DETERMINATION OF ABOVEGROUND CARBON SEQUESTRATION IN RESTORED FOREST BY FRAMEWORK SPECIES METHOD

KANLAYARAT JANTAWONG

DOCTOR OF PHILOSOPHY
IN ENVIRONMENTAL SCIENCE

GRADUATE SCHOOL
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THIS THESIS HAS BEEN APPROVED TO BE A PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
IN ENVIRONMENTAL SCIENCE

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24 November 2017

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CONTENTS

ข้อความแห่งการริเริ่ม

1) ดุษฎีนิพนธ์นี้ได้นำเสนอวิธีการใหม่ในการสำรวจมวลชีวภาพเหนือพื้นดินของต้นไม้ (Partial harvest method) โดยทำการเก็บข้อมูลมวลชีวภาพเหนือพื้นดินของต้นไม้หลายชนิดในแปลงอายุต่างๆกัน เพื่อเปรียบเทียบกับวิธีการสำรวจมวลชีวภาพที่ใช้กันทั่วไป อย่างเช่น การคำนวณอัลโลเมตริก และมีการสรุปในตอนท้ายถึงวิธีการที่เหมาะสมในการสำรวจมวลชีวภาพของต้นไม้

2) มีการสร้างแบบจำลองการเพิ่มมวลชีวภาพของต้นไม้ควบคู่ไปกับการสะสมคาร์บอนของต้นไม้ แบบจำลองนี้ได้มีการคำนวณเริ่มจากระดับต้นไม้แต่ละต้น จากนั้นจึงขยายขอบเขตให้เป็นในระดับพื้นที่ โดยอิงจากข้อมูลที่ทำการสำรวจในแปลงพื้นที่ศึกษา การสร้างแบบจำลองนี้ช่วยทำให้เกิดความเข้าใจและตระหนักรู้เกี่ยวกับข้อมูลที่จำเป็นสำหรับใช้ในการคำนวณ เพื่อให้แบบจำลองที่ได้มีความสมบูรณ์และสมจริงมากที่สุด

STATEMENTS OF ORIGINALITY

1. New method for above-ground biomass sampling (Partial harvest method) was tested with various tree species and plot ages and compared with widely used allometric equations. The suitable method for assessing above-ground biomass was suggested.

2. Tree growth modeling along with the efficiency of carbon absorption were constructed. The modeling was then expanded from a tree scale to area scale, based on the actual measurement in different plot ages. This modeling process identified the knowledge gaps for species specific tree growth model.

หัวข้อดุษฎีนิพนธ์	การหาปริมาณการสะสมคาร์บอนเหนือพื้นดินในพื้นที่ป่าที่ถูกฟื้นฟูด้วยวิธีพรรณไม้โครงสร้าง
ผู้เขียน	นางสาว กัลยารัตน์ จันต๊ะวงศ์
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	ผศ.ดร. ประสิทธิ์ วังภคพัฒนวงศ์ อาจารย์ที่ปรึกษาร่วม
	ศ. เกียรติคุณ เดวิด ฮิบส์ อาจารย์ที่ปรึกษาร่วม

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บทคัดย่อ

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      การทำลายพื้นที่ป่าเขตร้อนเป็นสาเหตุที่ทำให้แหล่งสะสมคาร์บอนบนบกลดลงและส่งผลถึงปัญหาการเปลี่ยนแปลงสภาพภูมิอากาศของโลก การฟื้นฟูพื้นที่ป่าในเขตร้อนจะช่วยแก้ปัญหาดังกล่าว แต่การวัดปริมาณว่าคาร์บอนที่ถูกดูดซับโดยพื้นที่ป่าที่เกิดจากการฟื้นฟูป่ายังมีน้อย ดังนั้นการศึกษาครั้งนี้ซึ่งได้มีการทดลองใช้วิธี Partial Harvest Method ในการเก็บข้อมูลปริมาตรต้นไม้ และมวลชีวภาพเหนือพื้นดิน กลุ่มตัวอย่างพันธุ์ไม้ที่ทำการศึกษาประกอบด้วยพันธุ์ไม้โครงสร้าง 11 ชนิด ในแปลงฟื้นฟูป่าอายุ 5 10 และ 14 ปี (R5, R10 และ R14 ตามลำดับ) เพื่อหาชนิดที่เหมาะสมสำหรับการเพิ่มปริมาณการสะสมคาร์บอนในการฟื้นฟูป่า ปริมาณคาร์บอนที่สะสมเหนือพื้นดินคำนวณโดยใช้ค่าความหนาแน่นเนื้อไม้ ปริมาตรต้นไม้ และมวลชีวภาพเหนือพื้นดิน ผลการศึกษาพบว่า ปริมาณเปอร์เซ็นต์คาร์บอนต่อมวลชีวภาพที่สะสมในเนื้อไม้ไม่มีความแตกต่างกันระหว่างอายุต้นไม้ และไม่มีความแตกต่างกันระหว่างชนิดต้นไม้ โดยพบว่ามีค่าเฉลี่ยของทุกชนิดที่ 44.67% ($\pm$0.54) ของมวลชีวภาพ ในแปลง R14 พบว่า ทองหลางป่า (*Erythrina subumbrans*) มีการเจริญเติบโตมากกว่าชนิดอื่นๆและสะสมปริมาณคาร์บอนเหนือพื้นดินมากกว่าชนิดอื่นๆ คือ 135.23 kgC/ต้น เมื่อเฉลี่ยค่าการสะสมคาร์บอนเหนือดินต่อต้นของทุกชนิด พบว่าในแปลง R5 R10 และ R14 มีค่าการสะสม 9.4, 29.0 และ 48.8 kgC/ต้น ตามลำดับ เมื่อเปรียบเทียบปริมาณคาร์บอนเหนือดินที่สะสมในพื้นที่ต่อเฮคแตร์ พบว่า ป่าธรรมชาติที่อยู่ใกล้เคียงกับแปลงฟื้นฟูป่ามีค่าการสะสมคาร์บอนเหนือดินมากที่สุด คือ 181.5

tC/ha รองลงมาคือ ป่าสนอายุประมาณ 40 ปี และแปลงฟื้นฟูป่าอายุ 14 ปี โดยมีค่าการสะสมคาร์บอน
เหนือพื้นดิน 124.1 และ 105.9 tC/ha ตามลำดับ จากผลการศึกษาพบว่าปริมาณคาร์บอนเหนือดินที่
สะสมในพื้นที่ป่าที่ฟื้นฟูด้วยวิธีการพันธุ์ไม้โครงสร้าง จะมีปริมาณเทียบเท่ากับป่าธรรมชาติภายใน
16-17 ปี

นอกจากนี้ การเลือกชนิดพันธุ์ไม้สำหรับฟื้นฟูป่ายังควรคำนึงถึงความสามารถในการดูดซับ
คาร์บอนอีกด้วย การศึกษาครั้งนี้ทำการทดสอบความสามารถในการดูดซับคาร์บอนโดยใช้พันธุ์ไม้
โครงสร้างจำนวน 8 ชนิดเพื่อเปรียบเทียบกัน โดยใช้เครื่อง LICOR รุ่น Li-6400 ทดสอบในระดับ
ความเข้มข้นของคาร์บอนไดออกไซด์ที่เทียบเท่ากับความเข้มข้นของคาร์บอนไดออกไซด์ในชั้น
บรรยากาศปัจจุบัน โดยทดสอบในระดับความเข้มแสงที่ต่างกัน โดยพบว่า ซ้อ (*Gmelina arborea*) มี
อัตราการสังเคราะห์แสงสูงสุดคือ 56.2 ± 15.2 μmol $CO_2/m^2/s$ ผลการศึกษาอัตราการสังเคราะห์แสง
ในระดับใบ จะนำมาคำนวณให้เป็นการสังเคราะห์แสงในระดับเรือนยอดของต้นไม้ และเปรียบเทียบ
กับผลจากการเก็บข้อมูลในภาคสนาม อย่างไรก็ตาม พบว่าการคำนวณให้ผลการประเมินที่มากเกิน
ความเป็นจริง อันเป็นผลมาจากการขาดข้อมูลบางอย่างที่จำเป็นในการคำนวณ เช่น การบดบังแสงอัน
เนื่องมาจากปัจจัยเมฆ

ผลปริมาณคาร์บอนเหนือดินที่สะสมในพื้นที่ป่าฟื้นฟูด้วยวิธีพันธุ์ไม้โครงสร้างจากการศึกษา
ในครั้งนี้ รวมกับปริมาณคาร์บอนใต้ดินในพื้นที่การศึกษาเดียวกัน (ข้อมูลทุติยภูมิ) ถูกนำมาประเมิน
ในประเด็นของการซื้อขายคาร์บอนในตลาดคาร์บอนภาคสมัครใจ (voluntary market) พบว่าในปีที่ 14
ของการฟื้นฟู ทั้งคาร์บอนเหนือดินและใต้ดิน จะสามารถสร้างรายได้มากถึง 11,308.4 US $ / ha หรือ
มีรายได้เฉลี่ยจากปีแรกถึงปีที่ 14 คือ 255.5 US $ /ha จากการศึกษาในครั้งนี้ สามารถสรุปได้ว่าการ
ฟื้นฟูป่าด้วยวิธีพันธุ์ไม้โครงสร้างสามารถสะสมปริมาณคาร์บอนในพื้นที่ในเวลาที่รวดเร็ว นอกจาก
ส่งเสริมการสะสมคาร์บอนแล้ว วิธีพันธุ์ไม้โครงสร้างยังช่วยฟื้นฟูความหลากหลายทางชีวภาพ ทำให้
ชุมชนที่อยู่โดยรอบป่าสามารถพึ่งพิงผลผลิตจากป่าและได้รับประโยชน์จากระบบนิเวศที่สมบูรณ์ ซึ่ง
สิ่งเหล่านี้ล้วนเป็นส่วนสำคัญของโครงการ REDD+ อันจะช่วยให้คนสามารถอยู่ร่วมกับป่าได้อย่าง
ยั่งยืน

Dissertation Title   Determination of Aboveground Carbon Sequestration in
                             Restored Forest by Framework Species Method

Author   Ms. Kanlayarat Jantawong

Degree   Doctor of Philosophy (Environmental Science)

Advisory Committee   Dr. Stephen Elliott   Advisor
                             Asst. Prof. Dr. Prasit Wangpakapattanawong   Co-advisor
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ABSTRACT

Tropical deforestation reduces the global terrestrial carbon sink and substantially contributes towards global climate change. Conversely, tropical forest restoration could help to mitigate the problem, but few measurements of how much carbon can be absorbed by forest restoration have been published. The objectives of the research presented here were therefore, to determine the above-ground carbon storage of restored forest and determine above-ground carbon-uptake rates of trees at the species level. Such information can support the efficient design of forest restoration projects for carbon sequestration and contribute towards the development of proper methods of forest restoration management, to both recover biodiversity and maximize carbon storage. This study used a partial harvesting method, to assess above-ground biomass and compare carbon sequestration among 11 framework tree species (selected to accelerate forest regeneration by suppressing weeds and attracting seed dispersers), in restoration plots, aged 5, 10 and 14 years old in northern Thailand. Above-ground carbon sequestration was derived from wood density, tree volume and above-ground biomass of 3 trees of each

of 11 tree species, in 5, 10 and 14-year old restoration plots (RF5, RF10 and RF14, respectively). Carbon concentration of stem wood did not vary significantly among the tree species tested or age of restoration ($p \leq 0.05$), averaging 44.67% (±0.54). In the oldest plot (RF14), *Erythrina subumbrans* grew significantly larger than the other species and sequestered the most above-ground carbon: 135.23 kgC/tree. Mean above-ground carbon sequestration per tree, across species for trees aged 5, 10 and 14 years old, was 9.4, 29.0 and 48.8 kgC/tree respectively. When considering above-ground carbon, sequestered on a scale of per hectare, natural forest (located nearby restoration plots) sequestered 181.5 tC/ha, which higher than that of a 40-year-old plantation nearby at 124.1 tC and plot R14, 105.9 tC/ha. Models, based on the field data, predicted a return to the above-ground carbon levels, typical of nearby mature forest by 16-17 years after implementation of forest restoration.

Eight framework tree species were tested for carbon uptake ability at the leaf-level using LICOR (model LI-6400) at a constant atmospheric concentration of CO_2 but with varied light intensity. *Gmelina arborea* attained the highest photosynthesis rate at 56.2 ± 15.2 µmol $CO_2/m^2/s$, while *Nyssa javanica* had the lowest rate at 18.6 ± 2.3 µmol $CO_2/m^2/s$. These results were then used in a model of carbon uptake rate at the tree-crown level and compared with field data. The model generally over-estimated carbon uptake, because of i) difficulty with including the effects of cloud cover on reducing light availability and ii) obtaining accurate equations to account for carbon lost via respiration.

The data and analyses were then applied to carbon trading scheme, using voluntary carbon credit prices and including secondary data for below-ground carbon, collected in the same location. By year 14 of restoration, using the framework tree species method, and accounting for both above-ground and below-ground carbon, the financial model predicted total revenue from sales of credits on the voluntary market of 11,308.4 US$/ha which would provide an average annual income of 255.5 US$/ha, after establishment cost have been taken into account. The framework species method is therefore capable of rapidly accumulating carbon, a property which, along with its acceleration of biodiversity recovery and provision of a wide range of forest products and ecological services to local people, meets both the requirements and safeguards of REDD+ projects.

CHAPTER 1

Introduction

1.1 Principles, Theory, Rationale and/ or Hypotheses

Climate change is a global concern. Global warming is caused by a buildup of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the atmosphere. Carbon circulates throughout the biosphere by the processes of photosynthesis, respiration, decomposition, and combustion (IPCC, 2000). Human activities have caused emissions of CO_2 to increase, through burning fossil fuels and land-use changes. According to the International Panel on Climate Change (IPCC), 1.6 billion tons of carbon is released annually by land-use changes, especially deforestation and forest degradation (Denman et al., 2007). The concentration of CO_2 in the atmosphere has risen from approximately 277 parts per million (ppm) in 1750 (Joos and Spahni, 2008), to approximately 400 ppm recorded at Mauna Loa station in 2013 (Le Quéré et al., 2015). The 9.9 billion tons of carbon in the form of CO_2 emitted from fossil fuels in 2015, 41% came from coal, 34% from oil, 19% from gas, 5.6% from cement production and 0.7% from flaring (Le Quéré, et al., 2016). CO_2 is the most abundant of the greenhouse gases, comprising about 76% of total emissions. About 65% is from fossil fuels and the industrial sector, whilst 11% is from deforestation and land use changes. Methane and nitrous oxide comprise only 16% and 6% of total greenhouse gases emission respectively (IPCC, 2014) (Fig 1). To reduce excess CO_2 in the atmosphere, the most effective and sustainable solution is to use plants to absorb and store carbon in biomass. Collectively, forests are the largest terrestrial vegetation carbon sinks. They absorb vast quantities of CO_2 via photosynthesis process and store its constituent carbon in complex organic molecules (particularly lignin and cellulose) in both above- and below- ground biomass. The carbon cycle involves the uptake of CO_2 by photosynthesis by plants.

Photosynthesis uses energy from sunlight to convert carbon dioxide into carbohydrates, which are subsequently metabolized to yield energy to drive cellular reactions. Carbon dioxide is finally released by respiration in several ways e.g. cellular respiration, which is the set of the metabolic reactions and processes that occur in organisms' cells to convert biochemical energy from nutrients into adenosine tri-phosphate (ATP) and then release waste products. Two waste products are H_2O and CO_2 created during this cycle (Cunningham, et. al., 1999). Forest ecosystems can be carbon sources and sinks and are, therefore, involved in international climate policy (Egoh, et. al., 2009), since land has the potential to sequester an additional 87 billion tons carbon by 2050 (Watson, et. al., 2000). Therefore, the assessment of biomass and carbon storage in forest ecosystems is useful to evaluating the global carbon sink capacity. Moreover, forest carbon data can contribute to policy planning in climate change mitigation for decreasing the greenhouse effects and climate regulation (Liang, et al., 2006).
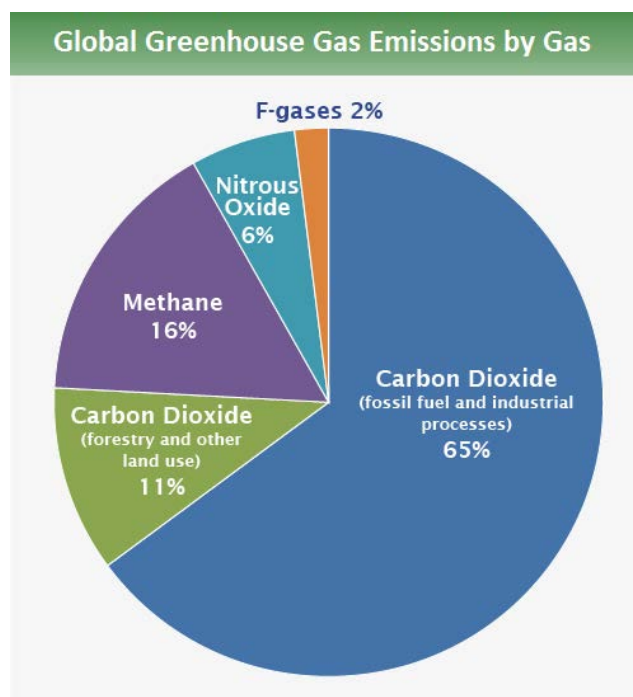
Figure 1 the key greenhouse gases emitted by human activities at the global scale (IPCC, 2014)

Current carbon stocks are much larger in soils than in vegetation such as in temperate forests, where soil carbon stock averages 100 Gt C, whilst the vegetation stores on average only 59 Gt C. (IPCC, 2000). In tropical forests, the soil carbon stock is about 216 Gt C, whilst in vegetation it is 212 Gt C. In the United States, forest absorb and store about 750 million metric tons of carbon dioxide each year, an amount equivalent to 10% of the country's CO_2 emissions (Hines et al., 2010). In Thailand, Nan province, primary forest accumulates a total carbon stock of 357.62 ± 28.51 Mg/ha (Pibumrung, et. al., 2008). However, forest loss and degradation in the tropics contribute 6–17% of all greenhouse gas emissions. Between 2000 and 2005, 1.75 million ha of forest was lost from protected areas in the humid tropics, resulting in emissions of 0.25–0.33 Pg C (Scharlemann et al., 2010). Forestry can be involved in climate change mitigation policies, by reducing emissions from deforestation and degradation. Increases in forest area by reforestation can also increase carbon sequestration. Moreover, proper forest management can also increase carbon density and biodiversity (Hurteau et. al., 2010).

The international community has proposed many schemes to mitigate climate change. The most widely accepted one has been REDD+, which stands for Reducing Emissions from Deforestation and Forest Degradation. Formulation of REDD+ began at the Montreal Conference of Parties (COP) in 2005. Originally conceived as a mechanism merely to reduce the rate at which CO_2 from forest destruction entered the atmosphere, the initiative was subsequently expanded to include "enhancement of carbon stocks" (UNFCCC, 2014) i.e. removal of CO_2 from the atmosphere by forest expansion and/or increasing stocking density. The scheme is providing funding and monitoring mechanisms for both forest conservation and restoration projects, which meet the goals of REDD+ of increasing the forest carbon sink, by increasing forest area, enhancing the sustainable management biodiversity and providing for local people's livelihoods. Funding comes from both established carbon credit markets, as well as specially created international funds (RECOFT, 2009). Nowadays, many Southeast Asia countries are implementing REDD+, including Lao PDR, Myanmar, Cambodia, Vietnam, Malaysia and Indonesia (http://redd.unfccc.int/, accessed on 30 Jul 2016).

However, at the present date, Thailand has not implemented any project under the REDD+ program. The authorities are currently revising the country's Readiness Preparation Proposal (R-PP) under the Forest Carbon Partnership Facility (FCPF), led by the World Bank (Thai Climate Justice Working Group, 2012). One thing that can persuade community to plant forest willingly, REDD+ is the good option to be considered. Furthermore, the Royal Forestry Department, Ministry of Natural Resources and Environment has declared a strategy to increase forest area in Thailand under the Twelfth National Economic and Social Development Plan. From 2016 to 2021, the forest area in Thailand should increase to at least 40% of country area, of which 25% should be conservation forest and 15% economic forest (Royal Forestry Department, 2016). In 2015, Thailand had forest cover of 31.6% or 102.4 million rai (Royal Forestry Department, 2016).

Carbon storage in forests can be traded on international markets to generate financial benefits from emission reductions, in compliance with commitments under the UN Climate Change Convention (Jong et al., 2000). The price for carbon sequestration should rise in the future, since carbon sequestration is costly (Sohngen & Mendelsohn, 2003) and land available for forest restoration is decreasing. Developed countries must find ways to offset their carbon emissions. Many countries started to include national development planning for the forestry sector (Basuki et al., 2009). To support national policy planning, based on current issues and mitigation, scientific research about carbon sequestration by forests has become more important, and many papers have been published on this subject. Since national policies rely on measurements of the flux of carbon between the atmosphere and plants, accurate measurements of biomass and carbon stored in forests are needed.

The interchange of carbon between plants and the atmosphere can be measured by using the LI-6400XT Portable Photosynthesis System to measure the rate of photosynthesis (Bassow & Bazzaz, 1998 and Pattison, et.al., 1998). Data from LI-6400 may be extrapolated to calculate the rate of CO_2 absorption by trees over a given area. Several factors also impact the amount of carbon stored, such as climate, topography, soil fertility, water supply, wood density, tree architecture and tree species (Henry et al.,

2010). Wood density data that are used to convert volume data into biomass are critical for biomass estimates (Fearnside, 1997). The most appropriate measure of biomass is basic density or oven-dry weight divided by wet volume biomass. Carbon in forests can also be estimated by both destructive and non-destructive methods. Many researchers use non-destructive methods to estimate biomass by using allometric equations (Nascimento & Laurance, 2002; Lowson, 2008; Pibumrung, et.al, 2008; Hurteau, et. al., 2011). On the other hand, many researchers tried to estimate biomass using direct methods, which involve felling trees and weighting every part (Sah et al., 2004). However, in case of large trees, instead of felling them, biomass measurements might be done by "partition harvesting". This method requires measuring the stem volume and wood density. Subsamples are collected and their dry weights, and volumes measured. The dry weight of the tree is calculated based on wood density and tree volume (Snowdon *et al.,* 2002).

Apart from above-ground biomass, carbon content is also important, because carbon, stored in a tree, comprises about half its biomass (IPCC, 2006). Carbon content of woody tissues can be measured using a CHN elemental analyzer with gas chromatography (Kraenzel et al., 2003). For example, Lamlom and Savidge (2003) reported that the carbon content of 22 hardwood tree species ranged from 46.27% to 49.97% (w/w). However, despite such accurate measurements, many publications estimate carbon content by assuming that biomass is 50% carbon (Jepsen, 2006; IPCC, 2006; Terakunpisut, et al., 2007). Accurate and more precise measurement of carbon absorbed by forest restoration therefore is needed for implementation of REDD+.

To restore forest to degraded or abandoned areas, knowledge of forestry and ecology are needed, to ensure the success of forest restoration projects. The goal of forest restoration is often stated as the recovery of ecological processes to levels typical of natural forest status. This research will add another benefit to forest restoration project, which is the carbon perspective. Nowadays and in the future, forest restoration will need to consider benefits derived from carbon sink expansion. Knowledge of which tree species to plant (or to encourage by natural regeneration) and how to manage restoration will help forest restoration projects to be more successful both ecologically,

and as carbon sinks. Aboveground biomass and carbon sequestration data can be used in models to predict the future biomass and carbon status of restoration sites.

Chiang Mai University's Forest Restoration Research Unit or FORRU has developed the forest restoration method, adapted from Australia (Goosem and Tucker, 1995) called the framework species method. Originally, developed to restore degraded forest in the Queensland, Australia, this technique involves planting 20-30 indigenous forest tree species (combinations of both pioneers and climax species) on restoration sites where natural regeneration is insufficient or hindered by anthropogenic disturbances. Planted trees restore basic forest structure and ecosystem functioning. The properties of framework tree species are: (i) indigenous tree species typical for the target forest ecosystem, (ii) high survival and growth rates (iii) dense, spreading crowns that shade out herbaceous weeds (iv) produce resources (e.g. fruit, nectar, nesting sites etc.) that attract seed-dispersing wildlife at a young age and (v) resilient after drought and fire (e.g. coppicing ability) (Elliott et al., 2013).

If knowledge of carbon sequestration and carbon trade are combined, additional financial incentives could be generated to promote forest restoration, not only to bring about ecological recovery, but also to expand the global carbon sink and contribute substantially towards climate change mitigation. Such restoration activity would sustainably support local communities in or near the forest enabling them to protect their forests over the long term and increase their income.

1.2 Objectives

The objectives of the research presented here were therefore to determine, i) the above-ground carbon storage capacity of restored forest and ii) the above-ground carbon-uptake rates of trees at the species level. Such information can support the efficient design of forest restoration projects for carbon sequestration and contribute towards the development of proper methods to forest restoration management to both recover biodiversity and maximize carbon storage.

CHAPTER 2

Literature Review

2.1 Climate Change

Earth's climate has undergone constant changes throughout geological history, the most recent examples of which have been ice ages and interglacial periods. However, the recent rapid changes in climate (known as global climate change or GCC) are largely caused by human activities. Over the last century, burning fossil fuel such as coal and oil has increased the atmospheric carbon dioxide (CO_2) concentration. The estimation of fossil fuel emissions by the Carbon Dioxide Information Analysis Center (CDIAC, 2014), said total global emissions has increased from 9.78 billion metric tons of carbon in 2013 to 9.86 billion metric tons in 2014. Fossil fuel emissions in 2014 were 0.6% above emissions in 2013 and 60% above emissions in 1990 (CDIAC, 2014). Over a decade, these emissions equate to 45 ppm of CO_2 or an increase of 11.5% (NOAA, 2017). The recent data of CO_2 concentration in the atmosphere recorded in March, 2017 was 407.05 ppm and the mean temperature in February 2016 was highest since 1880. (NASA, 2017). Carbon dioxide and other greenhouse gases can trap heat in the atmosphere. The increasing of greenhouse gases are clearly causing Earth's climate to warm (Fig. 2.1-2.2).
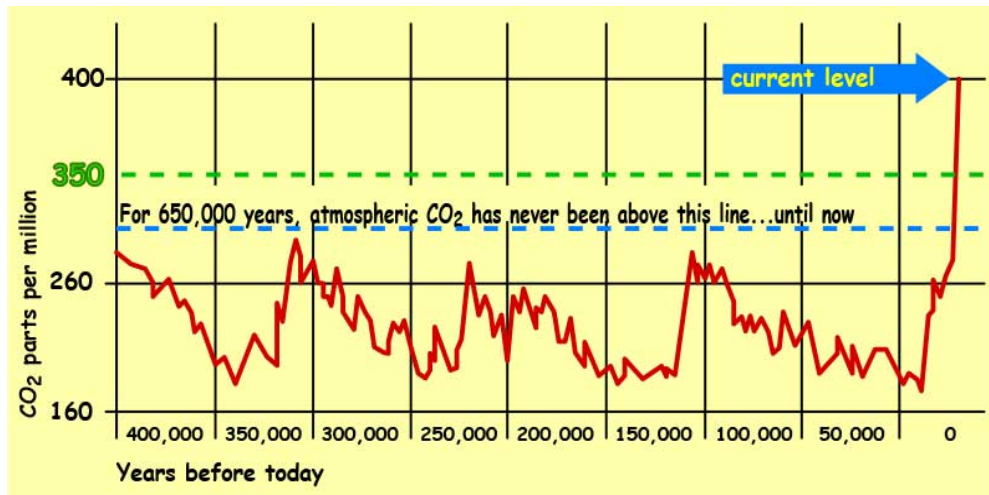
Figure 2.1 Atmospheric CO2 from 400,000 year ago, until the present. The final peak started in 1950. (NASA, 2017)
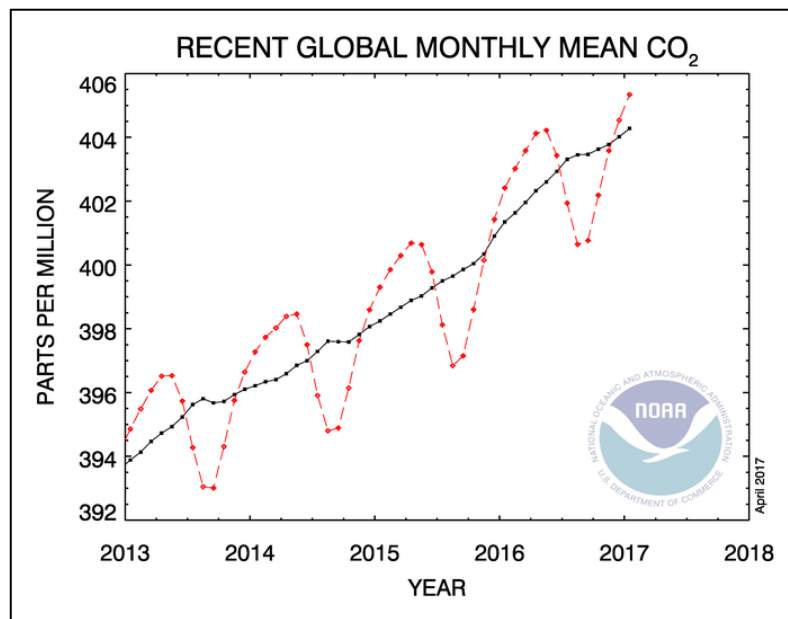
Figure 2.2 Recent monthly mean carbon dioxide, globally averaged over marine surface sites. The dashed red line represents the monthly mean values, centered on the middle. of each month. The black line represents the same, after correction for the average seasonal cycle. (NOAA, 2017).

