum pterocarpum* and *Pterocarpus indicus* that were comparable to the multiple leaf data. The should be some reasons behind this; for instance, measuring only one leaf without controlling other environmental factors may result in low precision. Morphological differences may be another reason. *Terminalia catappa* has large leaves with complex structure, so gripping different leaves may get different absorption rates because of different structure such as amount of chlorophyll in leaf, leaf inclination, amount of stomata, etc.

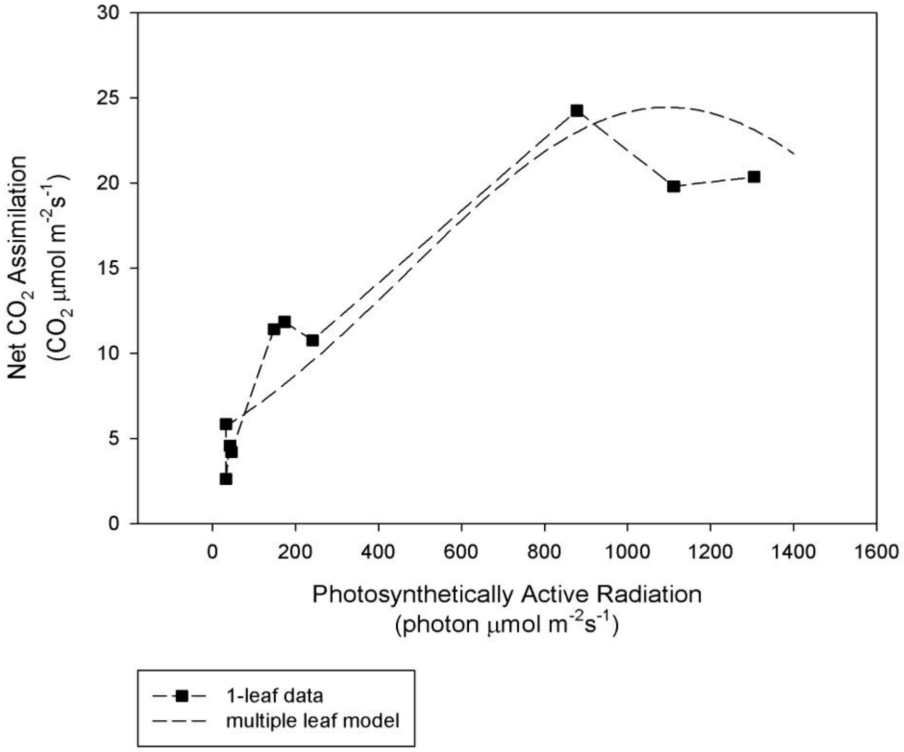

Figure 36 Comparison between data from 1-leaf measurement and regression from multiple leaf measurement in *Peltophorum pterocarpum*