The results of changing the atmospheric greenhouse are many, some certain effects could be described as follows:

Global temperature will become warmer. The average temperature increased by 2016 compared with previous year was 0.99 °C. Time series in Fig. 2.3 shows the five-year average variation of global surface temperatures from 1884 to 2016. (Fig. 2.3)
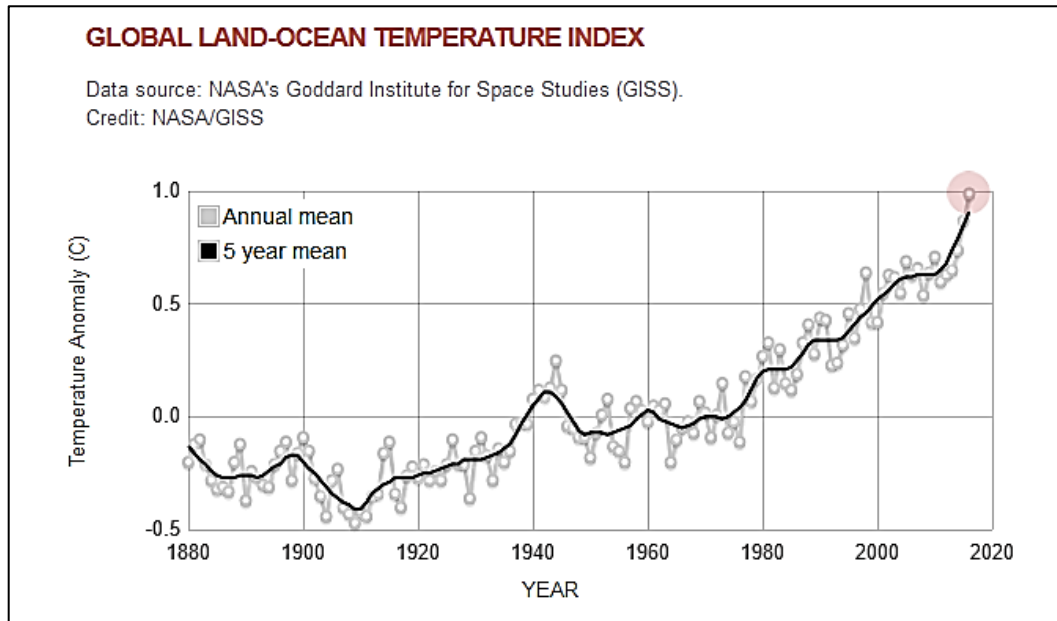
Figure 2.3 The change in global surface temperature. Year 2016 ranks as the warmest on record. (NASA, 2017).

Temperature increasing will warm the oceans and partially melt-down glaciers and other ice, increasing sea level by 3.4 mm per year (NASA, 2017). Ocean water will also expand as it warms, contributing further to sea level rise (Fig. 2.4).

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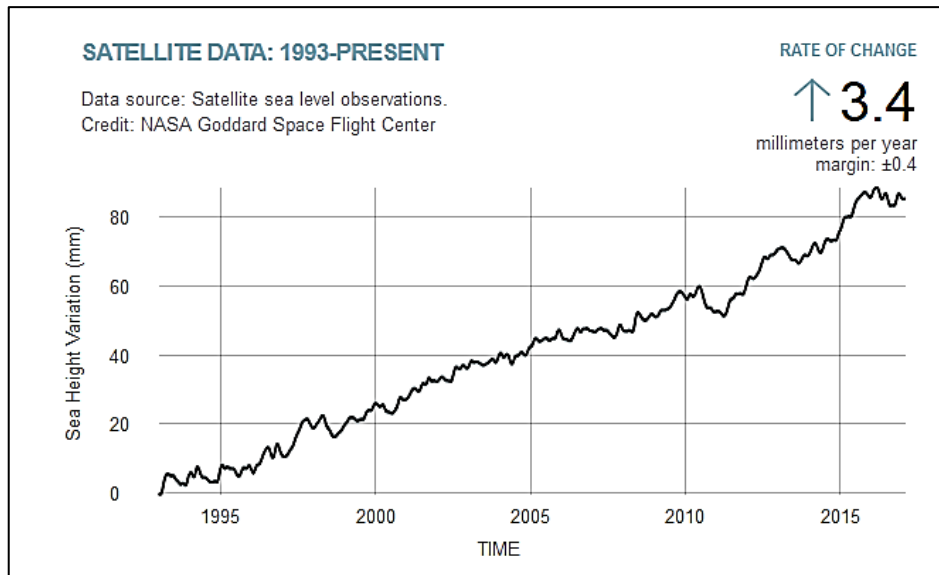
Figure 2.4 Satellite data of sea level rise from 1993 to the present (NASA, 2017)

Over the past century, vegetation has been gradually moving toward the poles and up mountain slopes or toward warmer equator where rainfall is greater (Gonzalez et al., 2010). 10% to 50% of global land may be very fragile. Temperate mixed forest, boreal coniferous forest and tundra and alpine biomes are the most vulnerable to biodiversity lost, due to potential increases wildfire. Meanwhile, tropical evergreen broadleaf forest and desert biomes are probably least vulnerability (Gonzalez et al., 2010).
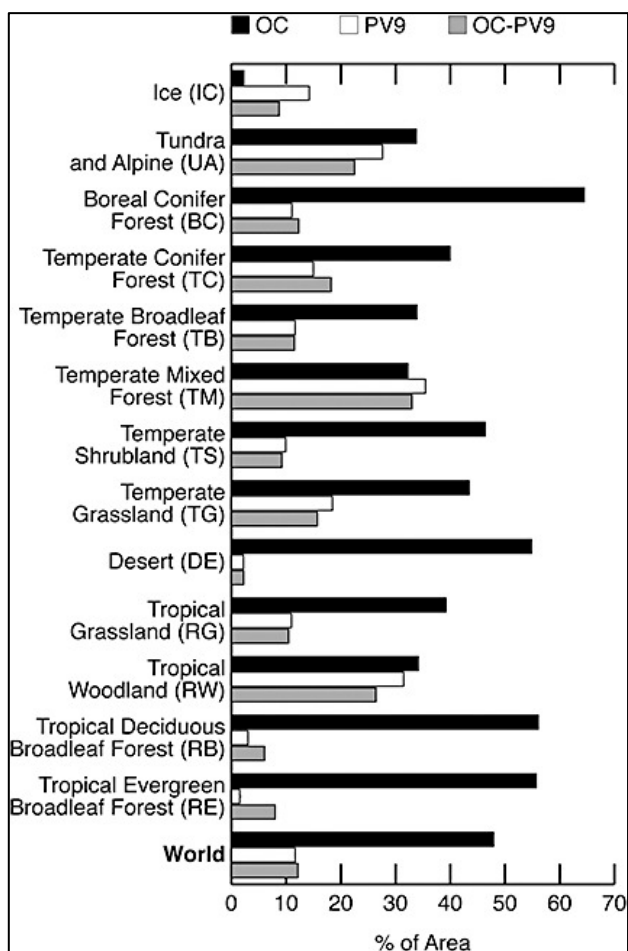
Figure 2.5 Fraction of biome area in areas of high to very high vulnerability under observed climate (OC, black), vegetation projections under nine general circulation model–emissions scenario combinations (PV9, white), overlap of observed climate and vegetation projections under nine general circulation model–emissions scenario combinations (OC-PV9, grey). (Gonzalez et al., 2010)

Such likely problems have prompted international negotiations to address the problem of GCC. The most recent international conference on climate change (the 21st meeting of the UNFCCC Conference of the Parties, or COP 21) was held at Paris, France from 30 November to 12 December 2015. The new agreement at COP21 established common commitments for every country, to put their best efforts into participating in climate change mitigation schemes and limit temperature increase to 1.5 °C (source: www.cop21paris.org). All parties are required to report regularly on their emissions and implementation efforts, and undergo international review.

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One of the most sustainable ways to reduce atmospheric CO_2 is to use plants to absorb CO_2, since plants use CO_2 for photosynthesis and release O_2 back into the atmosphere. Therefore, a better understanding of the carbon dynamic in forests and mechanisms that involve in forest carbon changes is important for projecting the future mitigation for atmospheric CO_2 levels and guiding the strategy of mitigation policies (Pan *et al.,* 2011)**.**

2.2 REDD+

Over the last 20 years, various studies have estimated that land-use change, including deforestation and forest degradation, accounts for 12-29% of global greenhouse gas emissions. REDD+, developed by the UN Framework Convention on Climate Change (UNFCCC), stands for Reducing Emissions from Deforestation and Forest Degradation in developing countries. This project aims to encourage forest conservation and sustainable management. Also, REDD+ is expected to be the main global tools to conserve and increase the forest area for carbon sink. Originally as REDD, it used to be a mechanism to reduce the emission of CO_2 from deforestation. Later on, REDD+ was subsequently expanded to include the carbon stocks enhancement such as expansion forest area for CO_2 removal (UNFCCC, 2014). If the financial mechanisms proposed by REDD+ are applied, it is expected that anthropogenic carbon emissions could be reduced by approximately 0.82 GtC/year, from 2015 -2050 (Khun and Sasaki, 2014). REDD+ offers a broad range of social, environmental and economic benefits to developing countries and forest communities (UN-REDD, 2016). There are two important safeguards must be applied to REDD+ project (UNFCCC, 2010). Firstly, the restoration must include the full and effective participation of relevant stakeholders which include indigenous peoples and local communities. It means that forest restoration project should provide as the same variety of forest products and ecological services as the original forest did for local communities. Secondly, it must be harmonized with the conservation of natural forests and biological diversity. The project must encourage the protection and conservation of natural forests and their ecosystem services and support social and environmental benefits. However, neither of these safeguards is going to be achieved through planting only fast-growing tree species or monoculture plantation (Alexander et

al., 2011). In order to meet both safeguards, the concept of "ecological restoration" (Lamb, 2015) must be applied to rebuild the structure and biodiversity-rich forests. Therefore, tropical reforestation could a potential plan for global climate change mitigation and led to ambitious global reforestation targets.

Bonn Challenge, established in 2011, with the goal to restore worldwide forest of 150 million hectares, by 2020. In 2014, UN Climate Summit, the New York Declaration on Forests decided to increase the forest area target and expand time scale to be 350 million hectares by 2030. By this figures, world forest would sequester approximately 1.7 GtC/year (Bonn Challenge, 2011).

As for Thailand, it is not yet implementing REDD+, but still in the process of establishing a national structure for a REDD+ working group under the Climate Change committee. The Department of National Parks, Wildlife and Plant Conservation will be the focal point but many other agencies will also be involved. The working group will be responsible for facilitating co-operation among all stakeholders, capacity building and setting up pilot projects.

Since the causes of deforestation and forest degradation is different among countries. The succession of REDD+ project relies on cooperation between government agencies (both national and local section) and local people who lives near or within forest. Kawasaki *et, al*. (2015) suggested an applied methodology for local agencies for smooth operation of REDD+ which included: 1) the use of available spatial data over the past decade of geographic information systems (GIS) to estimate land use and land-use change (LULUC) between forest and agriculture practice; 2) the assessment of carbon stock and carbon loss from conversion of forest to agricultural area and 3) the assessment of appropriate strategies to reinforce forests conservation and management, including sustainable agricultural production and include local communities in forest management.

2.3 The carbon cycle

In addition to the natural fluxes of carbon, human activities effect carbon stocks and exchanges through land-use change (IPCC 2000; Riebeek, 2011), although the burning of fossil fuels remains the dominant contributor to global carbon emissions. Land-use changes in the tropics have become an major concern for their impacts on the global carbon cycle and climate change (Carpenter et al., 2006; Blanc, Echard, and Herault 2009), although CO_2 emissions from forest conversion has decreased significantly, from an average of 4.0 Gt CO_2/year during 2001–2010 to 2.9 Gt CO_2/year during 2011–2015 (Federici et al., 2015). Moreover, remaining forests continue to function as carbon sink, with an average net removal of 2.2 Gt CO_2/year during 2001–2010, and 2.1 Gt CO_2/year during 2011–2015. Contrary to CO_2 emissions from deforestation, CO_2 emissions from forest degradation increased significantly, from 0.4 Gt CO_2/year in the 1990s, to 1.1 Gt CO_2/year in 2001–2010 and 1.0 Gt CO_2/year in 2011–2015. Emissions from deforestation were increasing from one-fourth in 2001–2010 of, to one-third in 2011–2015. Consequently, from 1991 to 2015, forest land was a net source of globally CO_2 emissions, averaging 1.52 Gt CO_2/year. (Fig. 2.6)

Annual Global Carbon Emissions
2015 Global Carbon Budget

Year	Total	Global Emissions Fossil Fuel & Cement	Land-Use Change
2014		9.795 GtC	~ 0.9 Gtc
2013		9.735 GtC	
2012		9.575 GtC	
2011		9.449 GtC	
2010	9.995 Gtc	9.140 GtC	0.855 GtC
2009	9.567 Gtc	8.700 GtC	0.867 GtC
2008	9.666 Gtc	8.740 GtC	0.926 GtC
2007	9.472 Gtc	8.532 GtC	0.940 GtC
2006	9.355 Gtc	8.363 GtC	0.992 GtC

Figure 2.6 Annual global carbon emissions. (Le Quéré *et al.*, 2015)

2.4 Carbon storage in terrestrial ecosystems & tropical forests

Terrestrial ecosystems capture substantial amounts of carbon in live biomass and decomposing organic matter, therefore play an important role in the global carbon cycle (IPCC, 2000). In addition, forests are valued for ecosystem services and perform as tools for carbon capturing and as carbon pool (Sedjo, 2001; Pan *et al*., 2011). Trees sequester carbon into above- and below-ground biomass. The biomass and carbon stocks in forests are important indicators of forest productivity, energy potential and capacity to sequester more carbon (FAO, 2015). Therefore, land-use practices with trees involved could be important tools to store excess atmospheric CO_2, due to their less cost consuming, high carbon uptake potential and environmental friendly, as well as social benefits (Dhruw *et al*., 2009; Wani and Qaisar, 2014). Over the past 25 years, carbon stocks in forest decreased by 17.4 Gt or equivalent to a reduction of 697 million tonnes per year (approximately 2.5 Gt of CO_2). The reduction is mainly caused from land used change (converting forest lands into agricultural area, settlements) and forest degradation (FAO, 2015). Evaluation of the role of terrestrial ecosystems in the global carbon budget and their responses to climate changes requires the understanding of ecosystem processes and a methodology to integrate interactions among these processes (Cao and Woodward, 1998; Xiao *et al.,* 2003). International negotiations, to limit greenhouse gases, require an understanding of the current and potential future role of forest C emissions and sequestration in both managed and non-managed forests (Pan *et al.,* 2011). Raich *et al.* (2014) suggested that young secondary forests and plantations, in the moist tropics, have rapid rates of biomass accumulation and thus sequester large amounts of carbon. Carbon sequestration studies commonly convert biomass to carbon by using the IPCC conversion factor of 0.5 or 0.47 for tropical forest (IPCC, 2006).

Chemical analysis of wood provides more accurate values of carbon concentrations in biomass. The dry combustion method using a CHN elemental analyzer (Raich, *et al*., 2014) is commonly used. The analyzer performs flash combustion to convert organic compounds into gas. During combustion (at ca. 1000 °C), carbon is converted to CO_2; hydrogen to H_2O; nitrogen to N_2 and sulphur to SO_2. Each gas is then separated and quantified by Gas Chromatography (Thompson, 2008) (Fig. 2.7). The use of elemental

analyzer for forest carbon measurements was first proposed by Ravindranath and Ostwald (2008) in Carbon Inventory Methods Handbook for Greenhouse Gas Inventory, Carbon Mitigation and Roundwood Production Projects. Chaiyo et al. (2013) also adopted the CHN elemental analyzer to estimate carbon content in an experimental biomass fuel, which was 46.0±0.1%. Tadang and Pumijumnong (2011) analyzed the carbon content in moist evergreen forest on Chang Island, Thailand by dry combustion and found 46.33% in average of dry weight.
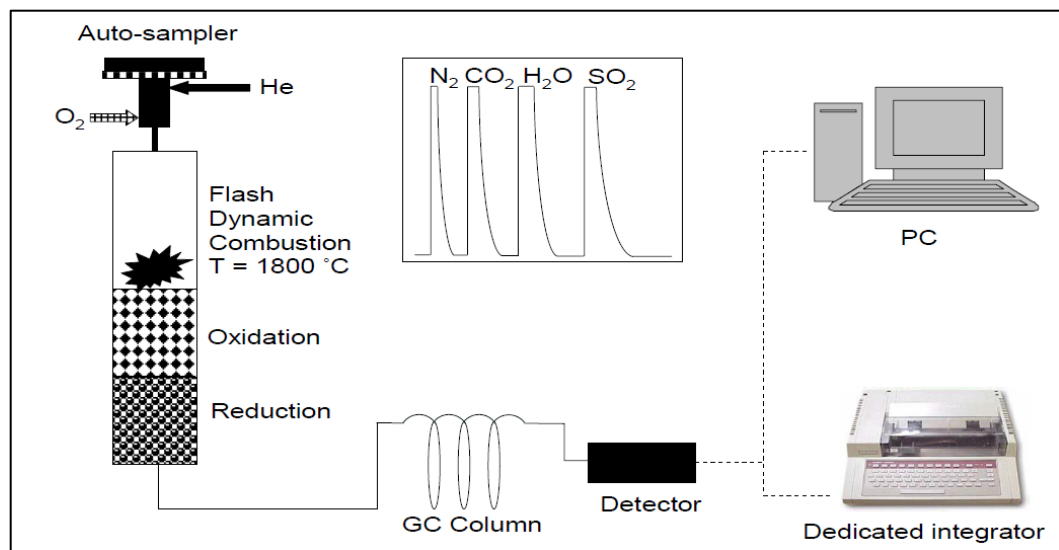
Figure 2.7 Principle and working flow chart of CHN elemental analyzer (The Royal Society of Chemistry, 2008)

2.5 Tree biomass

There are different approaches for calculating tree biomass. The most obvious method is simply to cut down the tree, dry it and weigh it (destructive sampling) (Ostadhashemi et al., 2014). The advantage of this method is accuracy of both total tree biomass and of its various components (leaves, branches, stems and roots). However, many trees would have to be felled for accurate calculation of means and variation. Drying and weighing such large volumes of material is usually impractical. However, Basuki et al. (2009) used the destructive method to assess the biomass and carbon stock in dry dipterocarp forest in Kalimantan, Indonesia. He felled 122 trees for his study.

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Tsutsumi et al. (1983) used destructive sampling to estimate the biomass of dry evergreen forest (DEF), mixed deciduous forest (MDF) and dry dipterocarp forest (DDF) in Thailand. Sixty trees of different sizes were felled, whereas Ogawa et al. (1965)'s study felled only 6 trees to sample evergreen forest. One of the advantages of the destructive method is that it can be used to generate allometric equations, linking easy-to-measure parameters of tree size (GBH, height etc.) to tree mass. Such equations can then be used for non-destructive estimates of tree mass. However, developing allometric equations for biomass assessment require destructive sampling, measured and weighed, and develop prediction equation from the resultant data. Destructive sampling is costly and generally unacceptable in conservation areas (MacFarlane et al., 2014).

Non-destructive methods require measurement of tree GBH (Girth at breast height) and height. Allometric equation are then applied for biomass calculation. Different allometric equations are used for each type of forest. The ones commonly used in Thailand are Brown's equation (Brown, 1997), Tsutsumi's equation (Tsutsumi et al., 1983) and Ogawa's equation (Ogawa et al., 1965). However, the non-destructive method has the disadvantage that it does not measure biomass directly and errors in applying allometric equations can be very large (Chave et al., 2005)

The partial harvest method was developed to try to reduce the problem described above. Partial sampling involves indirect measurements and/or subsampling of a tree to estimate its biomass. It involves two steps: i) stem and large branch biomass estimation from volume measurement, in combination with wood density estimation from core samples and ii) estimation of smaller branches biomass from regression sampling or by sub-sampling methods. Stem or branches biomass are calculated by multiplying stem volume with average wood density (Snowdon, 2002).

2.6 Photosynthesis

The term photosynthesis can be described as the metabolic partway that plants synthesise organic compounds from inorganic materials by using the energy from sunlight (Tamayo et al., 2001). The environmental factors that affect photosynthesis rate

are i) light, which is used to define shade-tolerant trees or sun-dependent trees; ii) water availability, which affects stomata closure and electron donors in photosynthesis; iii) temperature, which affects the enzymes involved in photosynthesis and other factors, such as iv) pollutants (e.g. sulfur dioxide) that inhibit photosynthesis or v) some herbicides that inhibit certain vital enzymes such as RUBISCO. However, the main limiting factors affecting photosynthesis are light intensity, CO_2 concentration and temperature. To integrate knowledge of photosynthesis and climate change mitigation, measurements of leaf and canopy-level carbon assimilation can provide information that can be applied to understand connections between environmental factors and physiological processes, which can then be broadened to estimate ecosystem fluxes (Winner *et al*., 2004).

Pearcy *et al*. (2004) assessed the role of species differences in architecture in light capture and carbon gain in their natural understory environment. Shade tolerant species or climax species captured both diffuse and direct light significantly more efficiently than for light-demanding, pioneer species. Moreover, pioneer species had greater daily assimilation, of both direct and diffuse light, due to significantly higher light availability where pioneer species grew, compared with where shade-tolerant species grew.

Several studies have attempted to estimate the rate of photosynthesis by using the LICOR 6400 portable photosynthesis system (Riddoch et al., 1991; Winner et al., 2004; Nicotra et al., 2008 and Gerardeaux et al., 2009). Net photosynthesis rates are expressed as rates of CO_2 uptake ($\mu molCO_2/m^2/s$). All of environmental parameters can be monitored and controlled from the console which is a data-logging computer. The data can be temporary stored in the Ram memory of the system or loaded through a wire port connected with user's computer. Measured and calculated variables, such as photosynthesis rate, conductance and internal CO_2 concentrations are displayed in real time. The hardware of the system consist of the console (Fig. 2.8) and the leaf chamber (the sensor head) (Fig. 2.9). The leaf chamber has tightly sealed gaskets that do not interact with H_2O or CO_2. The leaf chamber also contains a PAR light sensor parallel to the leaf surface, a thermocouple and a speed- variable mixing fan. The sensor head encloses a leaf surface and has integrated sensors for monitoring light, temperature, H_2O

and CO_2 levels. Light level and CO_2 concentration can be adjusted at any level from 0 to more than 2000 μ mol/m^2/s.

The incoming air is pumped through a controlled atmosphere. Plant leaf is enclosed in an assimilation chamber. The incoming air stream will be bypassed through a desiccant to get rid of the excess humidity and through a soda lime to catch any CO_2, before enter into the chamber (Tamayo et al., 2001). The input concentration of CO_2 and H_2O are adjusted by CO_2 scrubber ($Mg(ClO_4)_2$) and a desiccant that installed in the console. The control of humidity is also important since the stomata respond particularly to humidity. The selected levels of CO_2 are supplied by a CO_2 injector system. The desired CO_2 concentrations can be set by adjusting the levels of CO_2 of the incoming air until it reach the selected values or by using the external CO_2 injector system (CO_2 cartridge) (Fig. 2.10). Using the CO_2 cartridge can to provide a stable concentration at the desired value and maintain a constant rate of CO_2 concentration entering the chamber. The combination of light and CO_2 at any level can be set while the rest of the variables are held constant.

When the desire condition being set, air will be continuously passed through the leaf chamber to maintain the CO_2 concentration. The measurements rate of CO_2 fixed by a leaf is based on the differences of CO_2 in an air stream that is flowing into the leaf cuvette called "reference cell" compared to the air stream flowing out of it called "sample cell". (LI-COR, Inc., 2004) (Fig. 2.11).

Figure 2.8 Console box of LI-6400

Figure 2.9 Leaf chamber with CO_2 sensor head.

Figure 2.10 CO$_2$ cartridge used as the source of CO$_2$ injected.
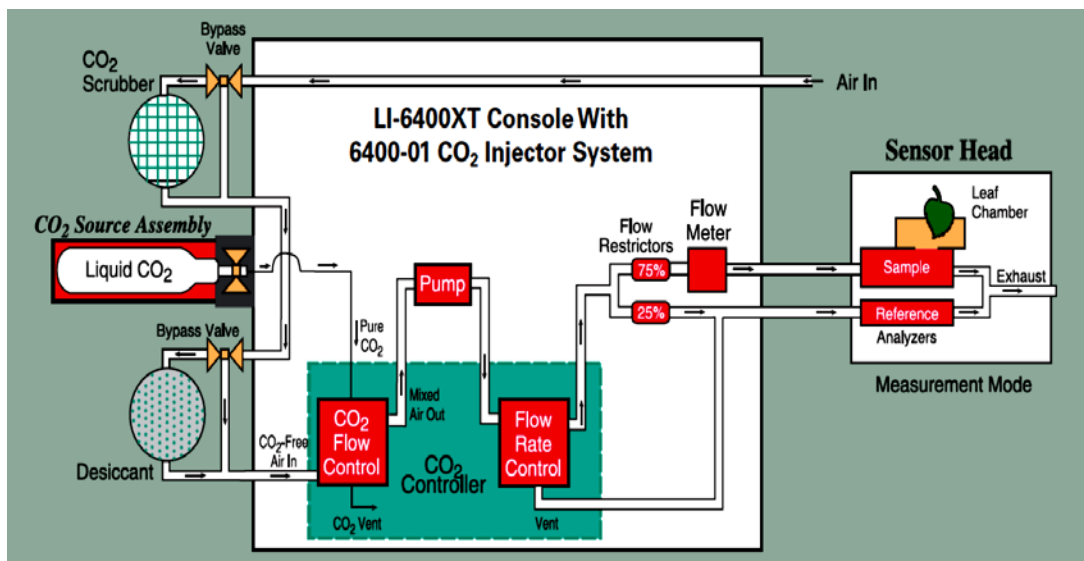
Figure 2.11 In an open system, photosynthesis are computed from the differences in CO$_2$ between in-chamber conditions and pre- chamber conditions (LI-COR, Inc., 2004).

2.7   Forest restoration

Developing countries are required to produce robust estimates of forest carbon stocks for successful implementation of climate change mitigation policies related to reducing emissions from deforestation and degradation (REDD) (Flinchbaugh, 2006).

In Thailand, in the upper Mae Sa Valley, Mae Rim District, Chiang Mai Province, Chiang Mai University's Forest Restoration Research Unit (FORRU-CMU) has been researching forest restoration since 1994, on a degraded, previously agricultural area. The method FORRU had adapted is the "Framework Species Method", which aims to accelerate biodiversity recovery and maximize carbon storage (FORRU, 2006, 2008). This method involves planting 20–30 indigenous mixture of pioneer and climax tree species, to gain rapid canopy closure. The characteristics of framework tree species are: (i) high survival when planted in degraded areas; (ii) rapid growth; (iii) dense and spreading crowns which suppress weed growth; and (iv) provision of resources (e.g. fruits or nectar-rich flowers) at an early age, that attract seed-dispersing animals (FORRU, 2006). Moreover, the seedlings of framework species should be easily propagated in nurseries. Trees should be able to produce seed in large amounts and be able to germinate to produce healthy seedlings for planting within a year (FORRU, 2006, 2008). The best-performing framework tree species have been identified and planted in target degraded areas (Elliott *et al*., 2003). Planting area must be cleared of weeds before planting by slashing and spraying with the non-residual herbicide, glyphosate. Tree saplings, of 20-30 indigenous species are planted randomly across the plots, spacing of 1.8 m in average. Various fertilizer, mulching and weeding regimes have been applied during the first two rainy seasons after planting. Fire breaks and fire prevention must be done before and throughout the dry season.

The IPCC (2000) suggested that newly planted or regenerating forests, without major disturbances (e.g. fire or tree felling) continue to uptake carbon for 20 to 50 years or more after establishment, depending on species and site conditions.

Thus, a young forest holds less carbon, but sequesters large amounts of carbon over time, whereas old forest sequesters less new carbon, but continue to store large volumes of carbon per unit land area over long periods of time. Managed forests offer the opportunity for influencing forest growth rates and providing for full stocking, both of which allow for more carbon sequestration. However, the strategies for climate change mitigation can be effective with proper planning of land use and land management, (Cathcart *et al.* 2007).

An important part of land management involves with land rights. The sustainable forest management needs to be clear in ownership and management rights. The information about forest ownership helps a better understanding in who responsible for forest management and utilization, and who benefits or loses from forest production. When forest tenure is stable, it promotes capital investment by government and private sector and motivate the sustainable use of forest resources (FAO, 2015).

2.8 Carbon trade

Carbon trading is the process of buying and selling permits and credits of CO_2 emission. It is an efforts to slow down the climate change problems. Once the carbon credits are certified by an independent agency, they can be sold on the carbon market (concawe, 2017). More and more countries have started to price carbon through cap and trade systems or a carbon tax as an incentive to reduce pollution (carbon market watch, 2017).

The concept of carbon market originally came from using a market mechanism to enhance a greenhouse gas emissions (GHG) reduction. Carbon credits are designed as the assets for buying and selling (TGO, 2014). The buying and selling carbon credits can be occurred in two markets:

1) The compliance market: which can be divided into three activities

- Joint Implementation (JI): this project is made for helping Annex I countries to reach their targets through the investment mechanism and project development in non - Annex I countries.

- Clean Development Mechanism (CDM): CDM similar with JI but the countries that engage in CDM project must be a developing country (non - Annex I countries). The amount of GHG reductions will be indicated and called "Certified Emission Reduction" (CER).

- Emissions Trading (ET): This mechanism helps to generate the selling and buying of GHG emissions for Annex I countries.

2) The voluntary market: There are two voluntary market active which are Chicago Climate Exchange (CCX) and Over-the-Counter (OTC).

Started from the Kyoto Protocol, 15 countries, which were member states of the EU when the protocol was agreed (EU-15), were committed to reduce their greenhouse gas emissions in the period of 2008 - 2012 to 8% below 1990 levels which is the reference year of the Kyoto Protocol. In 2009, the EU committed to a set the new reduction target as 20% below 1990 levels by 2020. One of the main policies setting out to meet its 2020 target is the EU Emissions Trading System (EU-ETS), the world's biggest carbon trading system (European Commission, 2016). The EU-ETS was initiated on 1 January 2005. It includes CO_2 emissions trading schemes, which originated in the UK and in Denmark, and merged into the EU-wide scheme in early 2005 (Gilbertson and Reyes, 2009). The EU ETS works on the 'cap and trade' principle. "Cap" is the overall volume of greenhouse gases that can be emitted by industrial factories and other companies that is subject to a cap set at EU level. Once "cap" being made, companies can receive or buy emission allowances so they can trade (European Commission, 2016). The EU-ETS sets targets for industrial sectors emissions in 3 phases.

Phase I: 2005 - 2007. During this period only CO_2 was controlled. The objective of Phase I was 1-2 % reduction but there was uncertainty about the emissions level being released by industries. Permits were generally given to the participating emitters at no charge (Kill et al., 2010) (Fig. 2.12).

Phase II: 2008 – 2012. The number of allowances was reduced by 6.5% and harmonize with the engagement period of the Kyoto Protocol. 2005 was set as the base year against which emissions changes are measured. The objectives is to reduce the emissions by 4.3 % to 2,083 $MtCO_2$ per year (Fig. 2.12).

Phase III: 2013 – 2020. The cap on emissions from industrial sectors including power plants is reduced by 1.74% every year. Therefore in 2020, greenhouse gas emissions from these sectors will be 21% lower than in 2005.

As for Thailand, quantity incentives were voluntarily used through promotion and development of Clean Development Mechanism (CDM) projects which generate income from sales of Certified Emission Reductions (CERs) (Leangcharoen, 2009). The developers of CDM projects and countries within the Annex I are trading credits through delegates, financial funds, and brokers (TGO, 2014).

Around one third of the credits traded on the market are from forest carbon projects which mostly generated in developing countries. Forest carbon projects can be accounting for carbon credits by showing that the project leads to the CO_2 emissions reduction from decrease deforestation and land use change. Moreover, forest carbon project can be demonstrated that changes in forest management lead to changes in carbon accumulation in vegetation since forest is the carbon sink and the atmospheric CO_2 removal machine. Prices for forest carbon projects currently vary between US$3 to 10 per ton CO_2. (concawe, 2017).
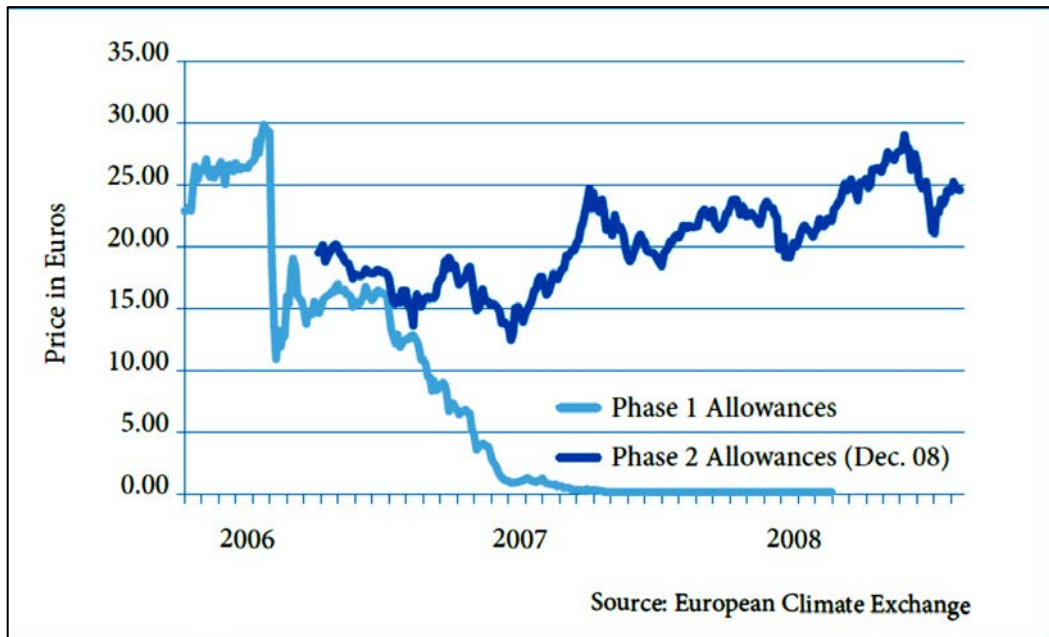
Figure 2.12 Carbon price (EU) of phase 1 (2005-2007) and phase 2 (2008-2012) (Kill et al., 2010).

2.9 Carbon sequestration modelling

Gross carbon budgets for vegetation in forest ecosystems are difficult to construct due to problems in scaling since the measurements made on small samples over short periods of time but had to extrapolate to bigger scale and longer period (Ryan 1991). However, the understanding of gross carbon fluxes through vegetation is crucial for patterns construction and future trends prediction in forest carbon sequestration. Finding the parameter and validation for models simulation also need information on gross carbon flux through vegetation in ecosystems (Ryan 1991). Net carbon stored or emitted during a particular interval (I) is given by the following two equations (Australian Greenhouse Office, 1998; Richards and Evans, 2000):

$$\Delta C_I \quad = \quad C_I - C_{I-1} \quad \text{and}$$
$$C_I \quad = \quad TR_I + L_I + V_I + S_I + WP_I$$

Terms and abbreviations are defined as follows:

ΔC_I	Net carbon sequestration increment or emission in interval I, (t C)
C_I	Total cumulative carbon stored at end of interval I, (t C)
TR_I	Carbon in Trees and Roots Pool at end of interval I, (t C)
L_I	Carbon in Litter Pool at end of interval I, (t C)
V_I	Carbon in Other Vegetation Pool at end of interval I, (t C)
S_I	Carbon in Soil Pool at end of interval I, (t C)
WP_I	Carbon in Wood products harvested or unsold during interval I, (t C)
(t C)	Tonnes carbon

There are several ways to predict and model the carbon pool and carbon flux either use the ready-to-use software such as FullCAM model or 3PG model or construct the equations based on statistical relationship between tree growth and environmental condition (Pretzsch et al., 2002). FullCAM integrate biomass, decomposition, soil carbon models and accounting tools as a single model that used to estimate carbon stock in transitional area such as afforestation, reforestation and deforestation and mixed area such as agroforestry (Richards, 2001). Several models were applied to forest ecosystem management and scenarios analysis. Hayat et al. (2017) modeling for individual tree growth which tested for stands of beech trees. Hayat's model analysis tree growth in level of cellular growth on apical and lateral meristem and applied related equations which were tree growth equations, growth control mechanism and carbon balance equations.

Some models estimate tree biomass from other trees part. One of them is "Functional branch analysis (FBA)" which using the theory called "pipe-model". Pipe model assumes that a tree consists of pipes that support a particular proportion of foliage by connecting each foliage element to the functional roots, based on the hypothesis that the sum of squared diameters of branches is equal to the squared diameter of stem or branch before branching occurs. FBA estimates tree volume from tree stem and branch measurements, using fractal branching rules, and combines volumes with wood density

of tree volume components (e.g., stems and twigs) to calculate mass (Macfarlane et al., 2013).

Apart from tree level modeling, there are large scale models that estimate carbon stock. Model CO2fix is an ecosystem-level model based on a carbon accounting of forest stands, including forest biomass, soils and products (Masera, 2001). CO2fix model structure is

$$Ct = Cbt + Cst + Cpt$$

Where; Cbt   is the total carbon stored in living (above + belowground)
                   biomass at any time "t"
      Cst   is the carbon stored in soil organic matter
      Cpt   is the carbon stored in forest products

Carbon, stored in living biomass, can be estimated through a forest cohort model that included competition, mortality, and logging damage mortality. Soil carbon is modeled using five stock pools that include litter and humus with different residence times. While carbon stored in wood products is modeled through a set of pools for short- medium- and long-lived products, and includes recycling (Masera, 2001).

Moreover, in recent days, there are several technologies aimed to estimate carbon in targeted area in large scale without field work or labors needed. One of such technology is LIDAR (Light Detection and Ranging). LiDAR uses laser light to estimates forest height/vertical structure and give results as Carbon 3-D satellite system combines Vegetation Canopy LiDAR (VCL) with horizontal imager. It is potential for satellite-based system to estimate global forest carbon stocks (Gibbs et al., 2007).

CHAPTER 3

Methodology

3.1 Study Site

The study area was in the Upper Mae Sa Valley, Mae Rim district, Chiang Mai Province, Thailand (at 18°52'N and 98°51'E) at 1,200 to 1,400 m elevation. The average temperature was 26.8 °C, with a dry season from November to April and a wet season from May to October (Fig. 3.1). Small fragments of disturbed, primary, upland, seasonally dry, evergreen forests remained in the valley, with a high frequency of tree species in the Fagaceae, such as *Castanopsis diversifolia* and *C. tribuloides*.

Within this catchment, 6 contrast sites at various stages of forest succession were selected for determination of carbon storage (Fig. 3.2). Three sites were restoration trials, planted with framework tree species in 1998 (R14), 2002 (R10) and 2007 (R5) (14, 10 and 5 years before the field work was done for this thesis) (Figs. 3.3-3.5). The trials were established by planting tree saplings 30-50 cm tall, 1.8 m apart, followed by fire prevention measures and weeding and fertilizer application 3 times per rainy season for 2 years after planting. The plot system forms a wildlife corridor along a ridge joining Dong Seng Forest (DSF) in the east to an unnamed, degraded forest remnant in the west. For a complete account of the study site and the restoration techniques applied, see Elliott et al. (2012).

The controls site (abandoned sites) demarcated at the time of tree planting in 1998, but then left to undergo natural regeneration, without restoration activities applied. The areas had been abandoned for more than 30 years, burnt and degraded, but subject to natural succession since 1998 (Fig. 3.6).

The degraded primary forest located nearby Mae Sa Mai village called Dong Seng forest. It was used as a base line for comparing results from the other sites (Fig. 3.7). Lastly, a monoculture plantation of *Pinus kesiya*, more than 20 years old, above the village was included to compare a monoculture plantation with the multi-species approach of the framework species method (Fig. 3.8).
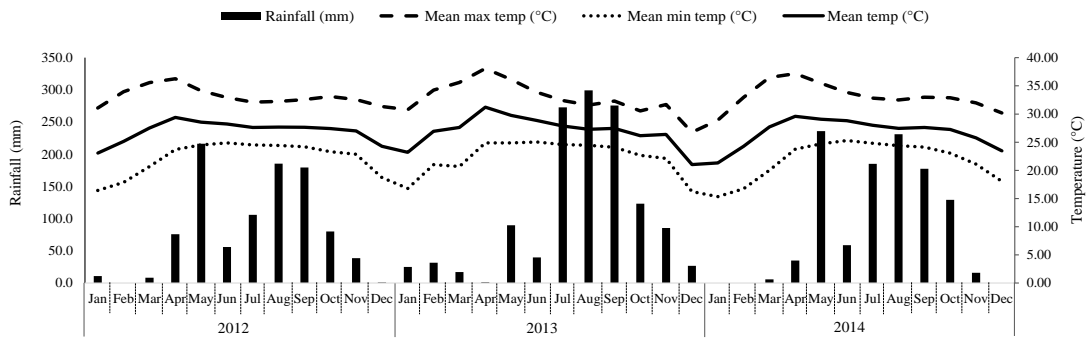
Figure 3.1 Rainfall, minimum, maximum and mean temperatures from the nearest meteorological station of Ban Mae Sa Mai Royal project (Ban Mae Sa Mai meteorological station, 2012 -2014).
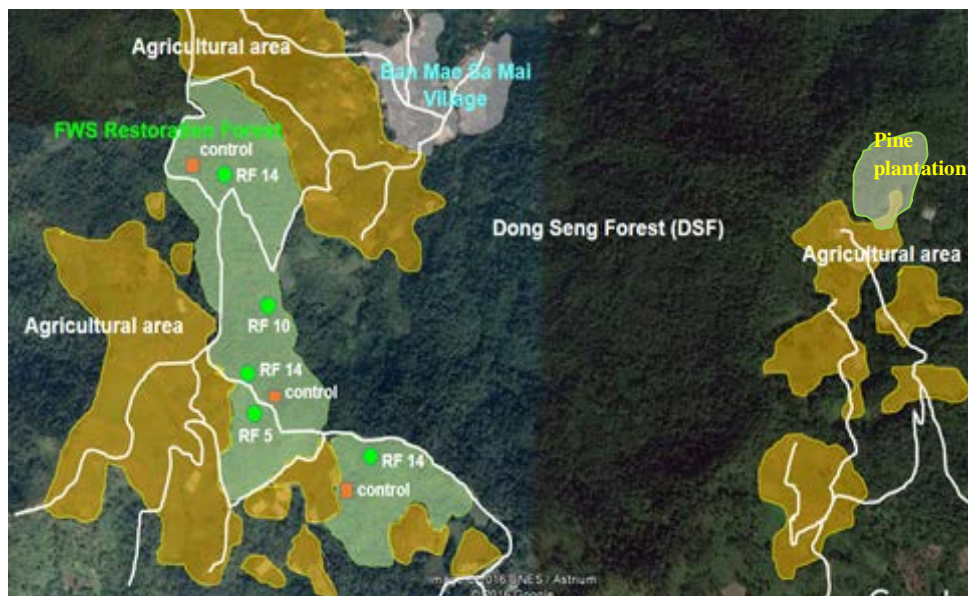
Figure 3.2 Map of forest restoration study plots including degraded primary forest located above Ban Mae Sa Mai village show the pine plots and the PDS plots as well.

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Figure 3.3 R14 plot (planted in 1998)
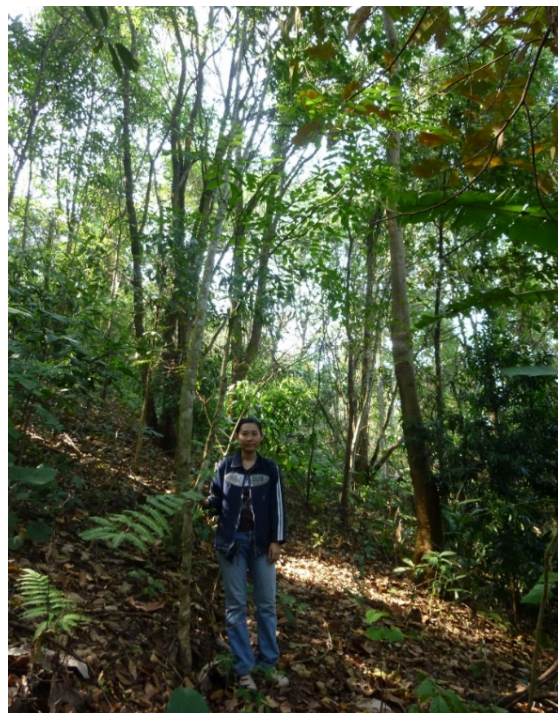
Figure 3.4 R10 plot (planted in 2002)

Figure 3.5 R5 plot (planted in 2007)

Figure 3.6 Control plot

Figure 3.7 Degraded primary forest (Dong Seng forest)

Figure 3.8 Pine forest (Dong Seng forest)

3.2 Comparing the tree volume, wood density, aboveground biomass using partial harvest technique and percentage of carbon content between different framework species.

Lists of the tree species that had been planted in each of the plots were compared, to find 11 species common to all 3 plots (Table 3.1).

A field survey was done to find 3 average-sized trees of each species for each planting year R14, R10 and R5 (totally 9 trees per species representing 3 ages). Each tree was tagged, its GPS location recorded, and was assessed for wood density, tree volume, aboveground dry biomass and carbon sequestration comparison.

Table 3.1 Selected species presented in all 3 restored plot aged R14, R10 and R5. The informations of successional status, family and leafing were from FORRU database.

No.	Species	Successional status	Leafing	Family	Thai name
1	*Bischofia javanica*	Pioneer	Deciduous	Euphorbiaceae	เติม
2	*Erythrina subumbrans*	Pioneer	Deciduous	Leguminosae	ทองหลางป่า
3	*Gmelina arborea*	Pioneer	Deciduous	Verbenaceae	ซ้อ
4	*Heynea trijuga*	Climax	Semi-deciduous	Meliaceae	ตาเสือทุ่ง
5	*Hovenia dulcis*	Climax	Deciduous	Rhamnaceae	หมอนหิน
6	*Melia toosendan*	Pioneer	Deciduous	Meliaceae	เลี่ยน
7	*Nyssa javanica*	Pioneer	Evergreen/ semi-deciduous	Nyssaceae	คางคาก

Table 3.1 (Continued)

No.	Species	Successional status	Leafing	Family	Thai name
8	*Prunus cerasoides*	Pioneer	Deciduous	Rosaceae	นางพญาเสือโคร่ง
9	*Sapindus rarak*	Climax	Deciduous	Sapindaceae	มะซัก
10	*Sarcosperma arboreum*	Climax	Evergreen	Sapotaceae	มะยาง
11	*Spondias axillaris*	Pioneer	Deciduous	Anacardiaceae	มะกัก

3.2.1 Tree volume

Tree volume was calculated from a combination of trunk and branch measurements. A partial harvesting method was developed, which required cutting only small parts of each tree to calculate tree volume and dry biomass (Snowdon *et al.*, 2002). The girth at breast height (GBH) was measured by tape measurement and tree height by a clinometer.

Branches were categorized as primary, secondary, tertiary and so on. Primary branches were those growing out from the main trunk; secondary branches were those that grew out from primary branches, whilst tertiary branches grew out from the secondary branches. Primary branches were counted and one was cut from each sample tree, to measure length and circumference (Fig. 3.9).
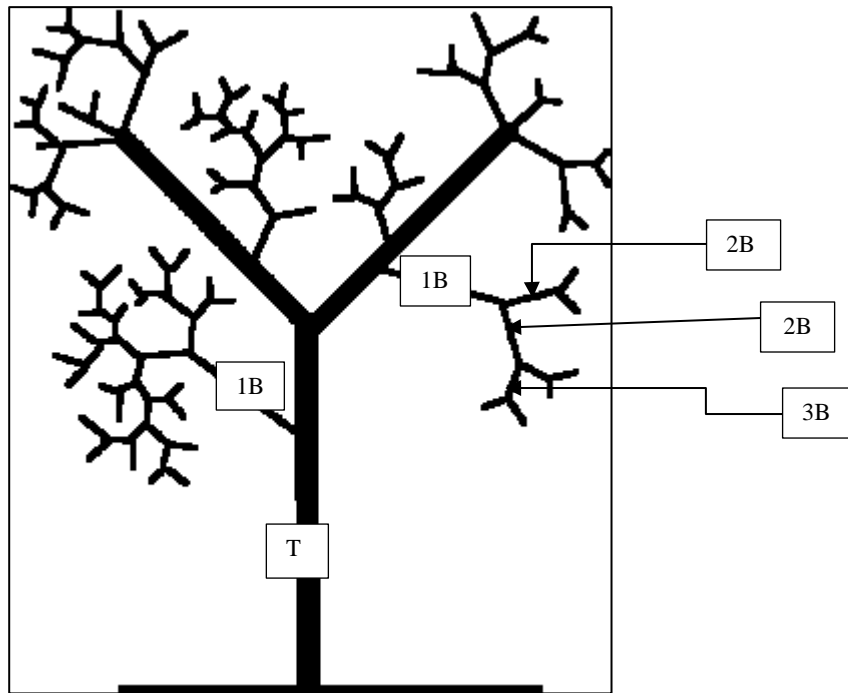
Figure 3.9 Tree parts: T = Trunk, 1B = Primary branch, 2B = Secondary branch, 3B =
Tertiary branch

- *Trunk volume*

Trunk diameter was measured at the base and top and the trunk volume was
calculated, using the formula for a frustum cone.

$$Volume = \frac{\pi}{3}h(R^2 + r^2 + R * r)$$
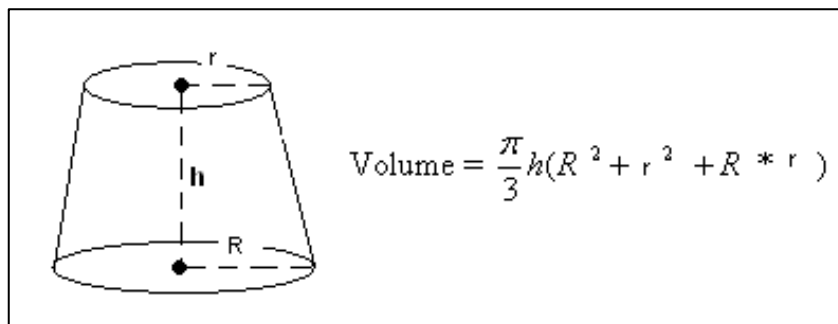
Figure 3.10 Diagram showing the calculation for frustum cone object, where h = height,
R = lower girth and r = upper girth (Snowdon *et al.,* 2002).

- Branch volume

Branch volume (for each branch order) (Fig. 3.9) was also calculated using the frustum cone formula above (Fig. 3.10). The calculation was explained in table 3.2

Table 3.2 Calculation of branch volume.

In the field	In the lab
1. Counted total number of primary branches.	
2. Cut one primary branch and bring to the lab.	
	3. Separated primary, secondary, tertiary branches and so on.
	4. Calculated volume of each branch order.
	5. Combined to calculate the total volume of the sampled branch.
6. Multiplied sample branch volume by the number of primary branches counted.	
7. Derived total branch volume and add to stem volume.	

- Total tree volume

Tree volume was calculated by combining volume from trunk with total volume from branches.

3.2.2 Wood density

Wood core samples were collected with an increment borer, 30 cm long, 5 mm diameter (Fig. 3.11). Tree trunks were bored half way through to collect wood samples. Oil paint was applied to the bore hole to prevent fungal infection. One wood sample was collected at breast height from each of 3 trees per species (Fig. 3.12). The wood samples were oven-dried at 70°C for 72 hours. Wood sample volume was derived from the formula used to calculate the volume of a cylinder. Wood density was calculated by dividing the sample mass with volume.

Figure 3.11 The increment borer with 2 threads, 30 cm. length and 5 mm. diameter.

Figure 3.12 Wood sample collected from tree trunk using increment borer.

3.2.3 Tree dry biomass

The dry biomass of the woody structures of each tree was calculated by multiplying wood density by tree volume. To this was added leaf dry biomass. Leaves from cut branches were oven-dried at 70 °C for 72 hours. Leaf mass was calculated by multiplying the leaf mass from one cut typical primary branch by the number of primary branches.

3.3 Comparing the aboveground biomass using allometric equations and carbon sequestration between different forest management regimes

Four different forest management regimes were included in this study: restored forest, controls, degraded primary forest and pine plantation. The R14 plots were used to represent the oldest most advanced restored forest. Pine forest was selected as a representative of monoculture management. Control plots represented natural regeneration and degraded primary forest was used as a baseline target for restoration (the most complex forest ecosystem that can be sustained in a human-dominated landscape). To compare the partial harvesting method with conventional non-destructive methods, based on measurements of GBH and allometric equation, circular plots (radius 5 m) were used to assess aboveground biomass and carbon sequestration in the pine plantation, restored forest and degraded primary forest whilst square plots of 1x1 meters were used in the control plots for destructive sampling.

3.3.1 Dry biomass

- Dry biomass in restored forest

The GBH and height of every tree (GBH ≥ 5 cm) located within the circular plots, 30 plots in total, was measured. Tree dry biomass was calculated by using allometric equation for Dry Evergreen Forest (Tsutsumi *et al*., 1983). Total dry biomass was calculated as tons per hectare (t/ha)

$$Ws = 0.0509\left(D^2H\right)^{0.919}$$
$$Wb = 0.00893\left(D^2H\right)^{0.977}$$
$$Wl = 0.0140\left(D^2H\right)^{0.669}$$
$$Wr = 0.0313\left(D^2H\right)^{0.0805}$$

… where Ws = Stem (kg), Wb = Branch (kg), Wl = Leaf (kg), Wr = Root (kg), H = Total height (m), D = Diameter at breast height (cm).

- Dry biomass in the control plots

Nine sample square plots of 1x1 meters were set up and the total vegetation was harvested and oven dried at 70 °C for 72 hours. Dried samples were directly weighed using a digital balance in grams to two decimal points. Dry mass was calculated for per square meter and converted to tons per hectare (t/ha).

- Dry biomass in degraded primary forest

In degraded primary forest, 10 circular plots were randomly established, avoiding paths. Tree GBH ≥ 5 cm and height in sampling plots were measured. The allometric equation for Dry Evergreen Forest (Tsutsumi *et al*., 1983) was used to calculate dry biomass. Wood samples were also collected from the trees for wood density analysis (method described in section 3.2.2) and carbon content analysis.

- Dry biomass in pine forest

In the pine plantation, 5 circular plots were set up within area of 40 x 40 square meters (Fig. 3.13). Study plots were dominated by pine trees mixed with small vegetation. Every pine trees in the sampling plots were measured for GBH and height. An allometric equation specific for *Pinus Kesiya* was used to determine dry biomass (Nongnuang et al., 2012). Wood samples were also collected from trees to determine wood density (see section 3.2.2) and carbon content.

$$Ws = 0.0503 \left(D^2 H\right)^{0.8775}$$
$$Wb = 0.0012 \left(D^2 H\right)^{1.0996}$$
$$Wl = 0.4536 \left(Wb\right)^{0.7933}$$

… where Ws = Stem (kg), Wb = Branch (kg), Wl = Leaf (kg), H = Total height (m), D = Diameter at breast height (cm).
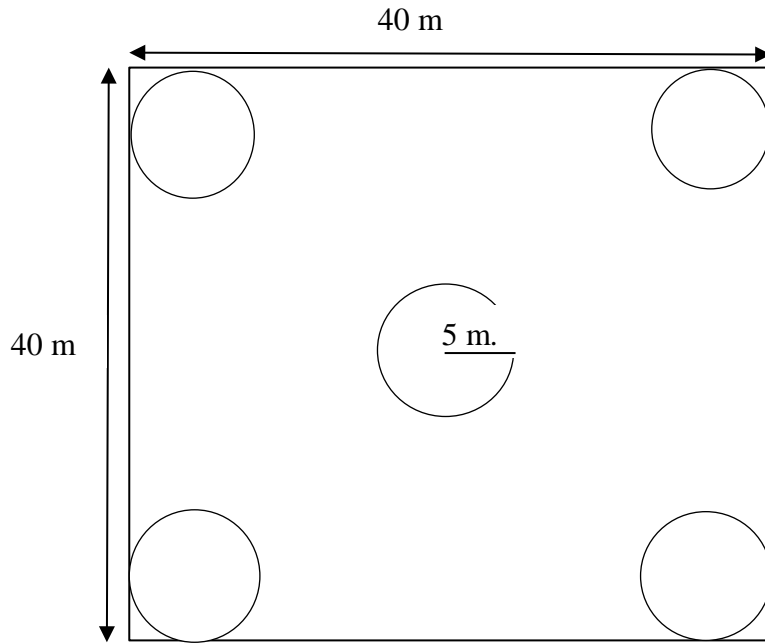
Figure 3.13 Sampling plots for pine plantation

3.4 Carbon percentage

Wood samples were ground using blender and sieved into small particle (Fig. 3.14). Samples were sent to the Faculty of Science, Kasetsart University's lab for carbon content analysis by using Carbon (C), Hydrogen (H), and Nitrogen (N) elemental analyzer. The percentage of carbon was multiplied by tree dry biomass of each species to derive the total carbon storage in trees.
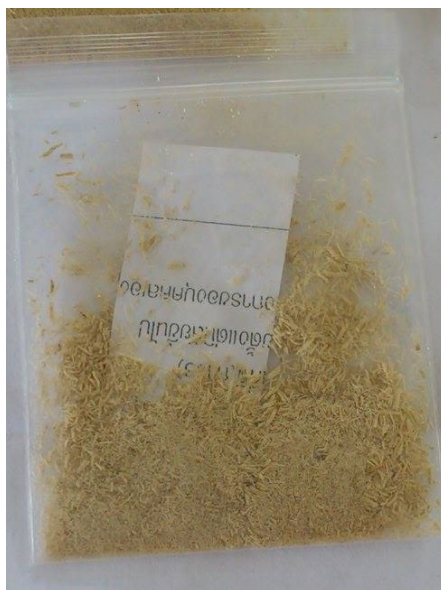
Figure 3.14 Wood sample after ground and sieved into small particle.