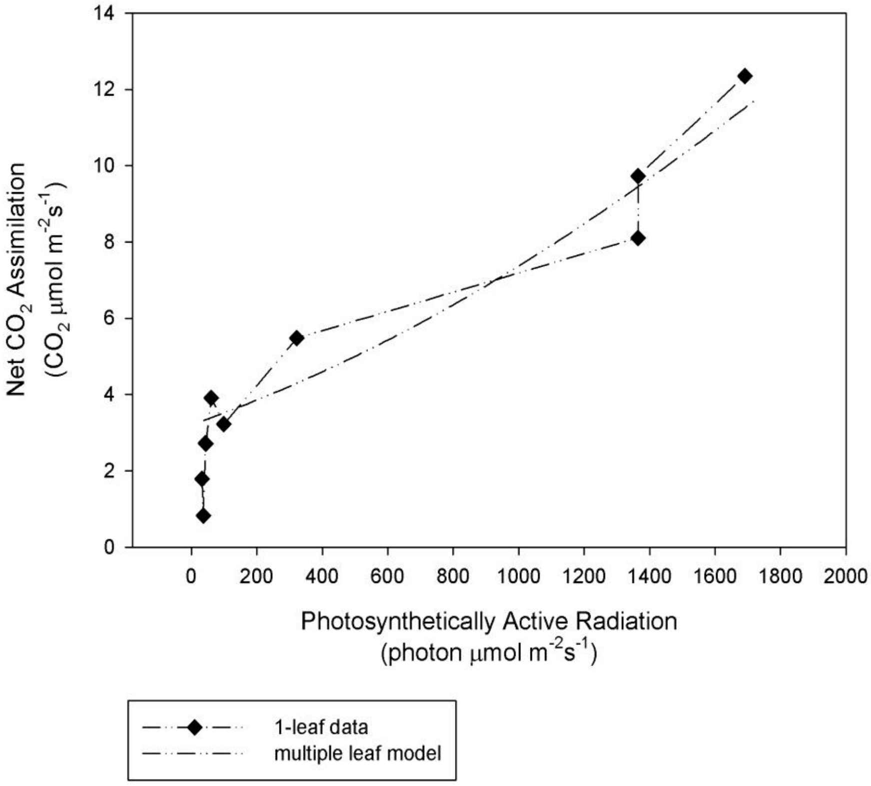

Figure 37 Comparison between data from 1-leaf measurement and regression from multiple leaf measurement in *Pterocarpus indicus*

CHAPTER V

Recommendation and Conclusion

5.1 Recommendation

5.1.1 Recommendation to experimental methods

According to the discussion on experimental method, it is clarified that not all species can use 1-leaf measurement to represent their carbon dioxide absorption characteristics. Measuring many leaves from many trees still be more explainable than measuring single leaf on single tree.

5.1.2 Recommendation for policies

According to the result analysis in 4.4, there should be more populations of *Samanea saman* and *Peltophorum pterocarpum* in the university. Still, there are other features of trees needed to be considered; to name but a few, shading, noise barrier, shelter belt, etc. Moreover, there is another plant besides the 4 species that could be applied in CO_2 absorption of the campus. Issara Paengsee (2009: 37) measured CO_2 uptake of a species of grasses, *Zoysia matrella* (L.) Merr; the result was that under approximately 1350 µmol $m^{-2}s^{-1}$ PAR and $29^{o}C$ air temperature, grasses had maximum CO_2 uptake rate at 32.8 µmol $m^{-2}s^{-1}$, which was significantly higher than any common tree.

Chulalongkorn university is located in the center of Bangkok, so there are the same overall environmental conditions – air temperature, light intensity, CO_2 concentration in the air, and relative humidity – as those in the other places of Bangkok. It is implied that any of the common species should have carbon dioxide absorption characteristics, responding to the factors, the same as those planted in the other places. Thereby, it is practicable to plant more *Samanea saman* and *Peltophorum pterocarpum* in Bangkok for more carbon sinks.

5.2 Conclusion

Having analyzed thoroughly, it should be concluded that the carbon dioxide absorption rate depends on the species of trees, given the same environmental factors. Light is the most influential factor in carbon dioxide absorption capacity of trees in the university. To clarify, the most influential environmental factor used to compare the carbon dioxide absorption is light intensity. It should be also said that *Peltophorum pterocarpum* is the most important species in CO_2 absorption in Chulalongkorn University in rainy season, while *Samanea saman* is the next one. For optimal carbon dioxide absorption capacity in the campus and also in Bangkok, *Samanea saman* and *Peltophorum pterocarpum* should be emphasized planting more. Good management of green area in Chulalongkorn University not only makes clean air for students and staffs, but also is beneficial for Bangkok people.