3.5 Relative growth rate calculation

The equation used in the calculation of tree's relative growth rate per year was

$$RGR = \frac{(\ln w_2 - \ln w_1)}{(t_2 - t_1)}$$

where RGR = relative growth rate and W_1 and W_2 are tree dry weights at times t_1 and t_2 (Hoffmann and Poorter, 2002).

3.5 Photosynthesis rate

Seeds of selected species (Table 3.3) were collected. The mother trees of each species which located in Doi Suthep – Pui National Park and Ban Mae Sa Mai were the source for seed collection. Timing for seeds collection depended on each species' phenology by the time of ripening period.

Seeds were cleaned to remove fruit flesh and air dried at ambient temperature for 1-2 days. Dry seeds of each species were packed in zip lock plastic bags which were then shipped by airmail to Oregon State University for germination and seedling establishment in a greenhouse under halogen sodium pressure lamps with the length of light availability of 12 hr, temperature at 25 °C and relative humidity at 80%. The rate of photosynthesis was measured using the LI-6400XT Portable Photosynthesis System. The LI-6400 is an open system design that allows variation of CO_2 concentration, light intensity, chamber temperature and other variables. Therefore, measurements of photosynthesis rate were based on the differences between CO_2 concentration injected through the leaf cuvette and CO_2 concentration after passing through each sample leaf (Fig. 3.15) (LI-COR Biosciences, Inc., 2004).

The photosynthesis rates of 3 seedlings of each species were measured. Leaves were divided into three types, representing three different kinds of leaf in a crown: i) young leaves (3rd leaves, counting down from the meristem), ii) mature sun leaves (the biggest leaves in the middle of crown, i.e. sun leaves) and iii) mature shade leaves (lowest in the crown) (Fig. 3.16).
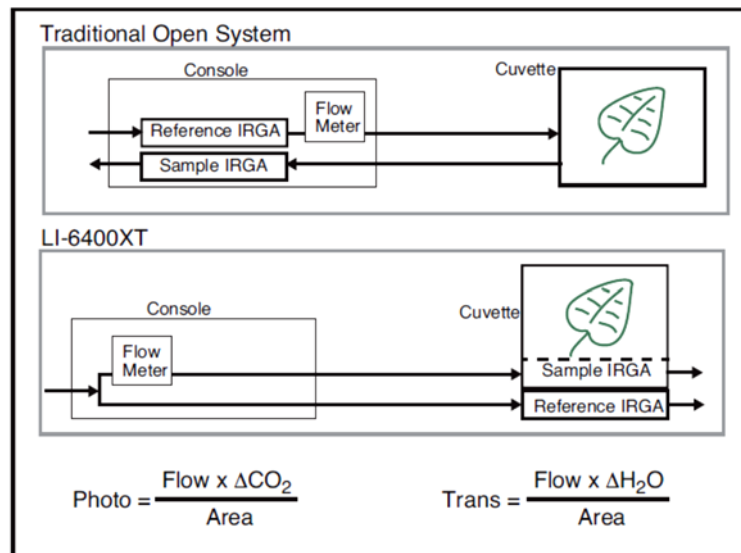
Figure 3.15 The open system of LI-6400, photosynthesis is computed from differences of CO_2 between in-chamber conditions and pre-chamber conditions (LI-COR Biosciences, Inc., 2004).
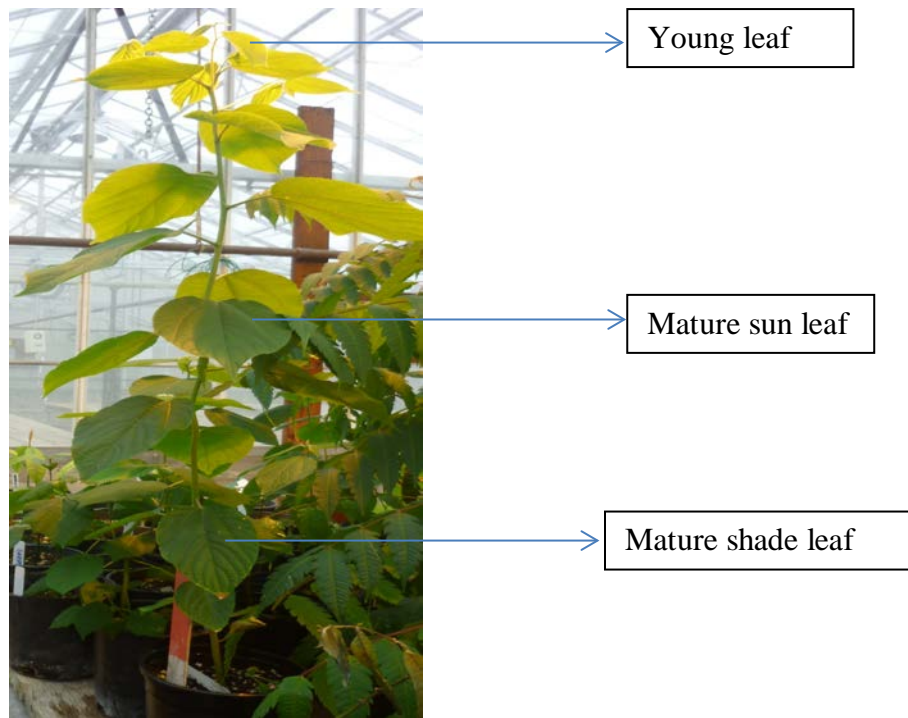
Figure 3.16 The different type of tested leaf to represent tree canopy

Table 3.3 Selected species for testing photosynthesis rate

Species	Family	Location	Seed collection period (year 2010-2011)
Bischofia javanica	Euphorbiaceae	Doi Suthep – Pui National Park	August – September
Erythrina subumbrans	Leguminosae	Ban Mae Sa Mai	March - April
Gmelina arborea	Verbenaceae	Doi Suthep – Pui National Park	April - May
Heynea trijuca	Meliaceae	Ban Mae Sa Mai	August - September
Hovenia dulcis	Rhamnaceae	Doi Suthep – Pui National Park	February - March
Melia toosendan	Meliaceae	Doi Suthep – Pui National Park	February - March

Table 3.3 (Continued)

Species	Family	Location	Seed collection period (year 2010-2011)
Nyssa javanica	Nyssaceae	Doi Suthep – Pui National Park	August - September
Prunus cerasoides	Rosaceae	Doi Suthep – Pui National Park	April - May

The CO_2 concentration was set at 400 μmol $CO_2/m^2/s$, using a CO_2 cartridge as a source for the CO_2 injector. Light intensity was varied from 50 to 2000 μmol/m^2/s with various intervals, as shown in Table 3.4. Tested leaves were put in a 1x1 cm^2 chamber area. CO_2 at the desired concentration was injected through the chamber, which was illuminated by the LEDs (Fig. 3.17). Seedlings were tested for photosynthetic rate at different CO_2 concentrations and light intensities by injecting each level of CO_2 concentration through the chamber at each value of light intensity. For example, at the preferred CO_2 concentration of 300 μmol/s, leaves were tested for photosynthesis rate with every value of light intensity from 50 – 2000 μmol/m^2/s.

Table 3.4 The range of light intensity and CO_2 concentration used for this research.

Light intensity (μmol/m^2/s)	CO_2 concentration (μmol/s)
50	
100	
300	
500	400
1000	
1500	
2000	

Figure 3.17 Set-up for photosynthesis measurements using the LI-6400

3.6 Modeling

To generate the modeling of carbon sequestration for framework species in restoration plots, data as follow were input in Excel spreadsheets;

- *Primary data*
  o Carbon sequestration of each selected species (kgC)
  o Photosynthesis rate of selected framework tree species (μmol $CO_2/m^2/s$)
  o Leaf area (cm^2)
  o Individual leaf mass (g)
  o Whole tree crown leaf mass (kg)
- *Secondary data*
  o Solar radiation in Chiang Mai ($MJ/m^2/day$) (Exell and Santibuppakul, 1983)
  o Carbon flow via litter fall of plot R5, R10 and R14 (ton/ha/year) (Kavinchan *et al.,* 2015)
  o Molecular mass of carbon and oxygen (g/mol)

- Leafing phenology (proportion of young and mature leaves) (FORRU database)

3.6.1 Carbon absorption rate

The data of solar radiation in Chiang Mai ($MJ/m^2/day$) was converted into the unit of $\mu mol/m^2/s$ as follows;

1) Converted $MJ/m^2/day$ into $J/m^2/day$ by multiplying with 10^6
2) Converted $J/m^2/day$ into $J/m^2/s$ by dividing by 86,400
3) $J/m^2/s$ is equal to w/m^2
4) Converted w/m^2 to $\mu mol/m^2/s$ (sunlight) by 4.57 $\mu mol/m^2/s$ = 1 w/m^2

The photosynthesis rate of each leaf type of each species at CO_2 concentrations of 400 ppm ($\mu mol/mol$) was measured. These following factors were applied to match the natural canopy status of each day in a year (365 days);

1) Leafing phonology of mature leaves and young leaves for each month in a year (leaf fall, bare branches and leaf flushing) was applied using data from FORRU's database. Percentage of emerging young leaves evaluate from the changing of young leaves of each month. Percentage of increasing mature leaves (young leaves that maturing into mature leaves) evaluate from the increasing of mature leaves of each month. Lastly, percentage of leaves fall evaluated from the decreasing of mature leaves

2) Leaf area index (LAI) data of Ban Mae Sa Mai restoration plots applied from field study of Rattapongsai in 2012 (unpublished data). In this case, the LAI data was then calculated to match with leafing phenology throughout the year. The maximum LAI in the wet season for the youngest plot was 4.6 which assumed as the maximum amount of leaves present in tree crown (100%). Therefore the percentage of leaves (sum of young and mature leaves) was applied with the maximum LAI to get the LAI number for each month.

$$LAI_m = \left(4.6 \times \%L_m\right)/100\%$$

where; LAI_m = Leaf area index of any month

$\%L_m$ = Percent of leaves in the crown of any month

3) Beer's light attenuation equation (Sands, 1995) was applied to estimate the amount of light available within the tree crowns. Light availability under the canopy of each month was calculated by applying the Beer's law equation.

$$L_i = L_0 \times EXP\left(-LAI_m \times k\right)$$

where; L_i = Light at any vertical position (i); expressed as a proportion of light reaching the top of the canopy

L_0 = Light at above canopy

LAI_m = Leaf area index of any month

k = Light extinction coefficient; in this case, light extinction coefficient for broadleaf forest was applied which is 0.59 (Zhang et al., 2014).

4) Percentage of ratio between leaves mass and tree mass was calculated, to derive tree crown growth. The data of leaves mass (kg/tree) and tree mass (kg/tree) of each species were used to calculated the percentage of ratio between leaves and tree mass in a tree. This ratio was then used to calculate increase in the young and mature leaf mass each day

5) Total leaf area of a tree of each species was calculated by using data on estimated total leaf mass per tree crown (from partial harvesting data), individual leaf mass and individual leaf area.

LMC = TM x %LT-ratio	Eq. 1
LMC_m = leaves dry mass (measured) * $\%L_m$	Eq. 2
LMC_y = leaves dry mass (measured) * $\%L_y$	Eq. 3

$$LA_m = [(la_m * (Eq.2 \times 1000))/ lm_m] \times 0.0001 \qquad Eq.\ 4$$

$$LA_y = [(la_y * (Eq.3 \times 1000))/ lm_y] \times 0.0001 \qquad Eq.\ 5$$

whereas;

LMC	= Total leaves mass in the crown (kg)
TM	= Tree mass (kg)
%LT-ratio	= Percent leaves-tree mass ratio
LMC_m	= Mature leaves mass in the crown (kg)
LMC_y	= Young leaves mass in the crown (kg)
$\%L_m$	= Percent of mature leaves of each month
$\%L_y$	= Percent of young leaves of each month
LA_m	= Area of mature leaves (m^2)
LA_y	= Area of young leaves (m^2)
la_m	= Area of individual mature leaf (cm^2)
la_y	= Area of individual young leaf (cm^2)
lm_m	= Individual mature leaf mass (g)
lm_y	= Individual young leaf mass (g)

6) Equations from the lab experiments, describing the relationship between light intensity PAR light ($\mu mol/m^2/s$) and photosynthesis rate ($\mu mol\ CO_2/m^2/s$) and of each leaf type of each species (Fig 4.14 a-h), were then used to calculated the photosynthesis rate in units of $\mu mol\ CO_2/m^2/s$ by each tree crown per day, according to the day length and light intensity for each day of the year. Young leaves and mature leaves were applied to PAR full sunlight. Shade leaves was applied to PAR under canopy light. Carbon fixed by each species was calculated to derive the rate of carbon uptake in unit of kgC/day (Table 4.8).

C fixed ($gC/m^2/day$) = [(CO_2 fixed ($\mu mol\ CO_2/m^2/s$) x 10^{-6}) x C molecular weight] x sunlight hours (s)

C fixed - mature (kgC/day) = [C fixed ($gC/m^2/day$) x LA_m (m^2)]/1000

C fixed - young (kgC/day) = [C fixed ($gC/m^2/day$) x LA_y (m^2)]/1000

Total C fixed in a crown (kgC/year/tree) = C fixed mature + C fixed young

3.6.2 Carbon sequestration projection

- Measured tree carbon of youngest plot (R5 plot) was used as the starting point of carbon sequestration projection starting at years 5.

- Tree carbon in year 6 was derived from the tree carbon in year 5, plus the total amount of carbon accumulated in one year (calculated in section 3.6.1)

- The carbon accumulated in year 6 derive from tree carbon in year 5 multiplied with percent relative rates of carbon accumulation per year of each species.

- Tree carbon in year 7 was derived from tree carbon in year 6 plus the total amount of carbon accumulated in year 6 and so on, each year from 8 to 14 years.

- Tree carbon from modeling for years 5, 10 and 14 was compared with the actual measurements of tree carbon from field work in plots R5, R10 and R14.

- The result of tree carbon weight (kgC) from modeling was used predict the total carbon weight of each framework tree species and ultimately to predict the carbon stored on an area basis from the proportion of species planted and their surviving density in period of time by assume the proportion of each species planted.

CHAPTER 4

Results

4.1 Comparing tree volume, wood density, above-ground biomass and stem wood carbon content among framework species

4.1.1 Density, volume and dry biomass sampling by partial harvest method

Differences in mean wood density (averaged across all species) among the plots were not significant (Duncan's Multiple Range test, $p \leq 0.05$). This means that wood density did not change significantly with tree age.

Consequently, comparisons among the species were performed on mean wood density, averaged across all plot ages (N=9). Wood density differed significantly among species (Duncan's Multiple Range test, $p \leq 0.05$) (Fig. 4.1). In general, the wood of fast-growing pioneer trees was less dense than that of late-successional species, but *Gmelina arborea* and *Prunus cerasoides* were notable exceptions, having higher than expected wood density for pioneer tree species. In this study, wood density of *G. arborea* ranged from 0.43 to 0.70 g/cm^3 (mean = 0.57 g/cm^3), whereas that of *P. cerasoides* ranged from 0.31 to 0.82 g/cm^3 (mean = 0.50 g/cm^3).
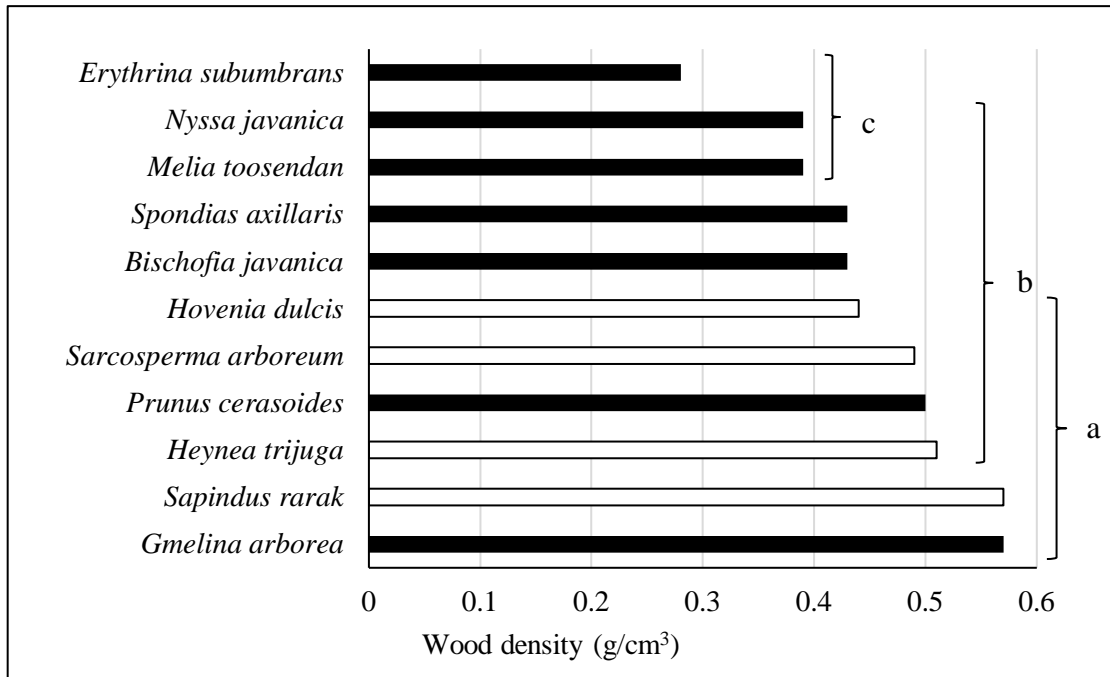
Figure 4.1 Species ranked in order of increasing mean wood density (g/cm^3), pooled across plots (N= 9). Black = pioneer species; white = later successional or climax species. Bars not sharing the same superscript are significantly different (p<0.05)

In general, mean tree volume (averaged across species) increased with plot age. Tree volume varied considerably among the species in the youngest plot, but gradually the differences among species became less as the trees grew larger (F- test = 100.10, p ≤ 0.05). In the younger R5 and R10 plots, *Spondias axillaris* trees attained highest mean volume (means ±SD, 0.11 ± 0.05 m^3 & 0.43 ±0.11 m^3, respectively), but this species was overtaken in the oldest R14 plot by *Erythrina subumbrans* trees, which attained the highest mean volume (0.99 ±0.30 m^3) (Fig. 4.2).
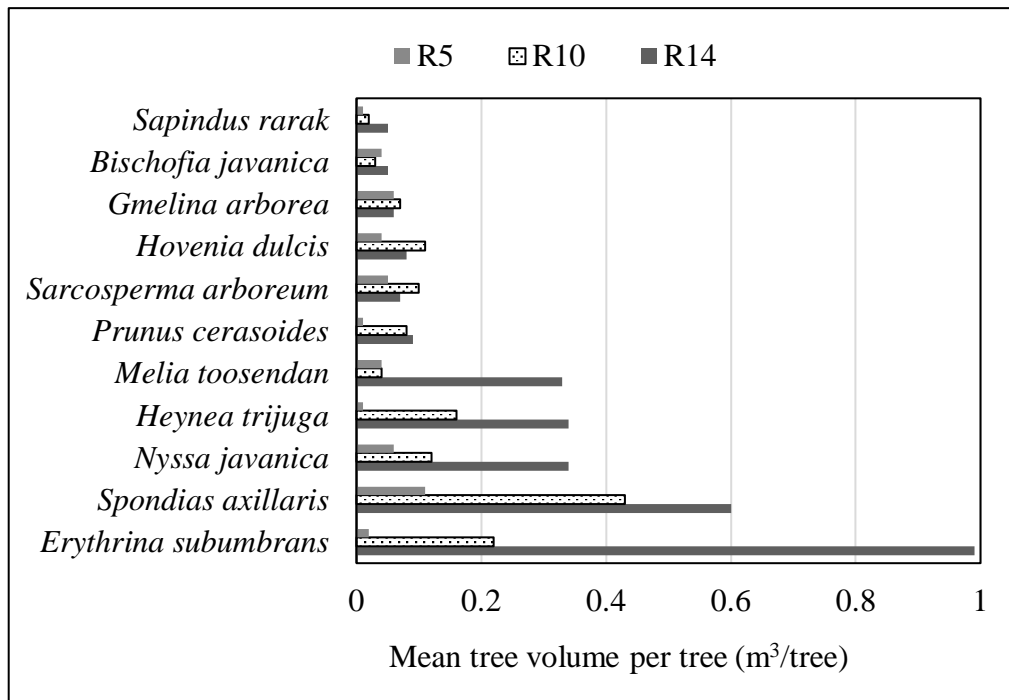
Figure 4.2 Mean tree volume per tree (m^3/tree) plot R14, R10 and R5

Although *Erythrina subumbrans* had the lowest wood density, it achieved the highest above-ground dry biomass (301.23 ± 91.83 kg/tree) in the oldest plot (R14), due to its rapid growth and consequently significantly higher biomass than any other species tested (p<0.05). In the R5 plot, *Gmelina arborea* and *Spondias axillaris* (48.03 ± 12.68 and 47.30 ± 35.37 kg/tree respectively) attained significantly higher above-ground dry biomass than that of other species in the same plot. For the faster-growing species, above-ground dry biomass increased exponentially with plot age, but for some of the slower-growing species, the limited sampling possible (3 trees per plot) was not sufficient to reveal a reliable size-age pattern (Fig. 4.3).
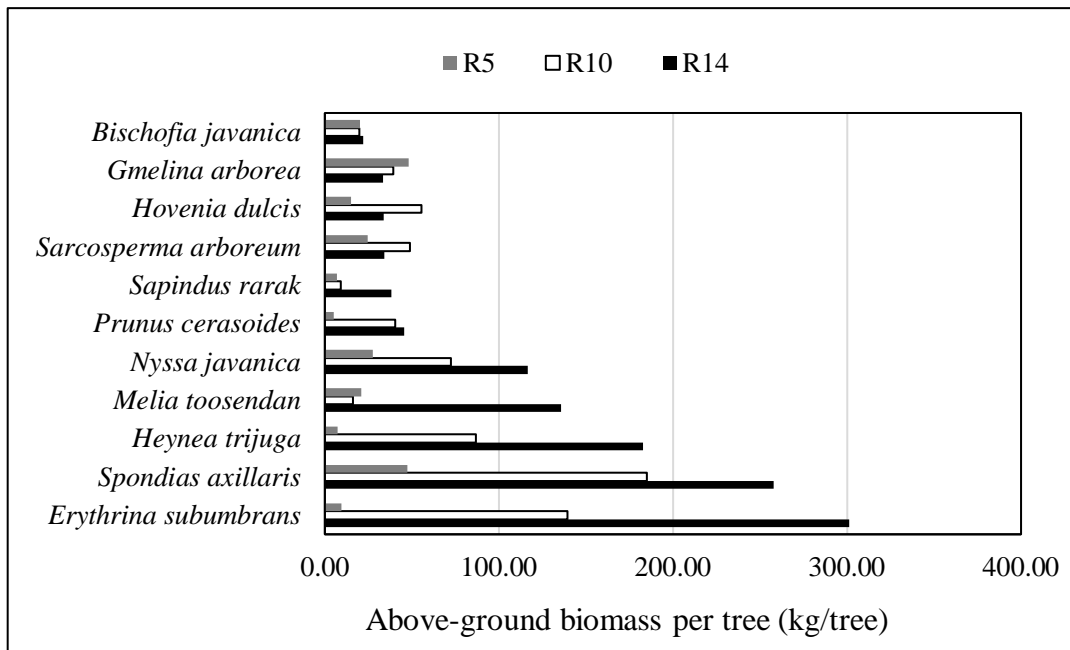
Figure 4.3 Species ranked in order of increasing biomass per tree and showing changes in biomass with age.

Trunks constituted most of the above-ground tree dry biomass (nearly 80%), followed by branches (around 17%) and leaves (3-5%). These relative percentages varied very little among species. The faster-growing species tended to allocate, proportionally, slightly more biomass to branches and slightly less towards trunks and leaves, but the trend was not statistically significant. As the trees aged, they tended to allocate very slightly more biomass towards branches and proportionally less towards the trunk and leaves, but again the trend was not statistically significant (Table 4.1- 4.2, Fig. 4.4).

Table 4.1 Mean above-ground dry biomass of selected framework tree species and their components 5, 10 and 14 years after planting. Data are mean masses (kg) of 3 trees per plot.

Species		RF5				RF10				RF14			
		Trunk	Branches	Leaves	Total	Trunk	Branches	Leaves	Total	Trunk	Branches	Leaves	Total
Bischofia javanica	X̄	15.2	3.9	0.9	20.1	15.72	3.30	0.79	19.81	16.99	4.14	0.89	22.02
	SD	± 3.22 [b]	± 1.43 [b]	± 0.22 [ab]	± 3.86 [ab]	± 8.26 b	±1.27 [b]	± 0.23 [cd]	± 8.24 [c]	± 8.00 [c]	± 1.27 [b]	± 0.24 [c]	± 7.84 [c]
Erythrina subumbrans	X̄	6.7	2.3	0.6	9.6	100.76	34.81	3.89	139.46	223.65	71.18	6.40	301.23
	SD	± 2.50 [b]	± 0.59 [b]	± 0.11 [b]	± 2.87 [b]	± 60.58 [ab]	± 15.06 [a]	± 1.14 [ab]	± 68.66 [ab]	± 82.73 [a]	± 18.70 [a]	± 1.43 [a]	± 91.83 [a]
Gmelina arborea	X̄	40.8	6.0	1.2	48.0	30.38	7.54	1.25	39.17	27.59	4.69	0.99	33.27
	SD	± 12.25 [ab]	± 1.72 [ab]	± 0.24 [ab]	± 12.68 [a]	± 20.94 [b]	± 2.99 [b]	± 0.58 [cd]	± 21.89 [bc]	± 5.09 [c]	± 0.53 [b]	± 0.17 [c]	± 4.54 [c]
Heynea trijuga	X̄	5.5	1.2	0.4	7.2	71.79	12.80	2.04	86.63	152.85	26.47	3.37	182.69
	SD	± 1.79 [b]	± 0.47 [b]	± 0.11 [b]	± 2.09 [b]	± 25.08 [b]	± 1.40 [b]	± 0.28 [bcd]	± 22.26 [bc]	± 35.88 [ab]	± 7.19 [b]	± 0.74 [bc]	± 38.10 [abc]
Hovenia dulcis	X̄	11.4	1.9	1.6	14.9	45.39	7.96	1.88	55.43	27.25	5.53	0.96	33.74
	SD	± 3.09 [b]	± 0.19 [b]	± 0.19 [ab]	± 2.76 [b]	± 27.96 [ab]	± 2.92 [b]	± 0.95 [abc]	± 3.32 [ab]	± 13.83 [c]	± 1.96 [b]	± 0.45 [c]	± 2.71 [c]
Melia toosendan	X̄	15.8	4.3	0.9	21.0	12.07	3.20	0.75	16.03	106.14	26.32	3.22	135.68
	SD	± 5.65 [b]	± 1.17 [b]	± 0.18 [ab]	± 5.97 [ab]	± 4.91 [b]	± 0.77 [b]	± 0.17 [cd]	± 4.37 [c]	± 13.70 [bc]	± 2.32 [b]	± 0.50 [bc]	± 13.90 [bc]
Nyssa javanica	X̄	20.5	5.8	1.1	27.4	58.44	12.19	1.89	72.52	89.68	23.66	3.10	116.43
	SD	± 8.19 [b]	± 2.79 [ab]	± 0.39 [ab]	± 9.96 [ab]	± 18.76 [b]	± 3.17 [b]	± 0.28 [bcd]	± 19.85 [bc]	± 64.33 [bc]	± 14.26 [b]	± 1.54 [bc]	± 71.62 [bc]
Prunus cerasoides	X̄	4.2	0.8	0.3	5.3	31.21	7.71	1.58	40.51	35.58	8.26	1.76	45.59
	SD	± 2.29 [b]	± 0.27 [b]	± 0.13 [b]	± 2.05 [b]	± 19.20 [ab]	± 3.47 [ab]	± 0.34 [abcd]	± 9.73 [bc]	± 23.17 [bc]	± 3.04 [b]	± 0.94 [bc]	± 9.97 [c]
Sapindus rarak	X̄	5.5	1.2	0.4	7.0	6.97	1.91	0.43	9.32	31.86	5.52	1.00	38.38
	SD	± 1.94 [b]	± 0.57 [b]	± 0.13 [b]	± 2.29 [b]	± 2.58 [b]	± 0.62 [b]	± 0.14 [d]	± 2.99 [c]	± 11.49 [c]	± 1.72 [b]	± 0.17 [c]	± 9.76 [c]
Sarcosperma arboreum	X̄	20.5	2.9	1.0	24.5	39.36	8.91	1.73	49.0	30.12	2.78	1.40	34.30
	SD	± 7.84 [b]	± 1.30 [b]	± 0.19 [ab]	± 7.01 [ab]	± 12.17 [b]	± 3.44 [b]	± 0.93 [bcd]	± 2.23 [bc]	± 16.05 [c]	± 1.36 [b]	± 0.39 [bc]	± 7.45 [c]

Table 4.1 (Continued)

Species		RF5				RF10				RF14			
		Trunk	Branches	Leaves	Total	Trunk	Branches	Leaves	Total	Trunk	Branches	Leaves	Total
Spondias axillaris	X̄	38.1	8.0	1.2	47.3	162.74	18.73	3.43	184.90	191.63	62.05	4.31	258.00
	SD	± 39.54 [a]	± 4.98 [a]	± 0.56 [a]	± 5.37 [a]	± 39.65 [a]	± 9.30 [a]	± 0.77 [a]	± 35.47 [a]	± 54.77 [bc]	± 23.17 [ab]	± 2.15 [ab]	± 69.15 [ab]

Table 4.2 Percentage allocation of above-ground dry biomass among components of selected framework tree species 5, 10 and 14 years after planting.