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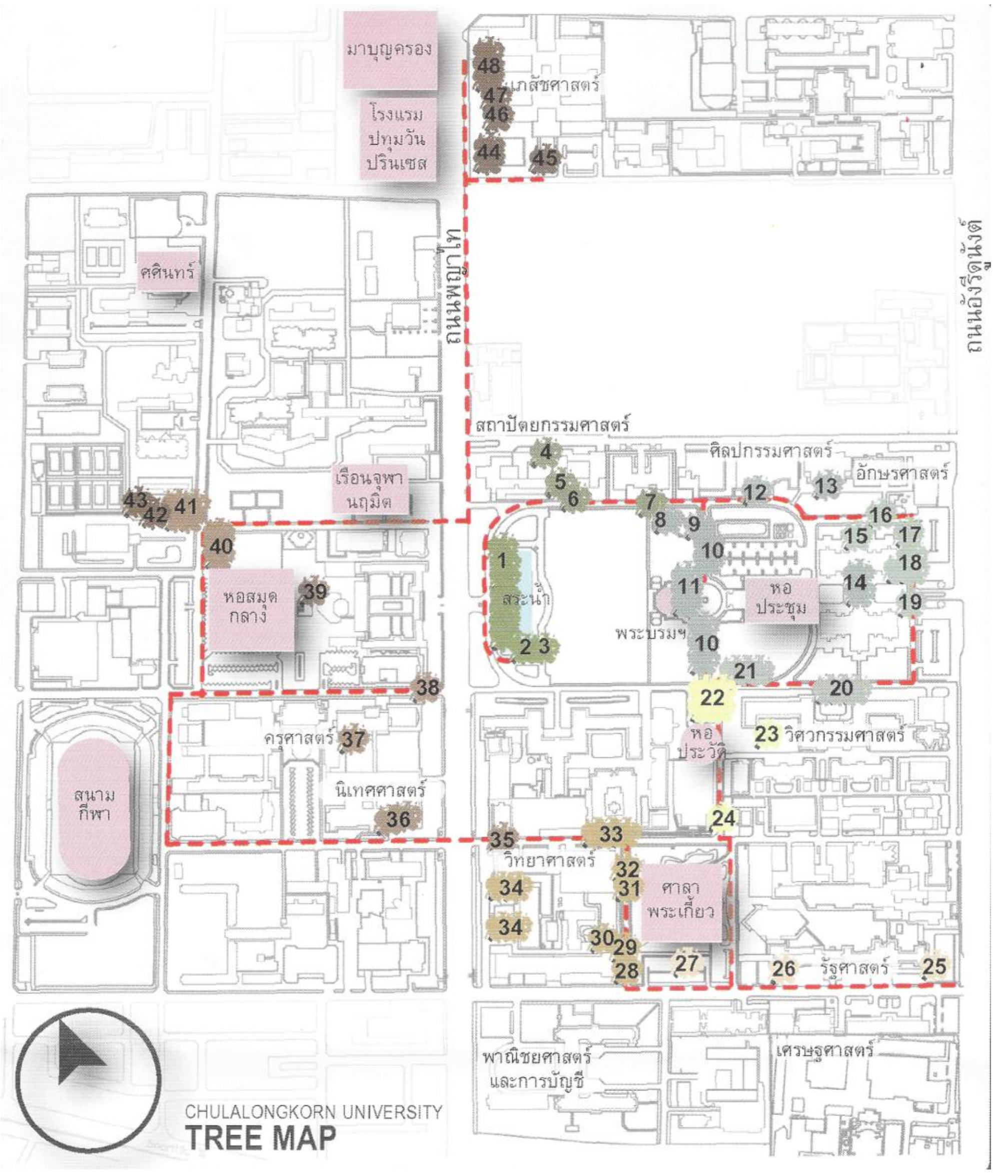
APPENDICES

APPENDIX A: Other figures - Campus map of tree by Office of Master Plan, Physical Resources Management, Chulalongkorn University



Note: *1= Peltophorum pterocarpum* (DC.) *2 = Streblus asper* Lour. *3 = Cassia bakeriana* *4 = Dipterocarpus alatus* Roxb. *5 = Spathodea campanulata* *6 = Glircidia sepium* (Jacq.) *7 = Albizia lebbek* Benth. *8 = Calophyllum inophyllum* L. 9 = *Mammea siamensis* (Miq.) *10 = Samanea saman* (Jacq.) *11 = Mimusops elengi* L. *12 = Erythrina variedata* L. *13 = Manilkara kauki* (L.) *14 = Schoutenia glomerata* King. *15 = Cassia grandis* L.f. *16 = Lagerstroemia floribunda* Jack. *17 = Delonix regia* (Bojer) *18 = Bauhinia purpurea* L. *19 =*

Lagerstroemia speciosa (L.) *20 = Tectonia grandis* L.f. *21 = Casuarina equisetifolia* L. *22 = Tabebuia rosea* (Bertol.) DC. *23 = Cassia fistula* L.
24 = Terminalia catappa L. *25 = Ficus annlata.* *26 = Ficus elastica* Roxb
27 = Ficus benjamina L. *28 = Plumeria Spp.* *29 = Barringtonia asiatica*
30 = Schefflera actinophylla (Endl.) *31 = Butea monosperma* O.Ktze.
32 = Magnolia sirindhorniae *33 = Tecoma stans* (L.) *34 = Terminalia ivoriensis 35 = Eugenia javanica*, Lamk. *36 = Callistermon Viminalis*
37 = Pithecellobium dulce Benth. *38 = Pterocarpus indicus* wild. *39 = Ficus religiosa* L. *40 = Cerbera odollam* Gaertn. *41 = Tamarindus indica* L.
42 = Couroupita guinensis Aubl. *43 = Ceiba pentandra* Gaertn.
44 = Hydnocarpus anthelmintica *45= Cassia siamea* Lamk. *46 = Vitex glabrata* R.Br. *47 = Hevea brasiliensis* Muell. *48 = Azadirachta indica* A.