Species	RF5			RF10			RF14		
	Trunk (%)	Branches (%)	Leaves (%)	Trunk (%)	Branches (%)	Leaves (%)	Trunk (%)	Branches (%)	Leaves (%)
Bischofia javanica	76.0	19.5	4.5	79.3	16.7	4.0	77.2	18.8	4.0
Gmelina arborea	85.0	12.5	2.5	77.7	19.2	3.2	82.9	14.1	3.0
Hovenia dulcis	76.5	12.8	10.7	82.1	14.5	3.4	80.8	16.4	2.8
Sarcosperma arboreum	84.0	11.9	4.1	78.8	17.8	3.5	87.8	8.1	4.1
Sapindus rarak	77.5	16.9	5.6	75.0	20.4	4.6	83.0	14.4	2.6
Prunus cerasoides	79.6	14.8	5.6	77.1	19.0	3.9	78.0	18.1	3.9
Nyssa javacia	75.1	20.9	4.0	80.6	16.8	2.6	77.0	20.3	2.7
Melia toosendan	75.6	20.1	4.3	75.4	19.9	4.7	78.2	19.4	2.4
Heynea trojuga	77.5	16.9	5.6	82.9	14.8	2.4	83.7	14.5	1.8
Spondias axillaris	80.5	16.9	2.5	88.0	10.1	1.9	74.3	24.1	1.7
Erythrina subumbrans	69.8	24.0	6.3	72.3	24.9	2.8	74.2	23.6	2.1
Mean	**77.9**	**17.0**	**5.1**	**79.0**	**17.6**	**3.3**	**79.7**	**17.4**	**2.8**
95% CL +/-	**2.5**	**2.3**	**1.3**	**2.6**	**2.3**	**0.5**	**2.5**	**2.7**	**0.5**
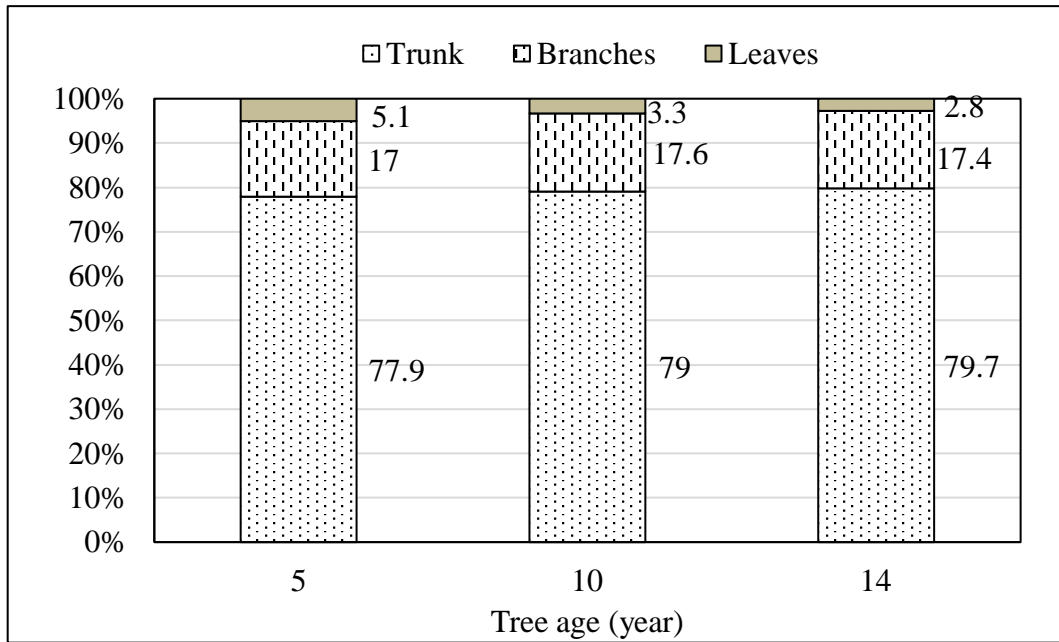
Figure 4.4 Small changes in average ratio (across all species) of percentage allocation of above-ground dry biomass among tree parts

4.1.2 Percent of carbon content in stem wood

The carbon concentration of the dry stem wood varied little among the species and among the plots, falling within the narrow range 43.18% to 45.89% (% of dry wood). The mean value was 44.67% ($\pm$ 0.54) with no significant differences among the species or the plots (Duncan's Multiple Range test, p $\leq$ 0.05).

In the younger plots, *Spondias axillaris* trees sequestered the most carbon, but by year 14, *Erythrina subumbrans* trees had overtaken them, storing more carbon than the trees of any other species of the same age. Both are pioneer species. *Heynea trijuga* (a late-successional species) was the third best performer, in term of carbon storage, whereas *Gmelina arborea* and *Bischofia javanica*, both considered to be pioneer species, performed unexpectedly poorly in term of carbon sequestration. (Table 4.3).

Wood carbon content varied little among the R14 plot, natural forest and pine forest (44.67%, 45.37% and 45.98%), but stem wood carbon content in the control plot was

substantially lower than that recorded for trees in the other sites (40.65%).

Table 4.3 Above-ground carbon sequestration of selected framework species across different aged plots. Species ranked in declining order of carbon storage in RF14 plot.

Species	% Carbon	Carbon sequestration (kgC/tree)		
		RF5	RF10	RF14
Erythrina subumbrans	44.49	4.30 ± 1.40	62.61 ± 33.91	135.23 ± 45.21
Spondias axillaris	45.05	21.24 ± 9.32	83.04 ± 21.34	115.87 ± 34.57
Heynea trijuga	44.04	3.16 ± 1.16	38.29 ± 10.97	80.74 ± 19.03
Melia toosendan	44.79	9.44 ± 2.35	7.22 ± 2.12	61.12 ± 6.79
Nyssa javanica	44.91	12.23 ± 6.65	32.32 ± 9.69	51.88 ± 34.87
Prunus cerasoides	44.89	2.37 ± 1.20	18.18 ± 8.42	20.47 ± 7.44
Sapindus rarak	44.36	3.10 ± 1.30	4.10 ± 1.38	16.90 ± 4.71
Sarcosperma arboreum	45.24	11.08 ± 4.08	22.17 ± 12.30	15.52 ± 9.09
Hovenia dulcis	44.56	6.66 ± 1.32	24.83 ± 13.44	15.11 ± 6.99
Gmelina arborea	44.20	14.76 ± 1.92	17.38 ± 8.63	21.31 ± 2.18
Bischofia javanica	44.89	8.93 ± 1.81	8.81 ± 3.99	9.80 ± 3.73
Mean across species	**44.67**	**9.44 ± 4.21**	**29.00 ± 13.42**	**48.85 ± 20.86**

When comparing the relative rates of carbon accumulation per year over 9 years (from 5 to 14 years old) among species, the carbon sequestration (kgC/tree) of each species was used for the calculation. The relative rates of carbon accumulation of *Erythrina subumbrans,* was the highest at 38% per year compared with the other species, whilst that of *Bischofia javanica* was the lowest at 1%. The species ranking of relative rate of carbon accumulation shown in Fig. 4.5.
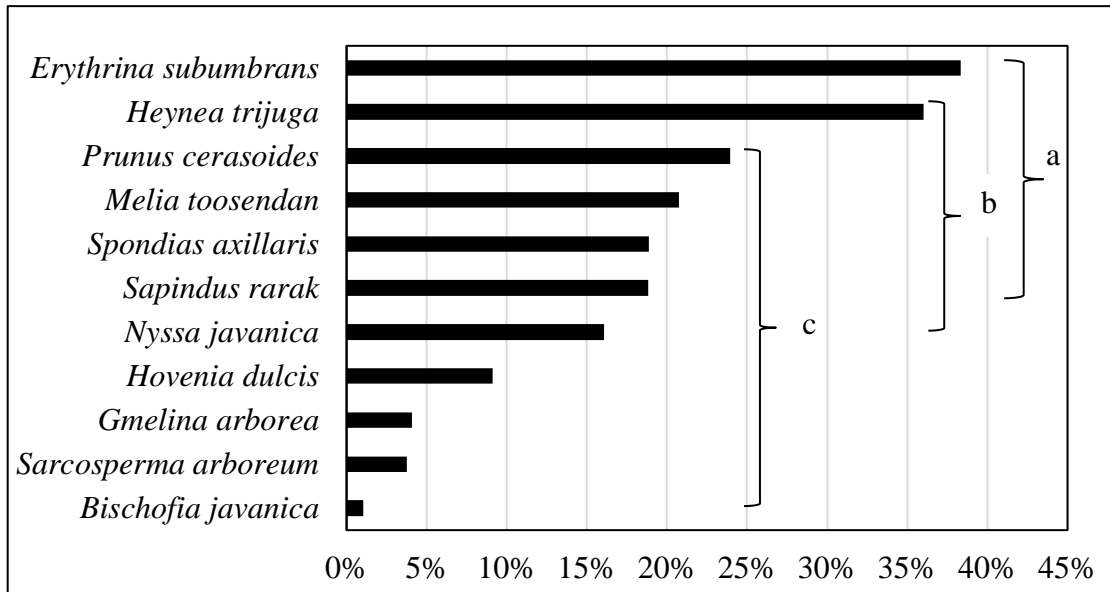
Figure 4.5 Percentage of relative rates of carbon accumulation per year from age 5 to 14 years old compared among framework tree species.

4.2 Comparing above-ground biomass per hectare and carbon sequestration per hectare among different forest management regimes

This results in this section were derived from the circular sample plots. Above-ground biomass of trees in the circular sample plots was calculated by allometric equations. The carbon sequestered per hectare was extrapolated from the mean mass of all the trees per 78-m^2-circle (from the allometric equations). The stocking density per hectare in the R14, R10, R5, natural forest and pine was 1,401, 1,529, 2,166, 2,105 and 535 trees/ha respectively. The highest above-ground biomass was recorded in natural forest (394.7 t/ha) followed by the monoculture pine plantation (~ 40 years old) at 372.6 t/ha. Then R14, R10 and R5 (237.1, 99.3 and 29.5 t/ha respectively, from oldest to youngest) whereas the control plot had the lowest (3.11 t/ha) as expected.

Consequently, natural forest sequestered 181.5 tC/ha, followed by the monoculture pine plantation, R14, R10, R5 and the control plots (124.1, 105.91, 44.3, 13.2 and 1.26 tC/ha respectively) (Fig. 4.6).

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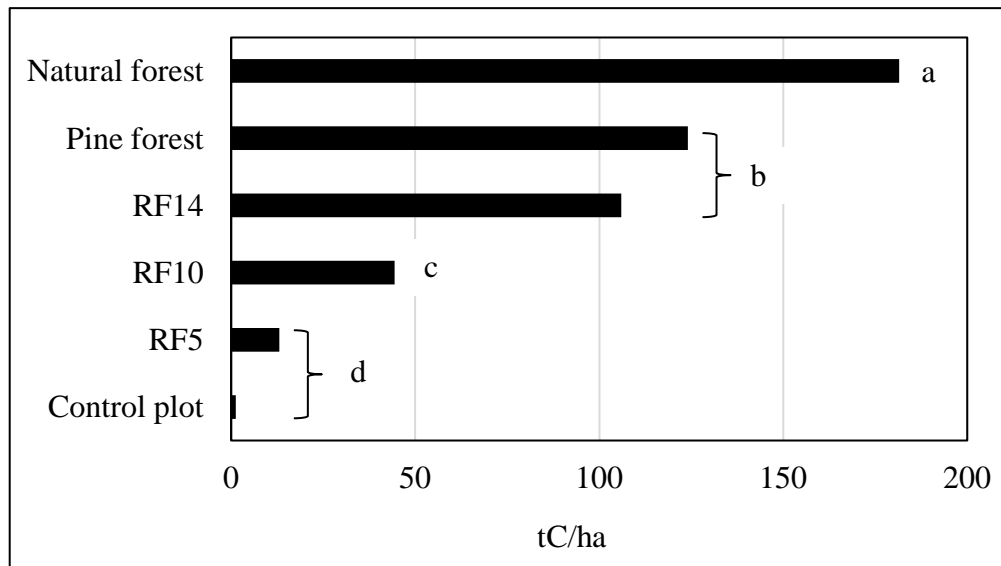
Figure 4.6 The above-ground carbon sequestration (tC/ha) compared between plot R14 (14 years old), plot R10 (10 years old), plot R5 (5 years old), natural forest, pine forest (> 20 years old) and control plot (14 years old).

4.3 Photosynthesis of selected framework species

4.3.1 Carbon uptake rate and carbon stock modeling

Eight framework tree species (*Bischofia javanica, Erythrina subumbrans, Gmelina arborea, Heynea trijuga, Hovenia dulcis, Melia toosendan, Nyssa javanica* and *Prunus cerasoides*) were tested for photosynthesis rate. Leaves were categorized into 3 types (young, mature and shade). CO_2 was set at 400 μmol $CO_2/m^2/s$ (similar to the current ambient atmospheric CO_2 concentration at time of the study (403.95 ppm, as of July 2017, (NOAA, 2017)) and injected through the chamber. Light intensity was varied from low to high intensity. Light response curves of each species shown in Fig. 4.7 a-b. Equations derived from trend lines as a relationship between photosynthesis rate and PAR in Fig 4.7 a-b of each leaf types and each species were used to calculate the light compensation point, where photosynthesis rate is zero. The maximum photosynthesis rate, light saturation point, photo inhibition point and light compensation point of each species extracted from the equation of light response shown in Table 4.4.

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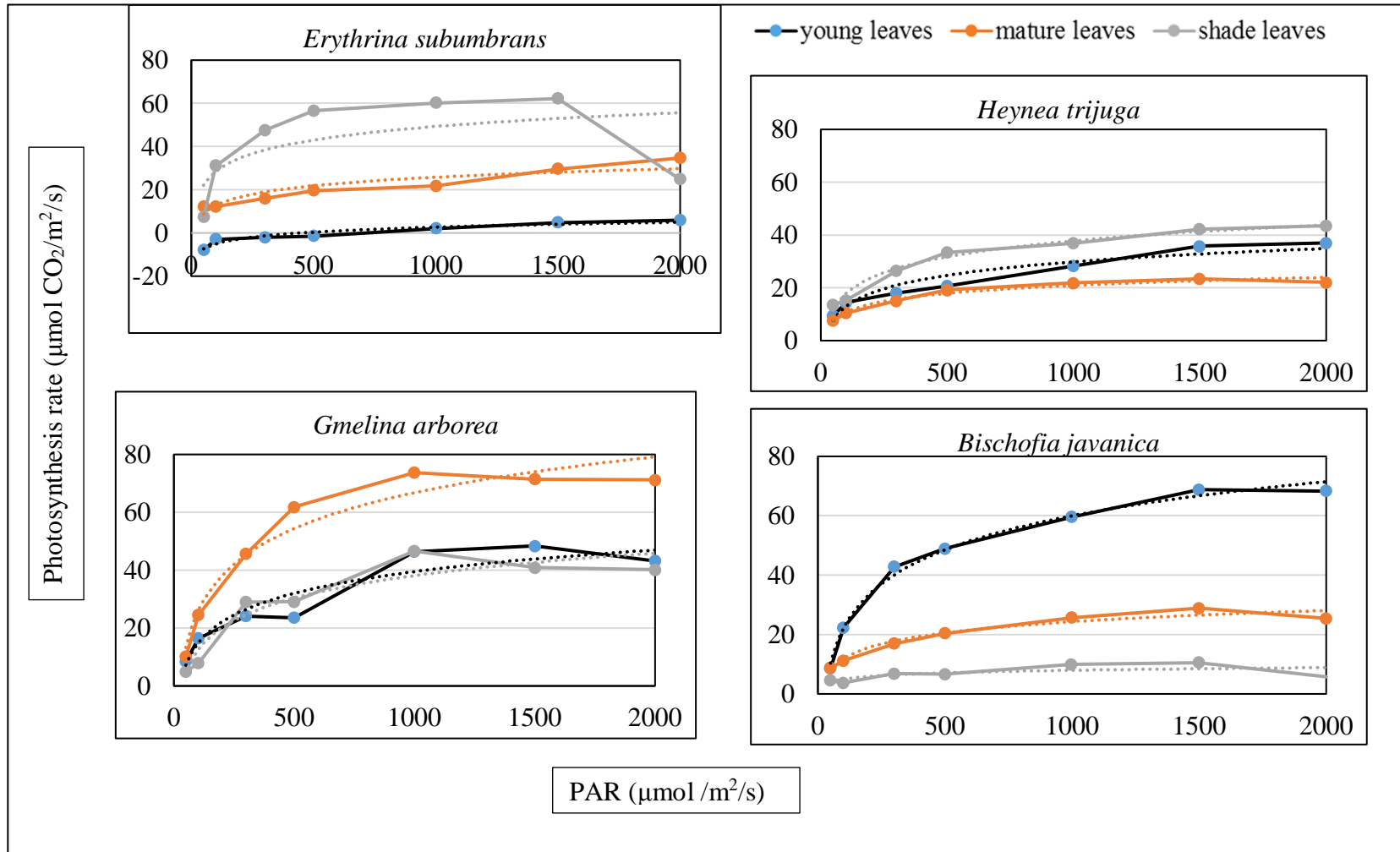
Figure 4.7 a Photosynthesis rate at CO_2 concentration of 400 ppm from light intensity 50 – 2,000 µmol/m^2/s. Black line, orange line and grey line indicate young, mature and shade leaves respectively.
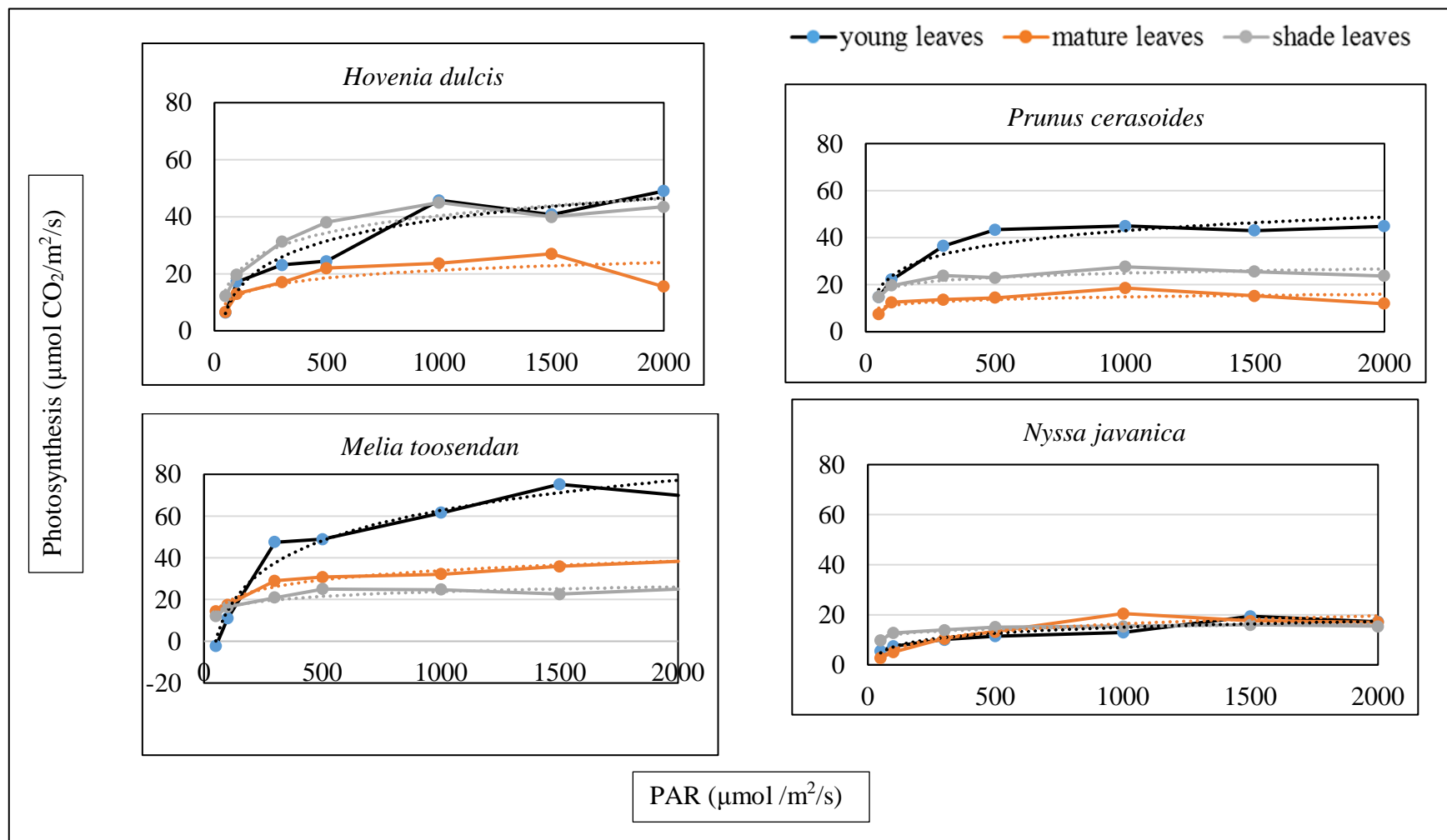
Figure 4.7 b Photosynthesis rate at CO_2 concentration of 400 ppm from light intensity 50 – 2,000 µmol/m^2/s. Black line, orange line and grey line indicate young, mature and shade leaves respectively.

Table 4.4 The maximum photosynthesis rate, light saturation point, photo inhibition point and light compensation point of each species. (N/A = not available, Y = young leaves, S = shade leaves and M = mature leaves)

Species	Maximum photosynthesis rate (μmol CO_2/m^2/s)			Light saturation point (μmol/m^2/s)			Photo inhibition point (μmol/m^2/s)			Light compensation point (μmol/m^2/s)		
	Y	S	M	Y	S	M	Y	S	M	Y	S	M
Erythrina subumbrans	5.9	62.2	34.7	2,000	1,500	2,000	N/A	2,000	N/A	350.0	-128.1	10.8
Nyssa javanica	19.4	16.0	20.5	1,500	1,500	1,000	2,000	N/A	1,500	12.3	0.03	27.7
Heynea trijuga	35.8	43.5	23.4	2,000	2,000	1,500	N/A	N/A	N/A	17.2	12.9	8.2
Prunus cerasoides	45.0	27.6	18.6	1,000	1,000	1,000	1,500	1,500	1,500	5.9	0.1	0.1
Gmelina arborea	48.4	46.6	73.7	1,500	1,000	1,000	2,000	1,000	N/A	25.7	33.3	23.8
Hovenia dulcis	49.0	45.0	27.0	2,000	1,000	1,000	N/A	1,500	2,000	28.2	9.6	4.3
Bischofia javanica	68.8	10.5	28.9	1,500	1,500	1,500	N/A	N/A	N/A	26.7	2.1	11.3
Melia toosendan	75.2	25.0	38.3	1,500	2,000	2,000	2,000	N/A	N/A	49.72	0.71	5.26

Averaging the maximum rate of photosynthesis, across species for each leaf type, young leaves had highest rate (43.4 ± 23.2), whilst shade and mature leaves had similar rates (34.6 ± 17.6 and 33.1 ± 17.7 µmol $CO_2/m^2/s$ respectively). However, these differences were not significant ($p < 0.05$, Duncan's multiple range test). When averaging the maximum rate of photosynthesis across leaf types for each species, *Gmelina arborea* had highest photosynthesis rate, 56.2 ±15.2 µmol $CO_2/m^2/s$ and *Nyssa javanica* had lowest, 18.6 ± 2.3 µmol $CO_2/m^2/s$. Other species had similar photosynthesis rates ranging from 30 to 46 µmol $CO_2/m^2/s$, as shown in Table 4.5 & Fig.4.8 ranked in order.

Table 4.5 Maximum photosynthesis rates, averaged across leaf types of each species and averaged across species for each leaf types. Means not sharing the same superscripts are significantly different ($p < 0.05$)

Species	Maximum photosynthesis rate (µmol $CO_2/m^2/s$)			
	Y	S	M	Average for all leaves types
Nyssa javanica	19.4	16	20.5	18.6 ± 2.3 [b]
Prunus cerasoides	45	27.6	18.6	30.4 ± 13.4 [ab]
Heynea trijuga	35.8	43.5	23.4	34.2 ± 10.1 [ab]
Erythrina subumbrans	5.92	62.2	34.7	34.3 ± 28.1 [ab]
Bischofia javanica	68.8	10.5	28.9	36.1 ± 29.8 [ab]
Hovenia dulcis	49	45	27	40.3 ± 11.7 [ab]
Melia toosendan	75.2	25	38.3	46.2 ±26.0 [ab]
Gmelina arborea	48.4	46.6	73.7	56.2 ±15.2 [a]
Average all species	43.4 ± 23.2 [a]	34.6 ± 17.6 [a]	33.1 ± 17.7 [a]	
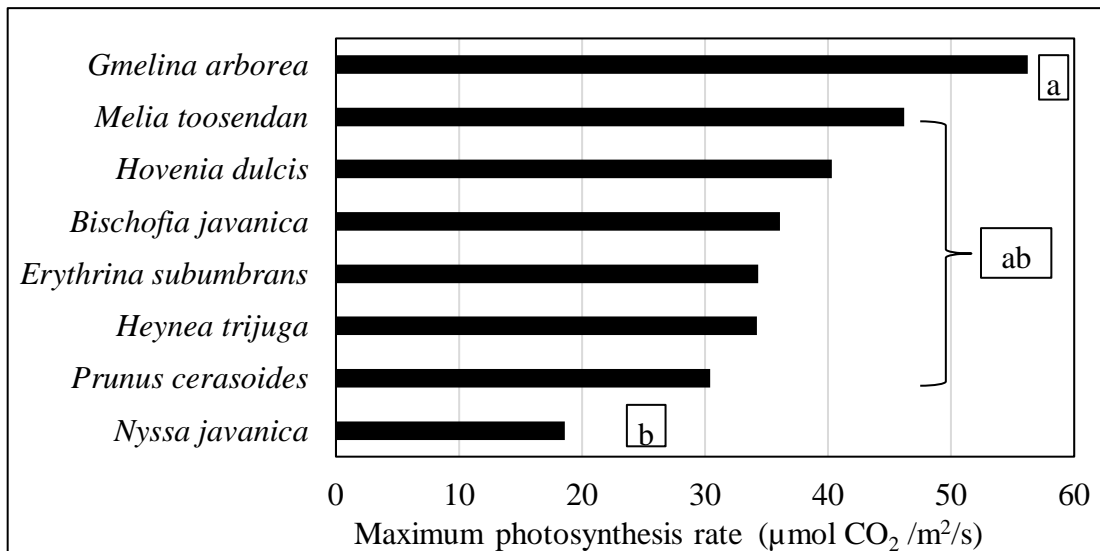
Figure 4.8 Maximum photosynthesis rate averaged across leaf types of each species (N=3). Bars not sharing the same superscripts are significantly different among species (p<0.05).

4.3.2 The relationship between photosynthesis rate and tree's relative growth rate and carbon accumulation

Maximum photosynthesis rate appeared to be unrelated to relative growth rate and carbon accumulation per tree (by partial harvesting). Although photosynthesis absorbs CO_2 and stores carbon as biomass. *G. arborea* had the maximum photosynthesis rate, but ranked 9th (out of 11) in relative growth rate and 10th in carbon accumulation per tree. Meanwhile *E. subumbrans*, with the highest relative growth rate and carbon accumulation per tree, ranked 5th in terms of maximum photosynthesis rate. Although *G. arborea* had the highest potential, in terms of photosynthesis, the species did not perform as well as *E. subambrans,* in terms of carbon accumulation in the field. This may have been due to differences in crown density.

Leaf mass per tree crown was averaged across trees aged 5, 10 and 14 years old. *E. subumbrans* tree had the most leaves by weigh, which could explain why *E. subambrans* had highest relative growth rate and carbon accumulation. As well as in *N. javanica*, though this species had the lowest of maximum photosynthesis rate but was not lowest in

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relative growth rate and carbon accumulation because leaves weight ranked in third out of eleventh (Fig. 5.9). Therefore, if we want to assess tree growth from photosynthetic efficiency, the amount of leaves must take into account for evaluation.
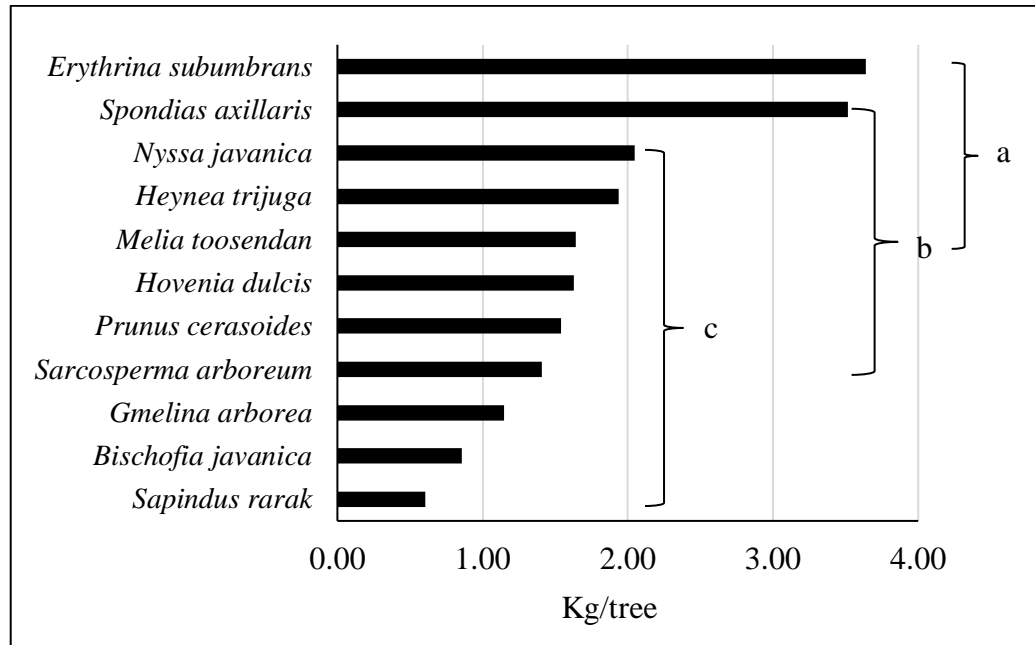
Figure 5.9 Leaves weight in a tree averaged across age 5, 10 and 14 years old.

4.4 Carbon sequestration modeling

4.4.1 Carbon absorption modeling

Secondary data of solar radiation in Chiang Mai, Thailand (Exell and Santibuppakul, 1984) were used for calculation (Table 4.6).

Table 4.6 Mean daily total diffuse solar radiation estimated by a simulation model, $MJ/m^2/day$ (Source: Exell and Santibuppakul, 1984).

Duration	Chiang Mai (MJ /m^2 /day)
14 Jan – 26 Feb	7.9
27 Feb – 12 Apr	10.1
13 Apr – 28 May	11.1

Table 4.6 (Continued)

Duration	Chiang Mai (MJ /m^2 /day)
29 May – 15 Jul	11.2
16 Jul – 31 Aug	10.7
1 Sep – 15 Oct	9.8
16 Oct – 29 Nov	7.1
30 Nov – 13 Jan	6.6

Units of MJ/m^2/day were then converted into μmol/m^2/s (approximate conversion value for radiation 400-700 nm), by using conversion factor adapted from Thimijan and Heins, 1983 (Table 4.7).

1) Converted MJ/m^2/day into J/m^2/day by multiplying by 10^6
2) Converted J/m^2/day into J/m^2/s by dividing with 86,400
3) J/m^2/s is equal to w/m^2
4) Converted w/m^2 to μmol/m^2/s (sunlight) by 4.57 μmol/m^2/s = 1 w/m^2

Table 4.7 The conversion table from unit of MJ/m^2/day into μmol/m^2/s. Source of conversion factors: Thimijan and Heins (1983)

Duration	MJ /m^2 day	J/m^2/day	J/m^2/s	w/m^2	μmol/m^2/s
14 Jan – 26 Feb	7.9	7,900,000	91.44	91.44	417.86
27 Feb – 12 Apr	10.1	10,100,000	116.90	116.90	534.22
13 Apr – 28 May	11.1	11,100,000	128.47	128.47	587.12
29 May – 15 Jul	11.2	11,200,000	129.63	129.63	592.41
16 Jul – 31 Aug	10.7	10,700,000	123.84	123.84	565.96
1 Sep – 15 Oct	9.8	9,800,000	113.43	113.43	518.36
16 Oct – 29 Nov	7.1	7,100,000	82.18	82.18	375.54
30 Nov – 13 Jan	6.6	6,600,000	76.39	76.39	349.10

The amount of light available to each tree, each day of the year, was then calculated and used to calculate the amount of carbon absorbed, by each tree crown, for each day of

the year. The calculation procedure was explained in Chapter 3 section 3.6.1. The daily figures were then accumulated to estimate the total amount of carbon that could be absorbed by a tree of each species in year 5. The total amount of carbon absorbed by a tree was then deducted by the relative rates of carbon accumulation per year, to derive total carbon allocated to roots allocation and respiration (Table 4.8).

Table 4.8 Total (sum of young and mature leaves) carbon absorption (kgC/year), Relative rates of carbon accumulation per year (%),C allocate to roots (kgC/year), C loss due to respiration (kgC/year) and Total C accumulate (kgC/year)

	Year 5			Year 14			Relative rates of carbon remaining for above-ground growth (after root allocation) per year (%)
	Total C absorb (kgC)	C allocated to roots (kgC)	C remain	Total C absorb (kgC)	C allocate to roots (kgC)	C remain	
Erythrina subumbrans	28.53	10.55	17.98	249.55	108.98	185.56	26%
Bischofia javanica	12.79	4.73	8.06	14.96	5.54	9.43	2%
Gmelina arborea	81.66	30.21	51.44	88.24	32.65	55.59	1%
Heynea trijuga	12.42	4.59	7.82	104.61	38.71	65.91	24%
Hovenia dulcis	63.14	23.36	39.78	67.05	24.81	42.24	1%
Melia toosendan	21.62	8.00	13.62	73.27	27.11	46.16	14%
Nyssa javanica	56.97	21.08	35.89	153.57	56.82	96.75	11%
Prunus cerasoides	8.62	3.19	5.43	52.30	19.35	32.95	20%

4.4.2 Tree growth modeling

The figures that were used in tree growth modeling consisted of;

- Carbon remaining after root allocation in year 5 (calculated in section 4.4.1) or (A)
- The result of tree carbon in plot R5 that was measured of each species or (B)
- Relative rates of carbon remaining for growth (after root allocation) per year (%) or (C)

Step of calculation of each year, started from year 5 to 14

Step 0 (staring in year 5): Start with carbon from field measurement in plot R5 and (A)

Step 1 (year 6): Calculated the carbon gained in year 6 by multiply (C) with (A), plus (A).

Step 2 (year 6): Calculated the carbon stock in a tree of year 6 by sum carbon gained in this year with carbon stock in a tree from previous year.

Step 3 (year 7): Calculated the carbon gained in year 6

Step 4 (year 7): Calculated tree carbon stock in year 7 by sum the carbon gained in year 6 with tree carbon stock of year 6.

... do the same for each succeeding year, until year 14.

Table 4.9 showed the example of tree carbon projection calculation in *B. javanica* from year 5 to 14. The full details of modeling calculation is attached in APPENDIX A.

When total above-ground carbon stock of each species were calculated from year 5 to 14, the results were then compared with the actual field measurement by the partial harvesting technique. In general, the model predictions over-estimated the mean carbon stock that was measured by field work (Fig 4.9 a-b). The equations from modeling curves of each species (shown in Table 4.10) were then used to calculate the mean and total carbon stock in forest restoration per hectare.

Table 4.9 Example of the modeling of carbon sequestration projection in *B. javanica* Note: alphabet in parentheses represented the number in the same box, %RCG = Relative rates of carbon remain for growth (after roots allocation) per year (%)

Year	5	6	7	8	9	10	11	12	13	14
Carbon accumulation, tC/tree	**0.0081** **(a)**	**0.0082** **(c)**	**0.0084** **(e)**	**0.0086** **(g)**	**0.0087** **(i)**	**0.0089** **(k)**	**0.0091** **(m)**	**0.0093** **(o)**	**0.0094** **(q)**	**0.0096** **(s)**
Calculation	*Calculated in section 4.4.1*	*[(a) * %RCG]+(a)*	*[(c) * %RCG]+ (c)*	*[(e) * %RCG]+ (e)*	*[(g) * %RCG]+ (g)*	*[(i) * %RCG] +(i)*	*[(k) * %RCG]+ (k)*	*[(m) * %RCG]+(m)*	*[(o) * %RCG]+ (o)*	*[(q) * %RCG]+ (q)*
Tree carbon stock, tC/tree (modeling)	**0.0089** **(b)**	**0.0170** **(d)**	**0.0252** **(f)**	**0.0336** **(h)**	**0.0422** **(j)**	**0.0509** **(l)**	**0.0598** **(n)**	**0.0689** **(p)**	**0.0781** **(r)**	**0.0876** **(t)**
Calculation	*Data from measurement in plot R5*	*(a) + (b)*	*(c) + (d)*	*(e) + (f)*	*(g) + (h)*	*(i) + (j)*	*(k) + (l)*	*(m) +(n)*	*(o) + (p)*	*(q) + (r)*

4.4.3 Forest restoration modeling

The results of above-ground carbon stock (tC/ha) predicting for 15 years was compared with the actual above-ground carbon stock (tC/ha). Although the modeling prediction did not match exactly with the actual measurement, the prediction did reveal that the above-ground carbon stock will continuously increase over years. The slow rate of increase showed during the beginning of restoration since stocking density decreased from year 1 to 10. But after year 10, the stocking density continuously increased which also caused the carbon stock in the area also increasing (Table 4.10, Fig 4.11).

Table 4.10 The modeling results of tree carbon stock of each species (tC/tree) and total carbon stock of each plot (tC/ha)

Species	tree carbon (tC/tree)		
	5	10	14
Erythrina subumbrans	0.004	0.141	0.314
Heynea trijuga	0.003	0.059	0.129
Melia toosendan	0.009	0.081	0.167
Nyssa javanica	0.012	0.226	0.441
Prunus cerasoides	0.002	0.049	0.101
Hovenia dulcis	0.007	0.217	0.473
Gmelina arborea	0.015	0.275	0.487
Bischofia javanica	0.009	0.141	0.314
mean (tC/tree)	**0.008**	**0.137**	**0.274**
stocking density (trees)	**1,401**	**1,529**	**2,166**
model (tC/ha)	**10.68**	**209.85**	**594.36**
measure (tC/ha)	**13.2**	**44.3**	**105.9**
Gap between modeling and measurement	**-2.52**	**165.55**	**488.46**
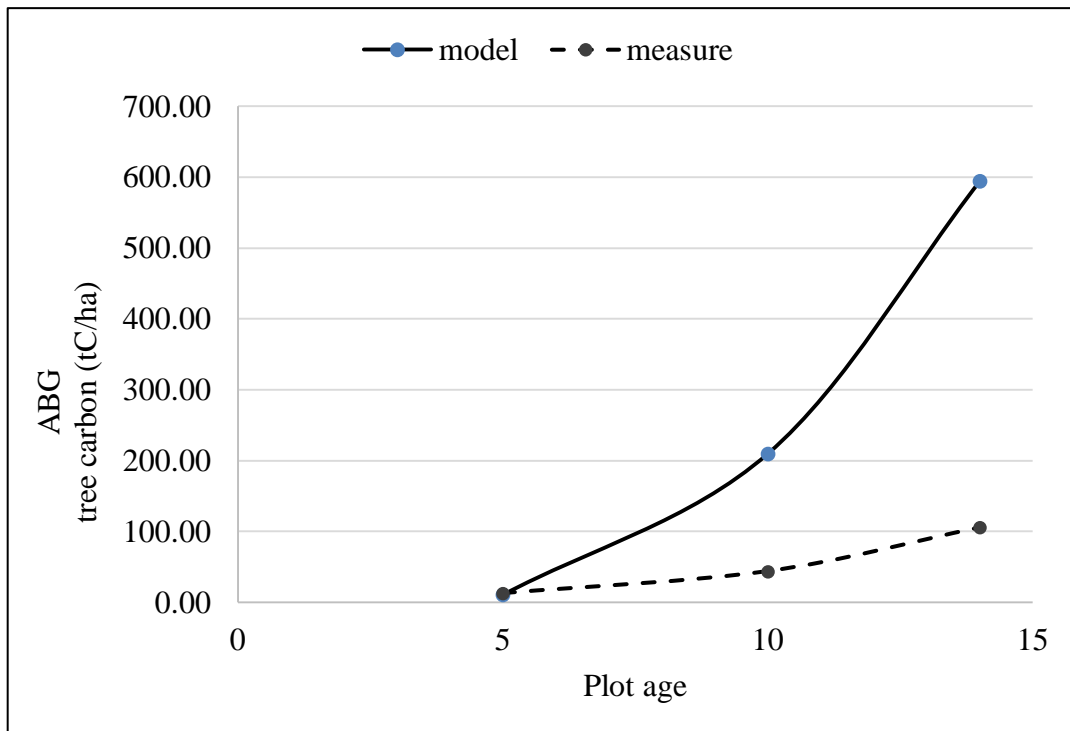
Figure 4.11 The comparison of the above-ground carbon stock (tC/ha) between

modeling calculation (from year 1 to 15) and actual field measurement

(Year 5, 10 and 14).

CHAPTER 5

Discussion

5.1 Comparing aboveground biomass and carbon sequestration among different framework tree species

In general, wood density of tropical trees is an indicator of species' successional status, fast-growing pioneer trees often have less dense wood than late-successional species (Henry *et al.*, 2010). The fast growth of pioneer trees is achieved to a large extent by cell expansion and water absorption, rather than cell division and thickening of cell walls with lignin (Henry *et al.*, 2010). *Erythrina subumbrans* was a clear example of such a growth strategy in this study. It was one of the fastest growing species and had the lowest wood density (significantly lower than that of most of the other species). However, *Gmelina arborea* and *Prunus cerasoides* were notable exceptions having higher than expected wood density for pioneer tree species.

The range of wood density values of *G. arborea* in this study ($0.43 – 0.70$ g/cm^3) compared similarly with those from other studies e.g. $0.34 – 0.49$ g/cm^3 (calculated from quoted values of 0.40-0.58 g/cm^3 at 15% moisture content) (PROSEA, 1994), 0.56 g/cm^3 in India (Benthall, 1984), $0.34 – 0.62$ g/cm^3 in Malaysia (Suliman & Lim, 1989) and 0.41-0.45 g/cm^3 (Brown, 1997). The species is commonly used for construction, because of its lightweight but hard wood (PROSEA, 1994).

Other published values for *P. cerasoides* could not be found, but for the genus *Prunus*, PROSEA (1994) states that the wood is light to medium-weight hard-wood, with densities over several species of $0.35 – 0.65$ g/cm^3 (calculated from the values 0.41-0.77, at 15% moisture content).

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Much of carbon accounting relies on allometric equations, whereby a hard-to-measure characteristic is predicted from an easy-to-measure one. Therefore, it is useful to determine relationships among variables in this study. Consequently, I attempted to determine the closeness and predictive power of the relationship between DBH and tree volume (using data from the oldest restoration plot, R14). The graph and equation are shown in Fig. 5.1. Tree species were separated by using different colors. The correlation was quite high ($R^2 = 0.8486$), indicating that DBH is quite a good indicator of tree volume. This is useful in that DBH (easily measured) can be used to generate a close approximation of tree volume in restoration projects, within the limits of the tree sizes study (range of DBH 3-30 cm), without the laborious measurements needed to perform partial harvesting.
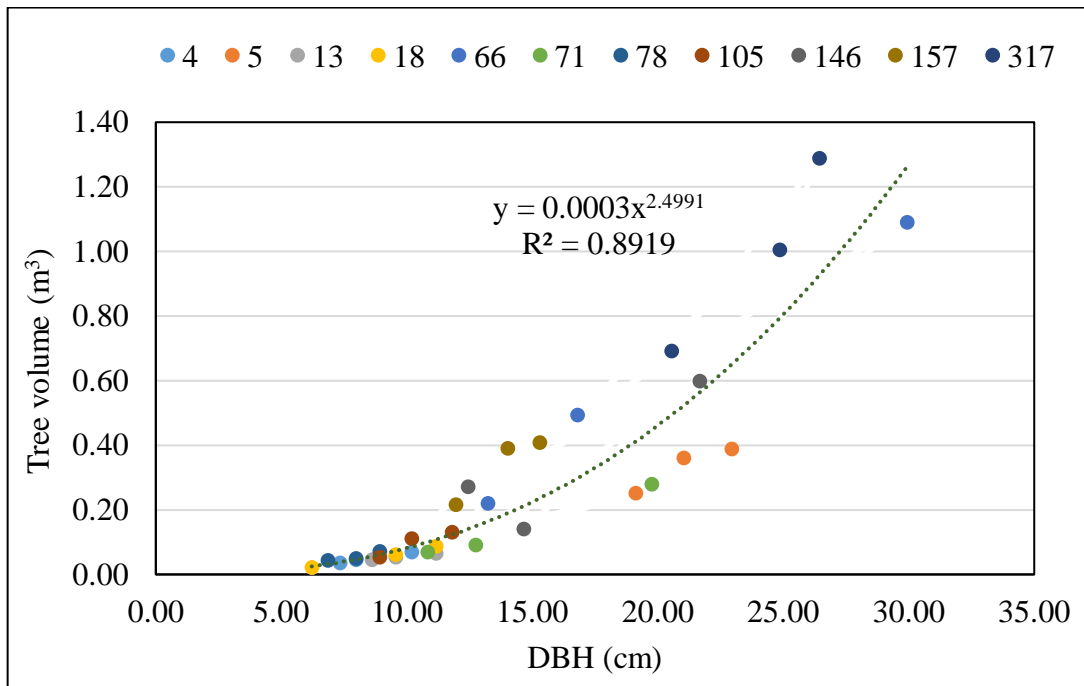
Figure 5.1 The relationship between tree volume (m^3) and DBH (cm) of trees in plot R14 express in exponential equation $y = 0.015e^{0.165x}$ ($R^2 = 0.8486$). Each color represent each tree species, using FORRU's species code number, 4 = *Bischofia javanica*, 5 = *Melia toosendan*, 13 = *Sapindus rarak*, 18 = *Hovenia dulcis*, 66 = *Spondias axillaris*, 71 = *Prunus cerasoides*, 78 = *Gmelina arborea*, 105 = *Sarcosperma arboretum*, 146 = *Nyssa javanica*, 157 = *Heynea trijuga* and 317 = *Erythrina subumbrans*.

5.1.1 Carbon percentage

This study demonstrated remarkably consistent percent carbon content of the stem wood (44.67% ±0.54) across all species tested in the restoration plots, although the plantation species, *Pinus kesiya* had 45.98% ± 0.52. These values were slightly lower than the standard published values, commonly used to calculate carbon storage for REDD+ projects and others that depend on carbon credits. For example, Brown (1997) recommended 50% and Tsutsumi (1983) 49.9 %. For trees, less than 10 cm diameter at breast height, IPCC (2006) recommends 46%, and for larger trees, 49%. This suggests that for seasonally dry tropical forests, current standard carbon accounting methods may slightly over-estimate the amount of carbon sequestered. As carbon concentration varies so little, differences in overall carbon storage among species is almost entirely attributable to differences in volume growth.

Results from some other authors are also lower than the recommended IPCC values. Analyzing data from stem cores of 59 Panamanian rainforest tree species, Martin and Thomas (2011) reported that C content varied substantially among species (from 41.9–51.6%). Furthermore, Wani and Qaisar (2014), working on *Cedrus deodara*, *Fraxinus floribunda* and *Ulmus wallichiana*, in the Kashmir Valley reported carbon per cent of wood of 45.41% for *Cedrus deodara*, 41.36% for *Fraxinus floribunda* and 40.78% for *Ulmus wallichiana*. Such results demonstrate not only that broad application of the IPCC values over estimate carbon accumulation, but also that species-specific per cent carbon values should be used to assess carbon sequestration by forest restoration, wherever such values are known. Furthermore, research to expand databases of such value should be undertaken as a matter of urgency.

5.1.2 Carbon sequestration

Since the percentage wood carbon content was not significantly different among the framework species tested (43.18% to 45.89%), the amount of carbon sequestered by trees of each species depended almost entirely on aboveground biomass. Therefore, it could safely be assumed that aboveground biomass directly affected carbon sequestration.

As the trees grew bigger, they sequestered more carbon in direct relation to their biomass increase. Therefore, not surprisingly, aboveground carbon sequestration increased over time: 13.17, 44.34 and 105.91 tC/ha for 5, 10 and 14 year-old restoration plots respectively (Table 5.1). Above-ground carbon sequestration in RF14 and the nearest mature forest remnant exceeded the amount reported in natural "dry evergreen" forest, growing under very similar climatic conditions in Thong Pha Phum National Forest, Kanchanaburi Province i.e. 70.29 ± 7.38 tC/ha (Terakunpisut et al., 2007). The value for the forest remnant in the present study even exceeded the value reported for so called "tropical rain" forest in Kanchanaburi i.e. 138 tC/ha and the RF14 value will clearly do so within the next 1 - 2 years.

The relative growth rate of above-ground carbon accumulation was compared between year 5-10 and year 10-14, the relative growth rate of above-ground carbon in year 5-10 was 24% per year and year 10-14 was 17% (Fig. 5.2). Clearly the greatest percent increase in carbon storage occurred when the trees were young. Because in early stage, trees had higher relative growth rate than the late stage and carbon sequestered directly affected from aboveground biomass so the percent increase was high in early stages and lower in later stages.

To derive carbon sequestered in tree roots, IPCC (2006b) recommends multiplying the above-ground biomass by a factor of 0.37 for tropical evergreen forests. Applied to the aboveground calculation, total estimated carbon sequestration in trees, including roots, then becomes 18.0, 60.7 and 144.8 tC/ha in the RF5, RF10 & RF14 plots, respectively.

The above figures for carbon stored in the trees was combined with published carbon levels in the same study area (Kavinchan et al., 2015) in litter (0.8, 0.2, 1.6, 1.8 and 2.7 tC/ha/year for control plot, R5, R10, R14 and natural forest respectively) and in soil (205.8, 254.4, 251.1, 161.8 and 244.9 tC/ha, likewise respectively). Although soil carbon data were collected in the same plots location, the data were collected when the plots were age at 2, 7 and 11 years old. Therefore, soil sampling with the same procedure in plot R5, R10 and R14 were made in February, 2018 to assess the present value of soil

carbon and to re-check the anomaly found in plot R14. The results of soil carbon stock at depth of 0-2 m in plots R5, R10 and R14 were 249.56, 255.75 and 170.39 tC/ha, respectively. It was clearly that the present results confirmed the anomaly dropping of soil carbon stock in R14 plot. Carbon that flows through litter fall obviously increases over years, as the trees grow and expand their crown and produce more leaves, which finally becomes litter fall. However, an anomaly was found in soil carbon, which dropped after year 7 causing lower than expected levels in plots R14 or R11 according to Kavinchan's study. The explanation for this event was that plot R14 had been cultivated for cabbage for a longer period than plot R10 and R5. Therefore, the history of land use caused carbon loss in upper soil layer and the carbon input had not yet reach the point to make soil carbon in plot R14 be more than plot R10 and R5 (Kavinchan et al, 2015). Since the anomaly of soil carbon occurred in the oldest plot in Kavinchan's study, therefore the result of soil carbon from plot R14 in Kavinchan's study will be exclude to make the prediction of total carbon in the present study more reliable. Therefore, after the anomaly exclusion, soil carbon and litter fall at the same plot age with this study, R5, R10 and R14 respectively were 1.0, 1.7 and 2.5 tC/ha/year for litter fall and 254.3, 259.5 and 262.1 tC/ha for soil carbon (Fig. 5.2, Table 5.1).
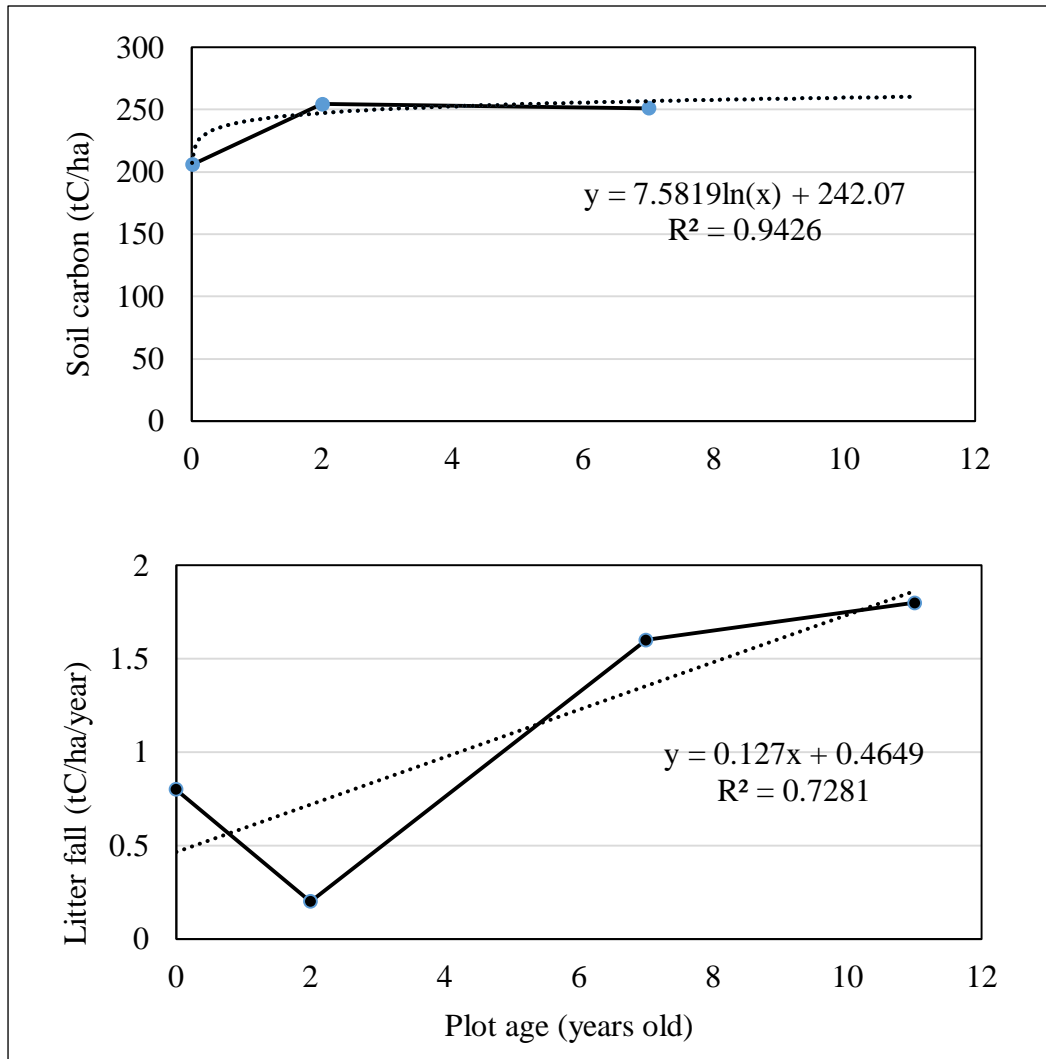
Figure 5.2 The relationship between plot age and soil carbon (tC/ha) and litter fall (tC/year/ha)

Table 5.1 Soil carbon (tC/ha) and litter fall (tC/ha/year) at the same plot age with this study (plot age of 5, 10 and 14 years)

Plot age	Litter fall (tC/ha/year)	Soil carbon (tC/ha)
5	1.0	254.3
10	1.7	259.5
14	2.5	262.1

Total carbon sequestration increased during the first 10 years after initiation of forest restoration activities, but slowed thereafter, resulting in 272.6, 313.4, 308.4 and 496.2 tC total carbon sequestration in plots R5, R10, R14 and natural forest respectively (Table 5.2), compared with only 210.9 tC/ha in the control plots. This latter figure is almost entirely residual soil carbon, remaining after deforestation about 30-40 years previously. The percent relative growth rate of carbon accumulation per year during 5 – 10 years was higher than that in 10 – 14 years (Fig 5.3, Table 5.2).
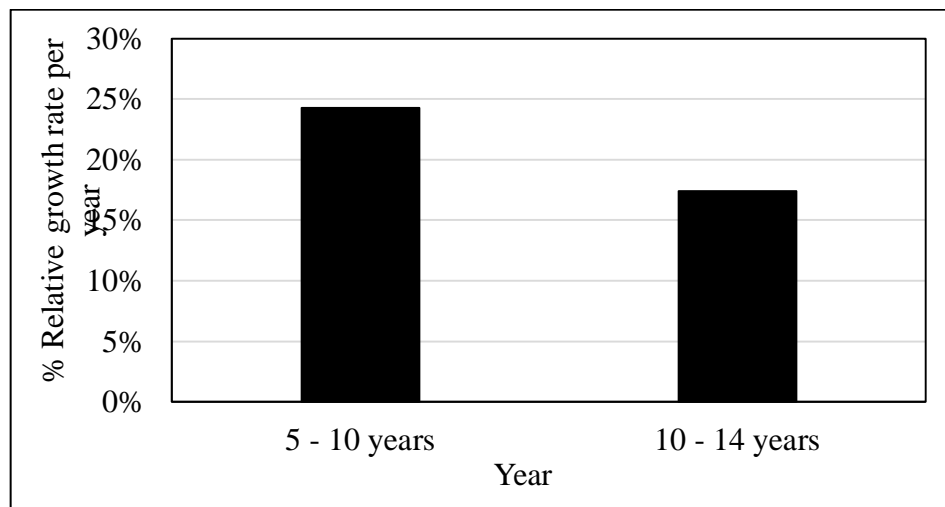
Figure 5.3 Percent of relative growth rate of carbon accumulation per year during 5 – 10 years and 10 – 14 years

Figure 5.4 presents the projected trend lines of carbon stock in above-ground (stem) + roots, below-ground (litter fall + soil) and total (above-ground + below-ground). When considering only above-ground + roots. The carbon stock tends to increase over time and will equal that in natural forest in around 18 years. In a related study, in the same area, Kavinchan et al. (2015) found that net inputs of carbon into the soil pool, via litterfall (taking into account decomposition) decline below control levels for at least 7 years after forest restoration commences (probably due to fire and weeding). Thereafter, inputs increase rapidly and were projected to attain natural forest levels in 18 - 20 years after tree planting. Therefore, most components of the carbon cycle in restoration plots approach levels similar to those of mature forest by around 20 years (Fig 5.4).