APPENDIX B: Information about common tree species

(Source: Plants of Thailand Research Unit, Faculty of Science, Chulalongkorn University, September 2011)

1. *Samanea saman (Jacq.)* Merr.

Family: LEGUMINOSAE-MIMOSOIDEAE

Common names: East Indian walnut, Rain Tree

Characteristics: It usually reaches 15 to 25 meters tall with umbrella shaped canopy. It has alternative compound leaves shaped like a feather. Leaves size around 2 - 4 centimeters long and 1 - 2 centimeters wide. Flowers are very lean and are gathered together in a head. There are long stamens usually in pink. The flowers usually bloom around August to February. Its origin is from tropical South America.

2. *Terminalia catappa* L.

Family: COMBRETACEAE

Common names: Bengal almond, Indian almond, Olive-bark tree, Sea Almond, Singapore almond, Tropical almond, Umbrella tree.

Characteristics: It usually has 8 to 20 meters tall. Leaves are large (, green, and single, but becoming red with old ages. Flowers are white, tiny, and are in branches between leaves. It has round oval fruits. The flowers bloom in 2 phases – February to April, and August to October. Its origins are Madagascar, East India, Malaysia, and Pacific Islands.

3. *Peltophorum pterocarpum* (DC.) Backer ex K.Heyne

Family: LEGUMINOSAE-CAESAL PINIOIDEAE

Common Names: Copper pod, Yellow flame

Characteristics: It is a deciduous plant that can reach to 25 meters. Its alternate leaves are and evenly compound like feather. The size of leaf is small, less than 5 centimeters long. The flowers are yellow with fragrance, and gather in branch. The flowers bloom around March to June. The fruit is elongated hard pod. It is the south-east Asian original plant.

4. *Pterocarpus indicus* wild.

Family: LEGUMINOSAE-PAPILIONOIDAE

Common Names: Burmese rosewood, Andaman redwood, Amboyna wood

Characteristics: It is a deciduous species, which can be grown up to 20 meters. Leaves are imparipinnate and alternate each other in a branchlet. It has thin and light pods. The shape of its flower is bean-like. The color of flower is yellow that it can be seen on the tree during February to May. It is originally in South-east Asia.

BIOGRAPHY

Chanon Suwanmontri, born 21th February 1988 in Bangkok, graduated with Honor in 2011 from Faculty of Economics, Chulalongkorn University (Bachelor of Economics). Majoring in environmental and natural resource economics, Chanon decided to deepen his knowledge in environmental science for Master of Science degree, Graduate School, Chulalongkorn University. During his study at Chulalongkorn University, Chanon Suwanmontri received various scholarships and award as follows : 1-year Undergraduate Exchange Program Scholarship at Saitama University, Japan, granted by Japan Student Services Organization (JASSO) during April 2008-March 2009; Teaching Assistantship granted by Faculty of Economics, Chulalongkorn University in 2010 ; and HM King Bhumibol Adulyadej's 72's Birthday Anniversary Scholarship granted by the Graduate School, Chulalongkorn University 2011- 20112 for his Master Degree in Environmental Science.

As well as economics and science studies, Chanon has also been regarded as a musician. He received Licentiate Diploma in Piano Performance with Highest Honor from Trinity College of Music, London, United Kingdom in 2010, which is equivalent to the performance component completion of a full-time undergraduate program at a music conservatoire. For working experiences, he participated in Saitama University Orchestra (1st violinist position) during April 2008 – March 2009. He has been a piano instructor for various music schools since 2006, ending with Alliance Française de Bangkok, Thailand in October 2012. Enhancing these experiences, Chanon has advanced skills in 3 foreign language -- Japanese (Japanese Language Proficiency Test Certificate level N2), French (Diplôme D'Études En Langue Française- niveau A1), and English.