Table 5.2 Carbon sequestration of each species and the percentage of accumulation per year

	Carbon sequestration				
	Control plot	RF5	RF10	RF14	Natural forest
Mean across species (kgC/tree)		9.4	29.0	48.9	86.21
Tree density stock (trees/ha)		1,401	1,529	2,166	2,105
Aboveground carbon sequestration + root (tC/ha)	1.73	18.0	60.7	144.8	248.6
Carbon from litter fall (tC/ha/year)	0.8	1.0	1.7	2.5	2.7
Soil organic carbon (0 -2 m depth, tC/ha)	205.8	254.3	259.5	262.1	244.9
Total carbon accumulation (tC/ha)	210.9	273.3	321.9	409.4	496.2
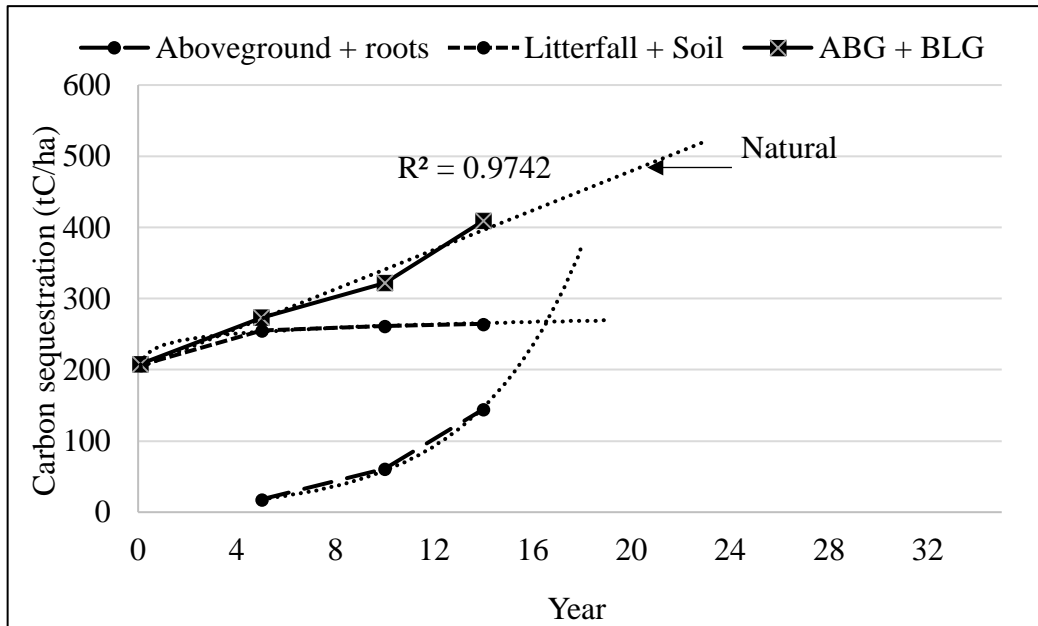
Figure 5.4 Above-ground (stem) + roots, below-ground (litter fall + soil) and total (above-ground + below-ground) carbon sequestration over time calculated from carbon per tree, averaged across all species (assuming even species mix) and the known stocking density in each of the plots. Projected trend line with $R^2 = 0.9724$ represents the total carbon sequestration.

Shimamoto et al., (2014) suggested that at the beginning of succession, fast-growing species accumulate more carbon than shade-tolerant species do in the later stages of succession. Therefore, mixing pioneer and climax species will generate continuous and long term of carbon accumulation in restored forests. Moreover, mixing tree species can avoid resource competition, since each species requires different amounts of resources, such as water, light and nutrient at different locations in the soil profile or at different heights above ground. So, each tree species can be grown properly and generate biomass efficiently by avoid competition with its neighbors – niche differentiation (Catterall et al., 2004; Wardell-Johnson et al., 2005).

Apart from carbon sequestration, the beneficial effects of the framework species method on biodiversity recovery have been well-documented in the same plot system as that used for the present study. Toktang (2005) recorded an increase in the species

richness of the bird community from about 30 before tree planting, to 88 after 6 years, when more than half (54%) of the bird species, recorded in natural forest, had recolonized the restored plots. Sinhaseni (2008) reported that seedlings of 73 non-planted tree species re-colonized the trial plot system within 8 - 9 years, most having germinated from seeds dispersed from nearby forest by birds (particularly bulbuls), fruit bats and civets. The species richness of mycorrhizal fungi and lichens also increased rapidly in the restored plots, exceeding that of natural forest (Nandakwang et al., 2008 & Phongchiewboon, 2008, respectively).

5.2 Comparing aboveground biomass and carbon sequestration between different management areas

Natural forest sequestered the most carbon per unit area (181.5 tC/ha) followed by the pine plantation (124.1 tC/ha) and then the restoration plots from oldest to youngest: R14, R10, R5 (105.9, 44.3, 13.2 respectively). Since the carbon sequestration was related directly with aboveground biomass and the pine trees in the plantation were much bigger than those in restored forest, it was not surprising that carbon sequestration in the pine plantation was higher than that in the restored forest plots. This was almost certainly due to the plantation age. Although the exact year of planting could not be ascertained, the trees were already large when FORRU started working in the area 20 years previously. From the interviewing with Mr. Kasem, the former head villager of Ban Mae Sa Mai and one of the conservation group founder of Ban Mae Sa Mai, he stated that pine forest was planted by RFD around 1970s. So the plantation was approximately 40 years old, so it had much more time, over which to accumulate carbon, compared with the restoration plots. Although the pine trees were larger than those in natural forest, the plantation stocking density was much lower (535 trees/ha) than in natural forest (2,105 trees/ha). The former equates with the regular spacing of 4 x 4 m between the pine trees, which was the standard stocking density used by the RFD when establishing pine plantations in the 1960's-90's. Moreover, trees growing in restored forest and natural forest were more varied in size than in the pine forest where all trees were of similar size and were therefore perfect competitors with each other. Therefore, carbon stored in natural forest per hectare was higher than in pine forest.

Aboveground carbon, stored in the oldest restored forest plot, R14 (105.91 tC/ha) was higher than in many other forests in Thailand. The carbon conversion factor from the field data derived from this study (0.44) was lower than suggested in other studies such as 0.5 (Terakunpisut et al., 2003; Jampanin, 2004; Nuanurai, 2005 and Petsri et al., 2007) and 0.47 (Chaiyo et al., 2011 and Chamnongpakdee and Udomsiriphong, 2015). However, tree age and forest type may affect carbon stock. Comparing the aboveground carbon stock in the youngest plot (R5, 5 years old) of this study (13.17 tC/ha) with similarly aged plots from other studies, such as 6-year-old fallow land (Pibumrung, 2008), plot R5 produced higher carbon stock than fallow land (5.91 tC/ha). This suggests that *active* restoration accumulates carbon faster than *passive* allowance of natural regeneration. The R5 plot also supported a higher carbon stock than a 6-year-old fallow, 5.91 tC/ha (Pibumrung, 2007).

When comparing the older restoration plots with similar forest types, the R14 plot stored 105.91 tC/ha aboveground carbon stock. That is higher than reported for dry evergreen forest at Thong Pha Phume (70.29 tC/ha) (Terakunpisut et al., 2003) and Kangkrajan National Park (103.85 tC/ha) (Nuanurai, 2005). The carbon stock of the R14 plots was also obviously higher than that of other monoculture plantations such as teak (41.13 tC/ha at 24 years old) (Petsri, et al., 2007) (Table 5.3).

Table 5.3 Carbon sequestration and aboveground biomass in different forest type in Thailand

Year	Reference	Study site	Carbon conversion factor	Age (years)	Forest type	Carbon (TonC/ha)
2012	This study	Ban Mae Sa Mai, Chiang Mai	0.44	5	Restoration 5 yrs old	13.17
				10	Restoration 10 yrs old	44.34
				14	Restoration 14 yrs old	105.91
				>20	Pine plantation	163.18
2003	Terakunpisut *et al.*.	Thong Pha Phume Forest	0.5	Natural	Tropical rain	137.73
				Natural	Dry evergreen	70.29
				Natural	Mixed deciduous	48.14
2004	Jampanil, S.	Kangkrajan National Park	0.5	Natural	Mixed deciduous	93.15
				Natural	Dry evergreen	37.13
				Natural	Hill evergreen	129.00
2005	Nuanurai, N.	Kangkrajan National Park	0.5	Natural	Dry dipterocarp	29.31
				Natural	Mixed deciduous	34
				Natural	Dry evergreen	103.85
				Natural	Moist evergreen	168.04

Table 5.3 (Continued)

Year	Author	Study site	Carbon conversion factor	Age (years)	Forest type	Carbon (TonC/ha)
2007	Pibumrung, P.	Nam Yao sub-watershed, Nan province		Natural	Hill evergreen	150.07
				26	Reforestation	40.70
				6	6-year-old fallow land	5.91
2007	Petsri, *et al*.	Hauy Kha Kaeng Wildlife Sanctuary	0.5	Natural	Mixed deciduous forest	71.60
		Thai Plywood Co. Ltd. Lansak district, Uthaithani province		6	Teak plantation	39.51
				15	Teak plantation	33.87
				23	Teak plantation	55.23
				24	Teak plantation	41.13
2010	Jundang, W.	Mancha Khiri Plantation, Khon Kaen Province		Natural	Dry dipterocarp	58.36
				4	Eucalypt plantations	64.7
				3	Eucalypt plantations	60.41
				2	Eucalypt plantations	54.55
				1	Eucalypt plantations	48.48

Table 5.3 (Continued)

Year	Author	Study site	Carbon conversion factor	Age (yrs)	Forest type	Carbon (TonC/ha)
2011	Chaiyo, *et al*.	Mae Nam Phachi Wildlife Sanctuary, Suan Pheung District, Ratchaburi province	0.47	Natural	Dry dipterocarp forest at 20-40% slope	43.22
				Natural	Dry dipterocarp forest at < 20% slope	14.55
				Natural	Mixed deciduous forest at <20% slope	27.94
2012	Sathienpeerakul, K.	Watershed area in North of Thailand, Chiang Mai		14 – 34	*Pinus kesiya*	9.52 - 86.77
2012	Nongnuang, S.	Boakaew watershed station, Samoeng district, Chiang Mai province		14 - 34	*Pinus kesiya*	9.52 – 8.77

Table 5.3 (Continued)

Year	Author	Study site	Carbon conversion factor	Age (yrs)	Forest type	Carbon (TonC/ha)
2013	Kiriratnikom, A.	Panpae Community Forest Bangkan District, Nakhon Si Thammarat Province		Natural		14.1
2013	Sathienpeerakul, K.	Boakaew watershed station, Samoeng district, Chiang Mai province		Natural	Fragmented in montane forests	107.2
2014	Chalermwong, P.	The upper southern rainforest ecosystem		Natural	Klong Panom rainforest (*Strombosia javanica* type)	141.841
				Natural	Kang Krung rainforest (*Shorea gratissima* type)	174.372
				Natural	Nam Tok Ngao rainforest (*Dipterocarpus kerrii*)	163.92

Table 5.3 (Continued)

Year	Author	Study site	Carbon conversion factor	Age (yrs)	Forest type	Carbon (TonC/ha)
2015	Maknoi, J.	Sirikit Botanical Garden		Natural	Pine-Deciduous dipterocarp forest	74.69
2015	Jamnongphugdee, K.	Mae Ping National Park, Chiang Mai and Lamphun	0.47	Natural	Deciduous dipterocarp	48.86

5.3 Comparing aboveground biomass estimated by different methods

I compared biomass estimates from partial harvesting with those that would have been derived from the allometric equations of Brown (1989, 1997) and Tsutsumi (1983).

5.3.1   The character of commonly used allometric equations

- *Brown (1989, 1997)*

$$ABG = \exp\left(-2.134 + 2.53\ln\left(DBH\right)\right)$$

where ABG is above-ground biomass (kg) and DBH is diameter at breast height (cm)

Brown used secondary data from various source divided by life zone (dry, moist and wet forest). Data from 5,300 individual trees were used to construct regression equation. The only variable used in the equation is DBH which is easily and rapidly measurable.

- *Tsutsumi (1983)*

$$W_S = 0.0509\left(D^2H\right)^{0.919}$$
$$W_B = 0.00893\left(D^2H\right)^{0.977}$$
$$W_L = 0.0140\left(D^2H\right)^{0.669}$$
$$W_R = 0.0313\left(D^2H\right)^{0.805}$$

where W_S = biomass of the stem (kg), W_B = biomass of branches (kg), W_L = biomass of leaves (kg), W_R = biomass of roots (kg), D = stem diameter over bark at 1.30 m above ground (cm) and H = tree height (m)

The study site in Tsutsumi's study consisted of dry evergreen forest (DEF), mixed deciduous forest (MDF) and dry dipterocarp forest (DDF). For biomass estimation, all

trees taller than 1.3 m in plots were cut. The felled trees used for biomass measurements were cut close to ground level and 63 trees were felled for this study during 1979 to 1981. A total of 6 trees of different sizes were selected for root biomass estimation. Tsutsumi's equations use 2 variables DBH and height. The latter is much more difficult to measure than DBH.

Dry mass estimation, using the relationship between DBH and height, was formerly purposed by Ogawa et al. (1965). The correlation between DBH and height for small trees (low DBH or low height) was strong but it was much less reliable for larger trees.

Fig. 5.5a shows the relationship between DBH and height for the trees in the circular plot survey of the current study (10 plots R14 and 10 plots in natural forest). The relationship follows a fairly strong logarithmic function: $y = 5.7153\ln(x) - 2.1115$ ($R^2 = 0.75$); where y=height (m) and x=DBH (cm). The correlation between height and DBH was high when trees are small (DBH 1-20 cm, N = 624) but found less correlated when trees are bigger (DBH 21 - 80 cm, N = 105) as shown in Fig. 5.5 b-c. The hyperbola relationship between H to D followed the same form as that reported by Ogawa et al. (1965), regardless of tree species.
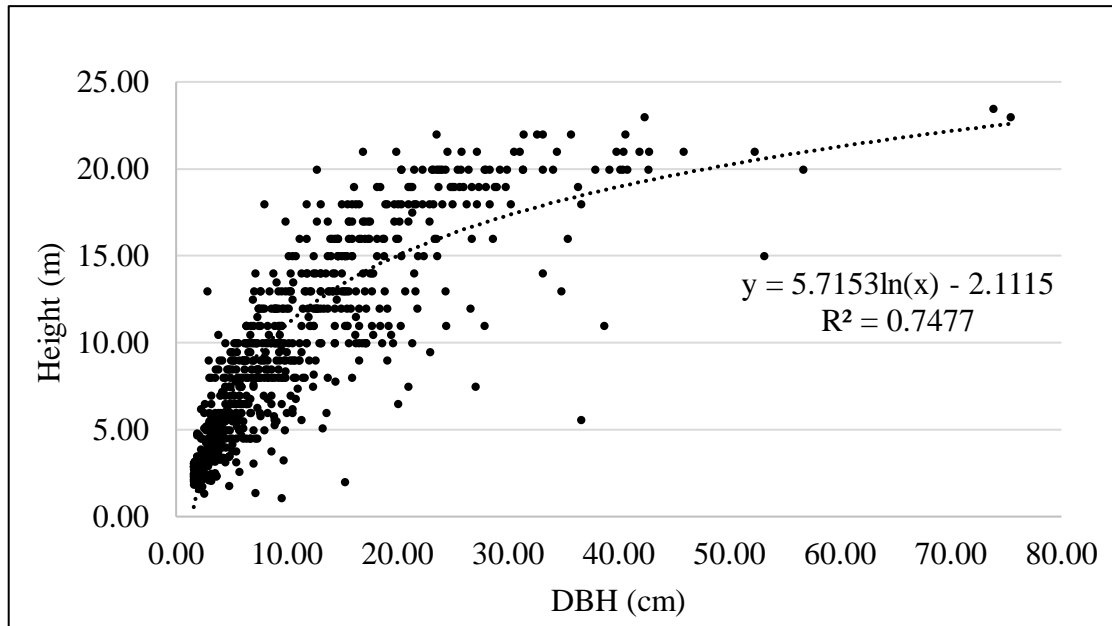
Figure 5.5 a The relationship between DBH and height ($R^2 = 0.7283$)
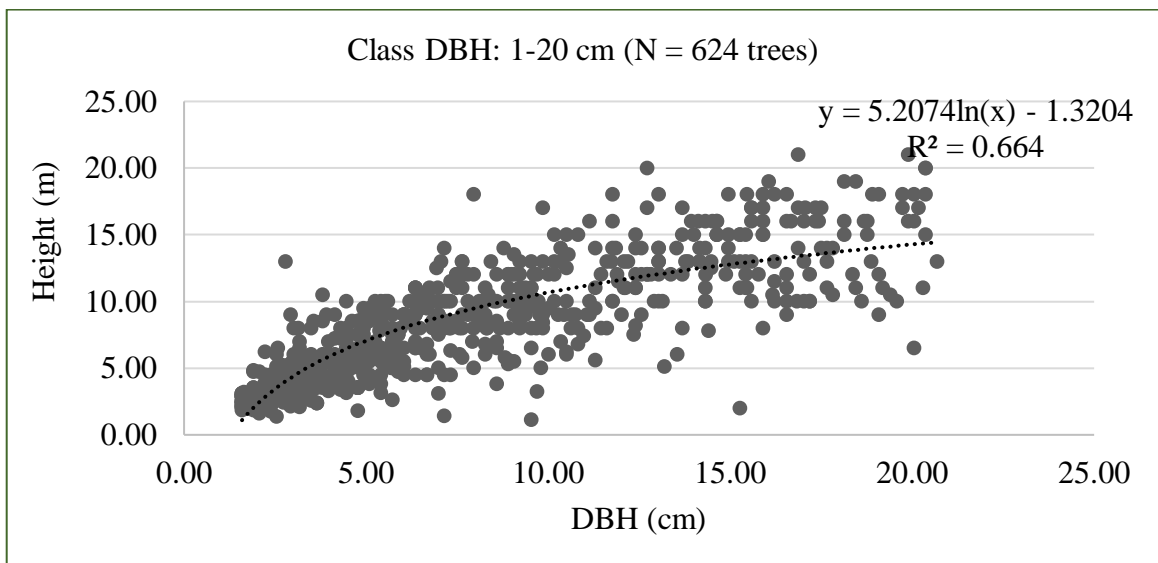
Figure 5.5 b The relationship between DBH and height, DBH class 1 – 20 cm

(N = 624, $R^2 = 0.664$)

Class DBH: 21-80 cm (N = 105 trees)

$$y = 4.2108\ln(x) + 4.0002$$
$$R^2 = 0.1051$$
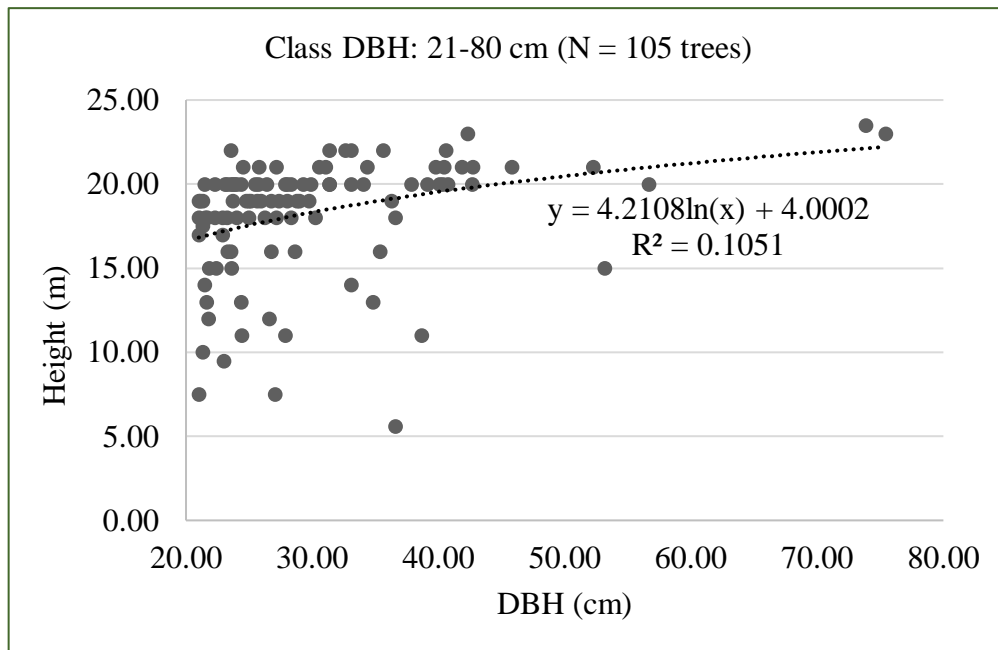
Figure 5.5 c The relationship between DBH and height, DBH class 21 – 80 cm

(N = 105, R^2 = 0.1051)

Fig 5.6 shows the 5 most common species in plots R5 and R10 to indicate their successional status. Mostly, the species tend to be grouped along the curve together, so it is hard to distinguish the different among color dots. It can be assumed that those species had similar successional status. Except C. *calathiformis*, that behave differently from the other species, since the dots are quite dispersed and not grouped along the curve. It can be assumed that C. *calathiformis* had different successional status from the other species. It was due to the performance of C. *calathiformis* which its seedlings were very well establish and well grown. Therefore, C. *calathiformis* that found in plot R5 and R10 were vary in size and caused the spreading dots in this graph.
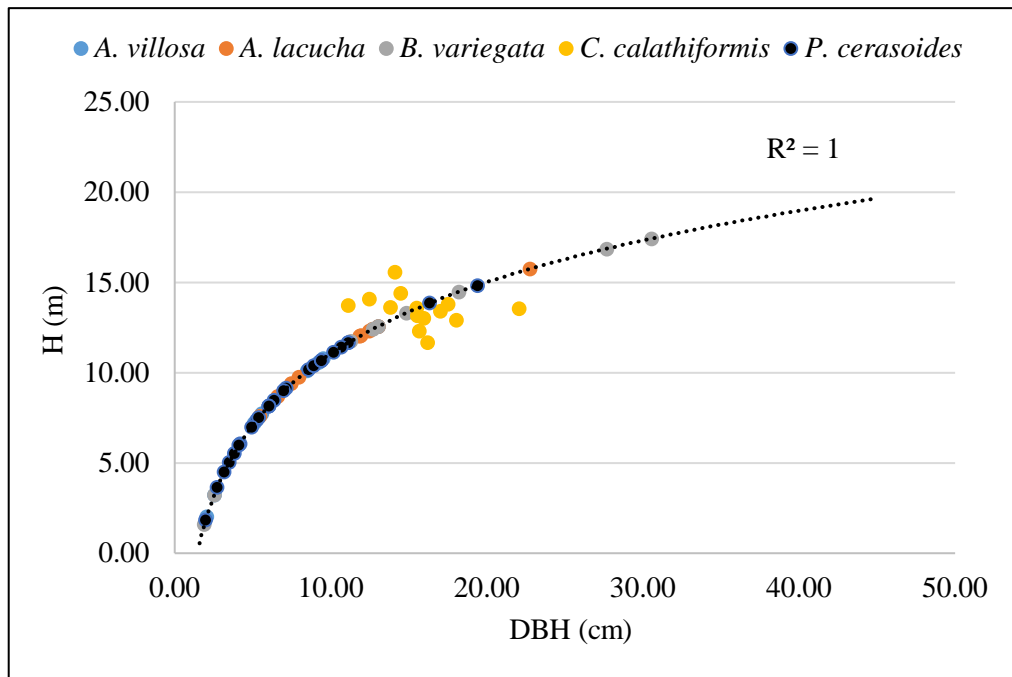
Figure 5.6 The relationship between height (m) and DBH (cm) of five mostly found species in plot R5 and R10. The different colors used for indicated different species. Trend line (R2 = 1) used for the similarity distribution of data.

However, Ogawa et al. (1965) suggested that dry mass estimation, using just DBH as the independent variable, could overestimate height for larger trees. Therefore, height was added as an independent variable for dry mass estimation. The dry mass of stem, branch, root and leaf per tree were more closely correlated with D^2H than DBH alone with different constants. Therefore, Tsutsumi's adopted D^2H as combined independent variables and proposed different equations for different tree parts (stem, branches, leaves and roots).

5.3.2 Comparison among Brown's equation, Tsutsumi's equation and the partial harvest method

For smaller trees (DBH <16 cm) differences among the 3 calculations (Brown's, Tsutsumi's and partial harvest) were small or nonexistent (Fig 5.7). However, differences started to show for trees of DBH>16 cm. The trend line for Brown's equations rose above that of Tsutsumi's equations and the partial harvest data. Trend line of Tsutsumi's

equation and the partial harvest data remained close, until around DBH>26 cm, when the Tsutsumi trend lie rose slightly above the partial harvest data. However, the relationship between DBH and ABG biomass was high, when calculated with Brown's equation (R^2 = 0.9603) because Brown's equation uses only DBH for calculation. Although Tsutsumi's equation had lower R^2 than Brown's (R^2 = 0.8363) it was because the equation did not depend only on DBH; height was also included for the calculation. Although R^2 from the partial harvest method was the lowest among three types of calculation (R^2 = 0.7118), it was not very different from Tsutsumi's.

Each type of calculation (Brown's and Tsutsumi's; Brown's and partial harvest and Tsutsumi's and partial harvest) was paired to see the relationship between each pair (Fig 5.8a-c). A linear trend line and R^2 was used to compare the relationships among the 3 pairs. Where DBH was small, the data points were grouped around the trend line, but became increasingly dispersed with increasing tree size. As shown in Fig. 5.8a-b, the data points scattered away from center line, as DBH exceeded about 50 cm. However, Fig. 5.8c was different from Figs. 5.8a-b, since the data points were grouped along center line, showing high correlation between Tsutsumi's equations and the partial harvest method. Paring of Tsutsumi's and partial harvest produced the highest R^2 (R^2 = 0.9307) followed by pairing of Brown's and Tsutsumi's (R^2 = 0.825, with differences averaging 29%) and paring of Brown's and partial harvest (R^2 = 0.6693, with differences averaging 24%) respectively. Therefore, for small trees, with DBH <16 cm, the 3 calculations produced similar results. However, for trees larger than 16 cm DBH the calculation method requires careful selection to avoid error and bias. Although the most accurate method for biomass calculation is the destructive sampling and directly weighing each tree part, destructive sampling is costly and generally unacceptable, where conservation is important especially for rare tree species (Macfarlane et al., 2014).
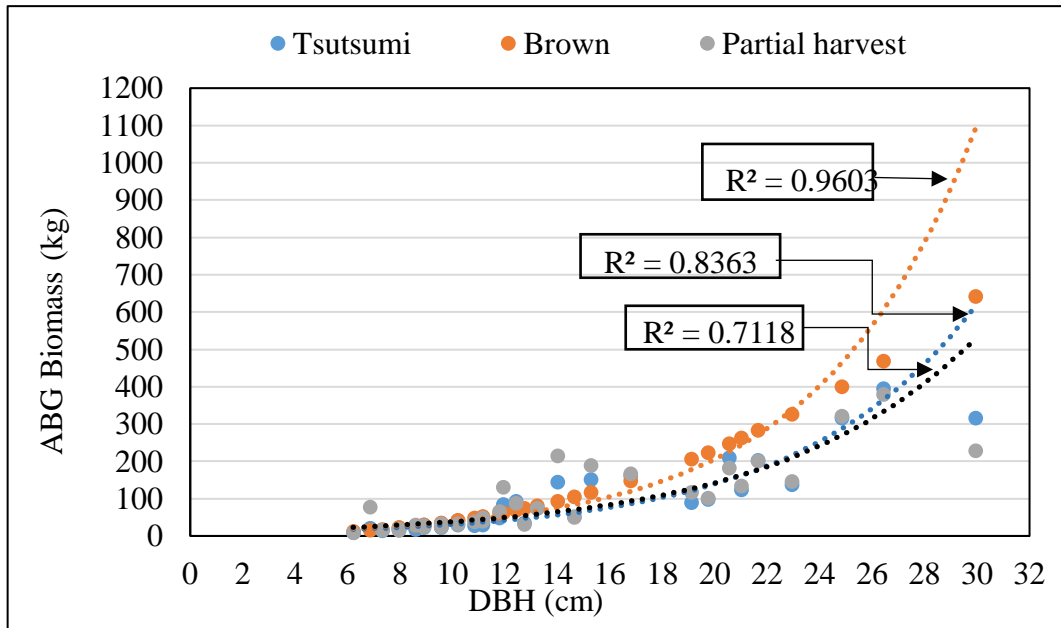
Figure 5.7 The comparison of aboveground biomass of individual tree from plot R14 derived from partial harvest method ($R^2 = 0.7118$) and allometric equation of Brown (1997, $R^2 = 0.9603$) and Tsutsumi (1983, $R^2 = 0.8363$) (N=33).
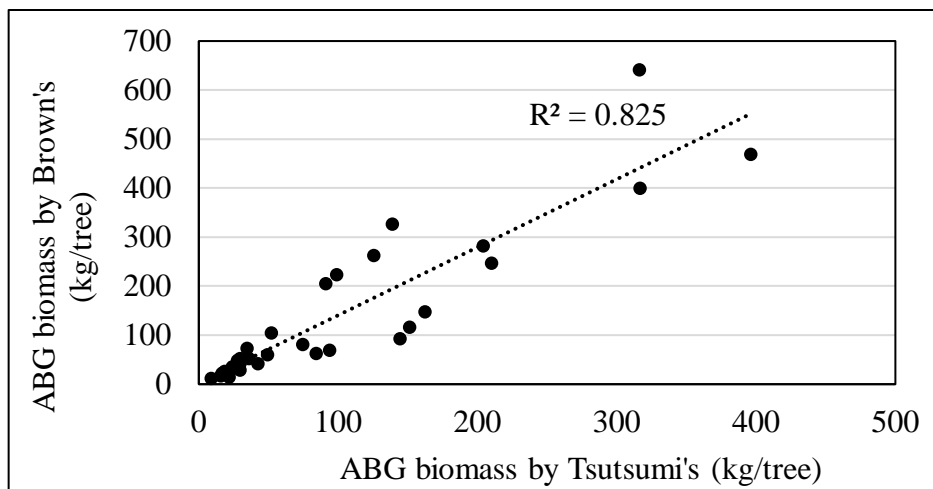
Figure 5.8a The relationship between the aboveground biomass of individual trees (N=33) calculated by Brown's and Tsutsumi allometric equations ($R^2 = 0.825$).
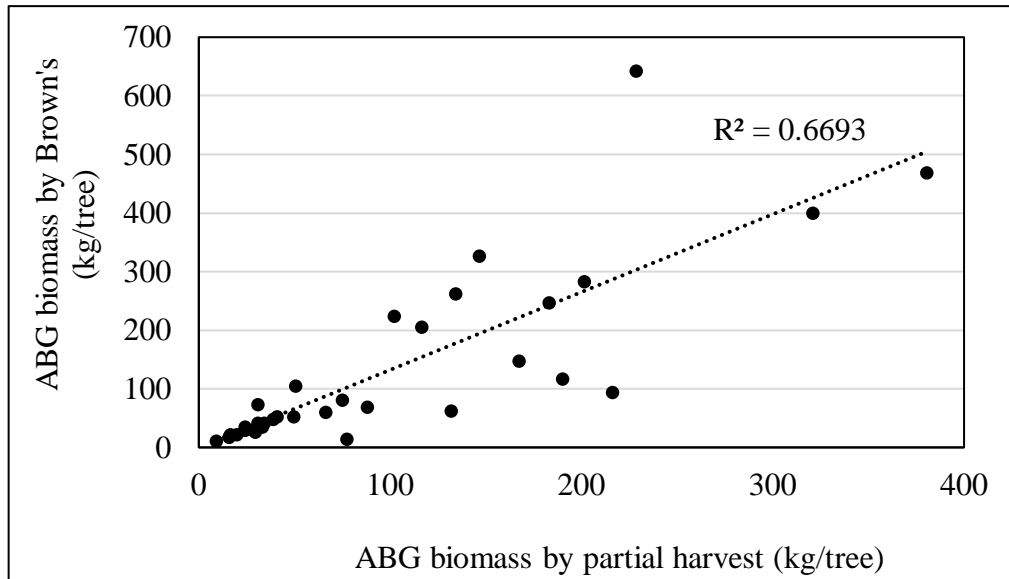
Figure 5.8b The relationship between the aboveground biomass of individual trees (N=33) calculated by Brown's allometric equations and partial harvest method (R^2 = 0.6693).
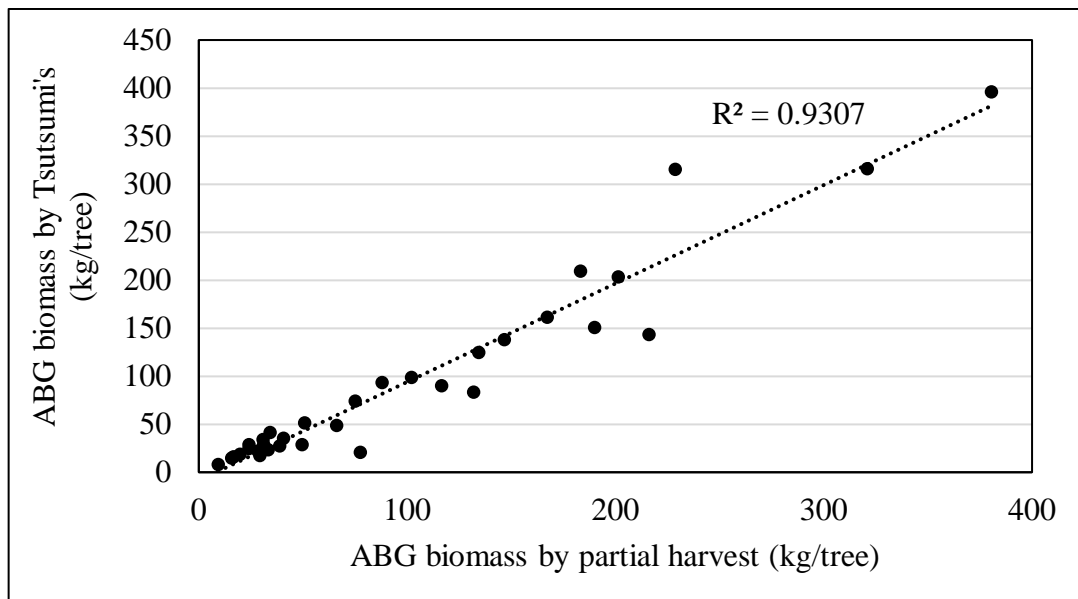
Figure 5.8c The relationship between the aboveground biomass of individual trees (N=33) calculated by Tsutsumi's allometric equations and partial harvest method (R^2 = 0.9307).

5.3.3 Discuss about the advantage and disadvantage of partial harvest method and allometric equations

- Advantage/disadvantage of partial harvest method

Partial harvesting can be useful where complete destructive sampling is not possible such as in a national park or conservation forest (Mekuria et al., 2011). It allowed derivation of above-ground tree biomass without tree felling. Moreover, this method is potentially more accurate than using allometric equations, since it is based on direct measurements of tree parts. Furthermore, allometric equations are species- and ecosystem-specific and quite often they are applied outside the range of data, upon which they are based.

However, the partial harvest method also has some disadvantages. Since the primary branch of a tree must be cut, researchers must climb the tree. It can be dangerous if the tree is very tall. Ladders and ropes must be used to sample the taller trees, which raises health and safety issues and tends to influence field workers to select smaller trees for sampling, which leads to underestimation of tree biomass. It is, therefore, important to carry out a preliminary survey of the study plots, to measure girth at breast height of as many trees as possible of each species selected, so that trees, closest to the average size, are selected for sampling. The time-consuming nature of partial harvesting (average 2 - 3 hours per tree) means that sample sizes tend to be very small, so selection of average trees is essential to make sure that the trees sampled are representative of each plot age. Moreover, it is sometimes difficult to count all the primary branches if the tree is tall or the crown is dense. Therefore, to adopt this method the following factors must be considered: i) labor, ii) time available and iii) tree sizes.

- Advantage/disadvantage of allometric equation

Allometric equations are useful when absolute accuracy is not the main consideration e.g. where relative changes over time are the main focus. This method is rapid, since only measurements of DBH/GBH and height are required. This means that

many trees can be surveyed over a short period with few people. Furthermore, the size of trees is not a problem.

However, the disadvantage of using allometric equation could be either over- or under- estimation of biomass. Also the commonly used equations such as Brown's or Ogawa's were derived from harvested trees in specific forest types and areas, so their applicability to other forest types may be unreliable. Nam et al. (2016) stated that the problem with most allometric models is that one equation is developed by combining all species in one or several specific locations. Therefore, those models ignore species diversity and inter-specific trait variations both of which are particularly high in tropical forests. Also, the allometric model should not be applied to trees outside of the diameter range of the samples used to construct the allometric model. Moreover, various factors such as topography, hydrology and soil nutrient availability may cause bias in results (GFOI, 2016).

5.4   Photosynthesis

5.4.1   Physiology features

Photosynthesis curves of selected species, described in section 4.3, were analyzed for the following physiological characteristics: maximum photosynthesis point, light saturation point, photoinhibition point and light compensation point. Within the canopy, some leaves are fully expose to sunlight, others exist deep within the canopy and become shaded leaves (Amthor and Baldocchi, 2001). Factors that affect canopy photosynthesis are light interception, leaf angles with respect to sunlight, the position of leaves both vertically and horizontally and environmental conditions such as temperature and CO_2 concentration (Amthor and Baldocchi, 2001). Therefore, the selection of young, mature and shade leaves were intended to represent the different types of leaves within the canopy.

For young leaves, *Melia toosendan* showed highest photosynthesis rate, 75.20 μmol $CO_2/m^2/s$ at light 1,500 μmol $/m^2/s$ which means that *Melia toosendan* reaches light saturation point at 1,500 μmol $/m^2/s$. Assimilation rate increases more slowly at higher irradiances, until eventually a plateau is reached, at which further increases in irradiance do not increase the rate of CO_2 assimilation (Evans and Caemmerer, 2010). When the light level reaches 2000 μmol $/m^2/s$, young leaves of *Melia toosendan* started to reach photoinhibition as photosynthesis dropped to 69.9 μmol $CO_2/m^2/s$. Young leaves of every species except *Erythrina subumbrans*, *Heynea trijuga* and *Hovenia dulcis* reached a photoinhibition point at 1,500 – 2,000 μmol $/m^2/s$. Photoinhibition occurs when plants are exposed to strong light resulting in inhibition of the activity of photosystem II (Murata et al., 2007). All the species tested, except *Prunus cerasoides,* reached a light saturation point at 1,500 – 2,000 μmol $/m^2/s$. For C3 plants, less rubisco is allocated to shaded leaves than to sunlit leaves. Therefore, photosynthesis of shaded leaves becomes light saturated at lower light levels (causing overall photosynthesis capacity to be lower) than for leaves at the top of canopy (Amthor and Baldocchi, 2001)

The light compensation points is the amount of light at which the rate of photosynthesis matches the rate of respiration and the net carbon dioxide assimilation is zero. Early successional tree species tend to have high light compensation points than shade-tolerant climax species (Bazzaz and Carlson, 1982) – as seen with *Erythrina subumbrans* which had a higher light compensation point compared with the other tested species (350 μmol $/m^2/s$).

For shade leaves, *Erythrina subumbrans* had the highest photosynthesis rate, 62.20 μmol $CO_2/m^2/s$ at light 1,500 μmol $/m^2/s$, which started to decline at 2,000 μmol $/m^2/s$. *Hovenia dulcis* had the second highest photosynthesis rate which occurred at lower light levels (1,000 μmol $/m^2/s$). Lastly, for mature leaves, *Gmelina arborea* attained the highest photosynthesis rate, 73.70 μmol $CO_2/m^2/s$ at light 1,000 μmol $/m^2/s$. Mostly mature leaves found to reach light saturated point at 1,000 μmol $/m^2/s$.

Averaging the peak rate of photosynthesis across all species, for each leaf types, young leaves had highest rate, while shade and mature leaves had similar rates, 43.4 ±

23.2, 34.6 ± 17.6 and 33.1 ± 17.7 respectively. The photosynthetic capacity of leaves varies widely, according to light, water and nutrient availability and these differences in capacity usually reflect RuBisCO content[1]. As stated by Evans and Caemmerer (2010), sun leaves have greater CO_2 assimilation capacities than those in shaded environments and shade leaves achieve a lower maximum rate of assimilation than sun leaves. Shade plants also have anatomical and physiological properties leading to photosynthetic characteristics different from those of sun plants (Boardman, 1977; Zhang et al., 1995). However, the results from this study did not shown significant differences between shade leaves and mature leaves. Moreover, the light saturation points for shade leaves and mature leaves were not obviously different. Both leaf types reached light saturation point around 1,000 – 2,000.

Foliage, acclimated to high irradiance, or sun leaves, respond more plastically to rapid changes in leaf light environment, and is more resistant to heat and water stress (Niinemets, 2007). Moreover, a study of light acclimation in *Bischofia javanica* suggested that the species has a wide acclimation potential to changes in light availability that might occur in nature, following gap creation or canopy closure (Kamaluddin and Grace, 1993). Leaf photosynthetic components, such as pigments, chloroplasts, grana and stomata develop in young leaves according to the light environment at that time. However, re-acclimation to low light is possible in older leaves by shifting nitrogen allocation from RuBisCO to light- harvesting proteins thus limiting electron transport to light-harvesting proteins (Niinemets, 2007). Since photosynthesis rates between sun and shade leaves were not very different, Dusenge et al. (2014) suggested to use successional status, instead of sun and shade character, to assess the ability of photosynthesis.

Averaging the maximum rate of photosynthesis across leaf types for each species, *Gmelina arborea* had highest photosynthesis rate, 56.2 and *Nyssa javanica* had lowest photosynthesis rate, 18.6. Other species had similar photosynthesis rates ranging from 30 – 46. From this result, *Gmelina arborea* could provide the most carbon absorption efficiency in forest restoration projects (compared among the species tested in this study).

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[1] Ribulose-1,5-bisphosphate carboxylase/oxygenase, an enzyme which catalyzes the first major step by which plants convert atmospheric carbon dioxide to energy-rich organic compounds.

Rasineni et al. (2011) selected *Gmelina arborea* to determine the photosynthesis efficiency under CO_2 concentration of 460 µmol/mol which slightly higher than that in this study. Their results suggested that Gmelina sequestered about 2 kgC/tree after 120 days of treatment It is also conceivable that greater biomass allocation to stem tissue of *Gmelina arborea,* grown under high CO_2 levels, was due to the fact that the stem is the primary carbon sink in *Gmelina arborea*, which reflects the normal storage strategy of this fast-growing tree species.

5.5   Modeling

5.5.1 Source of errors

The results of carbon accumulation of each species from modeling calculation did not much exceeded. The model was based on two parts, tree growth modeling and carbon absorption modeling. Tree growth modeling was derived directly from field measurements. Meanwhile carbon absorption was modelled from greenhouse determinations of photosynthesis rate at the leaf-level, extrapolated to tree-crown level. The carbon absorption calculation and carbon loss, due to respiration, was expected to be source of errors in tree carbon modeling.

Carbon absorption was calculated by a complex series of equations involving multiple factors, such leaf area and weight, both at the individual leaf level and the tree crown level. Moreover, CO_2 absorption was converted from a very small unit (µmol) into a much larger unit (kilograms), which allows magnification of errors. In reality, leaves overlap and shade each other, causing different amounts of light to reach each leaf within a tree crown. Furthermore, the photosynthesis rate of leaves varies throughout the day, with angle of the sun ad cloudiness. However, the model assumes that each leaf of each type (young and mature leaves) receives a certain amount of light and absorbs a certain amount of carbon. Consequently, the model predicted unrealistically high carbon absorption. Moreover, carbon in a tree can be loss due to litter fall and respiration activity. This modeling did not have the exact number of carbon loss due litter fall and respiration

for each species. But instead calculated carbon loss from total carbon absorption minus total carbon accumulation.

Though the model, developed in this study, overestimated results of carbon accumulation compared with actual field measurements, and the percent different between actual measurement and modeling was high. The process of model construction provided opportunities identify knowledge gaps. Since lacking of many important parameter in species-specific scale, the averaged number such as light available had to be applied. Therefore it caused the unrealistic results for each species.

The carbon model lacked many important data, which may have resulted in the model departing from reality:

- *Attenuation of light availability within trees crown*

Although the sunlight arriving at Earth for any given location and date is well known, leaves in a tree crown receive different proportions of the available sunlight depending on their position with the tree crown. Those at the top receive more sunlight than those further down. The greenhouse experiments used carefully control lighting conditions, but light the exact amount of light reaching every leaf in the tree crowns was not known in the field, so the carbon absorption rate is subject to error. To approximate for this effect I included the equation of Beer's Law of Light Attenuation (Cournac et al., 2002) into the model. The model might therefore have been improved with actual light attenuation measurements in the field to test the validity of using this equation. Light availability typically varies ~50-fold within the canopies of closed vegetation stands (Niinemets, 2007). Therefore, if the actual crowns of the trees used in this study attenuated light availability more than that predicted by Beer's Law, that could contribute to the overestimation of the carbon absorption by the model compared with field measurements.

- *Climatic conditions*

Cloudiness, directly affects light availability, but could not be included in the model. The baseline light availability before attenuation by Beer's law was applied was therefore full sunlight, since cloudiness data were not available. Therefore, the model almost certainly over-estimates light actually available for photosynthesis and this may account for some of the overestimation of carbon accumulation. Temperature also affects the rate of photosynthesis. Heat increases RuBisCO enzyme activity and stomatal conductance and leads to higher CO_2 capture (Santrucek and Sage, 1996). Fluctuations in daily temperature were not include in the model.

- *Tree respiration rate*

Measurements in the greenhouse were of net change in carbon dioxide content between the inflow and out flow of gases through the Licor. The change was due to a combination of CO_2 taken up by photosynthesis and that given off by respiration (hence the light compensation points mentioned earlier). However, in trees, gaseous exchange occurs through surfaces other than leaves. For example, CO_2 from reparation of non-photosynthetic tissues that surround the woody parts is released via lenticels which could be the gap that seen in the output of modeling compared with actual measurement (shown in Chapter 4, Fig. 4.11). As claimed by Ryan (1991) that total respiration can consume more than 50% of total carbon fixed by photosynthesis. Both trunk and branches should be included in respiration estimation at the stand level (Damesis, 2003). Therefore, upon the absent of this parameter, this model had to calculated the carbon loss due to respiration from total carbon absorption minus total carbon accumulation and then separated for above-ground carbon loss due to roots allocation and respiration. However, the species-specific data of respiration is required for accuracy.

- *Tree growth status*

The photosynthesis rate used in this model was obtained from actual measurement in a greenhouse of the sapling stage of each tree species. Leaves on saplings usually have higher photosynthetic nitrogen-use efficiency and lower water-use efficiency than those on mature trees (Mediavilla et al., 2002). Therefore, this is another potential source of over-estimation of carbon absorption by the more mature trees, if the higher rates of photosynthesis of saplings is applied to calculate carbon absorption by older trees. Moreover, carbon absorption in the greenhouse was measured as μmol $CO_2/m^2/s$ for a tiny area of leaf and then extrapolated up to tC/year for whole trees. This would have allowed magnification of the overestimate from the greenhouse.

- *Stomatal conductance*

Stomata are the gateway for gas exchange in epidermis of leaves and young stems but generally located more at leaves (Hubbard et al., 2001). Opening and closure of stomata are triggered by water pressure in a tree to prevent water loss. Normally, stomata open at dawn, reaching maximum near noon, and decline when the temperature reaches maximum in a day, to prevent water loss (Allen & Pearcy, 2000). This lowers gaseous exchange as the stomata close and CO_2 cannot enter plant tissue. However, this model did not include the stomata factor in calculation and assume that the gas exchange occurs at the same rate all day. Thus, it can cause the overestimation of CO_2 absorption rate in a day.

- *Crown architecture*

Crown architecture including leaf area and arrangement, greatly affects the light capture efficiency of plants (Pearcy et al. 2004). It varies both within and among tree because of plastic adjustments of crown architecture in response to light conditions. Crown shape and leaf arrangement can adjust to shaded environments (to maximize

photosynthesis) or fully exposed conditions (to avoid damaging excess of light energy) (Valladares, & Pearcy, 2000).

- *Carbon flow due to litter fall of each species*

Carbon flow through litter directly was another factor affecting net carbon sequestration above ground in trees. Although there was data taken by Kavinchan (2015) in the same study plots, it was area-based, not species specific. Therefore, in this model, litter fall factor had to be evaluated from FORRU's leaf phenology data as a percentage for each month in a year. If any month found the decreasing of mature leaves, it can be assumed that it probably due to leaves fall and be considered as percent of litter fall.

- *Linear addition*

This tree carbon projection modeling used linear addition that carbon added up every day as a results of carbon absorption from the day before. It can caused the overestimation for the amount of carbon absorption since we treated the trees in this modeling to be grown linearly but in reality trees are not grow as a linear but tend to be more logistic curve. Therefore, to reduce the overestimation from this problem, relative carbon accumulation rates per year was take into account for calculation.

5.6 Carbon offset

Forest carbon projects can generate carbon credits by demonstrating that the project leads to reduced CO_2 emissions from deforestation and/or land use change (Forest Trends' Ecosystem Marketplace, 2017). To evaluate the potential carbon-based income from forest restoration, the average price of carbon trading on the voluntary market (concawe, 2017) was used to estimate the potential income flow that could be derived from carbon sequestration, during forest restoration projects, if such projects follow REDD+ protocols.

The economic tools that entrepreneurs who responsible for Greenhouse gases emission choose for emission reduction is either; (i) specified the amount of GHGs emission or (ii) trading in carbon market for rights to release GHGs. After reducing GHG emissions as much as possible, entrepreneurs also need to support low carbon activity typically by purchasing carbon offsets. A carbon offset represents one ton of carbon dioxide equivalent (tCO_2e) that hasn't been emitted into the atmosphere (Forest Trends' Ecosystem Marketplace, 2017). There are two types of carbon markets, the compliance market and the voluntary market. Around one-third of the credits traded on the market are from forest carbon projects and forest carbon credits is mostly generated in developing countries (concawe, 2017). Thailand joined carbon trading in terms of voluntary market through Clean Development Mechanism (CDM) (Laengcharoen, 2008). Currently, the prices of carbon credits in voluntary market are ranging from US\$ 3 to 10 per ton CO_2 for forest carbon projects. Therefore, in this section, the calculation for income from forest restoration project will use the highest price given by concawe (2017) which is 10 US \$/tCO_2.

The price of carbon in control plot, R5, R10 and R14 plots was derived from the measured carbon sequestration both aboveground and belowground (including soil) (tC/ha), converted into tCO_2/ha and then multiplied by the carbon price (10 US \$/tCO_2) of voluntary market. In this case, the carbon offset value in voluntary market obtained from Hamrick and Goldstein (2016) which was 10 US \$/ tCO_2. Using this carbon offset price, the income of 7,638.6 US \$/ha that gain from restoration project began at the first year of restoration project even if there were no trees planting yet, because carbon in soil and litter which stored in the area is take into account. When restore forest for 5 years, the income will increase to 9,996.9 US \$/ha or 471.6 US \$/year/ha and reach 11,493.1 US \$/ha in year 10 or 299.2 US \$/year/ha. However, since soil carbon dropped in year 14, it was directly affect the income which decrease to 11,308.4 US \$/ha (Table 5.5).

Table 5.5 The calculation of income gain from carbon offset in restoration project.

Plot age (year)	ABG + Roots tC/ha	Litter + Soil (tC/ha)	Total (tC/ha)	Value per ha (US $ / tCO_2)	Value increment	Average income per year per ha (US $)
0	1.7	206.6	208.3	7,638.6	-	-
5	18.0	254.6	272.6	9,996.9	2,358.2	471.6
10	60.7	259.5	320.2	11,742.4	1,745.5	349.1
14	144.8	262.1	406.9	14,920.0	3,177.6	794.4
0-14				7,281.4		520.1

The costs of restoration were provided by FORRU using 2015 values for labor, transportation, materials, planting stock production from locally collected seeds plus weeding fertilizer application and monitoring over 2 rainy seasons subsequent to tree planting i.e. the full complete costs of 2+ years' work needed to bring a forest restoration plot to the point of initiation of canopy closure. Assuming complete absence of natural regeneration (which is rare in northern Thailand except on mine sites), 3,086 trees/ha would be planted (average spacing 1.8 m between trees). The summary of expense of year 1 and year 2 shown in Table 5.6. The total cost for restoration in 1 hectare with zero natural regeneration was totally 5,631 US $; 4,479 US $ in year 1 and 1,152 US $ in year 2. However, assuming that there was 50% natural regeneration in the area, the total cost would be reduced to 4,431 US $ over 2 years. Factor that affect total cost the most is natural regeneration, if the area has some natural regeneration, it will reduce the total cost for restoration project as shown in Table 5.6 a-b and Fig. 5.10.

Table 5.6a The summary of total cost per hectare (US $) for forest restoration project in 10 hectare (assume 0 natural regeneration in the area).

	Year 1 (US $)	Year 2 (US $)	TOTAL (US $)	%
Planting Stock	1,672.63	-	1,672.63	29.68
Materials and Equipment	378.27	132.39	510.67	9.93
Transportation	108.00	20.66	128.65	14.00
Labor	1,223.00	545.76	1,768.77	31.39
Project staff inputs – supervision and admin etc.	59.13	25.38	84.50	15.00
Total	3,441.03	724.19	4,165.22	100.00

Table 5.6b The summary of total cost (US $) for forest restoration in 10 hectare (assume 50% natural regeneration in the area).

	Year 1 (US $)	Year 2 (US $)	TOTAL (US $)	%
Planting Stock	836.31	-	836.31	18.84
Materials and Equipment	306.72	132.39	439.12	11.00
Transportation	80.12	20.66	100.78	17.05
Labor	968.55	543.29	1,511.84	34.06
Project staff inputs – supervision and admin etc.	59.13	25.38	84.50	19.04
Total	2,250.83	721.72	2,972.55	100.00
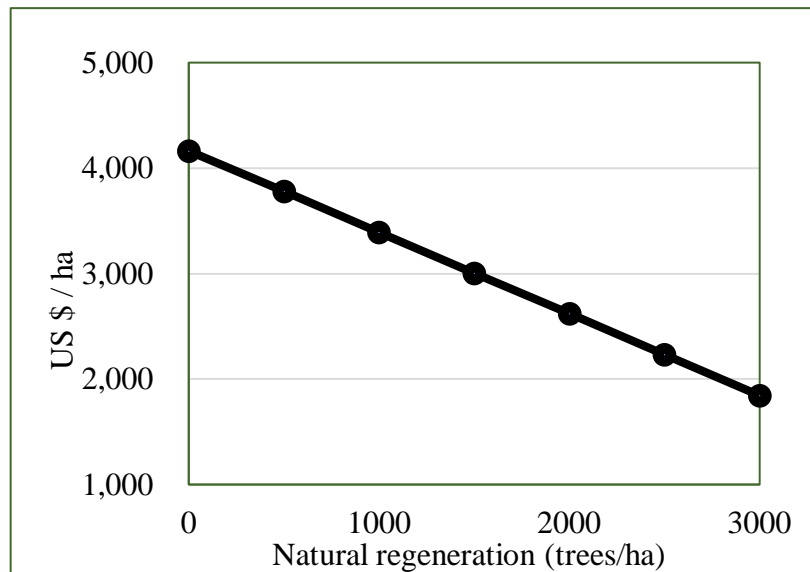
Figure 5.10 Graph showing relationship between full cost of restoration (over 2+ years from planting stock production to initiation of canopy closure) and amount of pre-existing natural regeneration when initiating a restoration project in US $/ha. Regenerants include trees, sapling and seedling as well as live coppicing tree stumps taller than 50 cm (source FORRU-CMU unpublished data, 2015. Costs are specific for local economy of northern Thailand, 2015.

The total cost of restoration was then use to evaluated the long-term net income from carbon offset in voluntary market. The average income per year per hectare in Table 5.5 was used in profit calculation. The income shown in Table 5.7a seems deducted after year 11 due to the reduction of soil carbon stored in plot R14. Therefore, it affected the cumulative profit from year 11-14. Since the anomaly reduction of soil carbon, if we considering the profit only from aboveground carbon (exclude litter and soil) (Table 5.7b), the cumulative profit tend to increase over years and become positive after 8 years, in case of zero NR and 7 years, in case of 50% NR. (Fig.5.11). This means after 7-8 years of restoration, the profit will continue and increase every years since the cost is only invest for the first two years.

Table 5.7a Profit calculation for total carbon offset (aboveground and belowground) in forest restoration compare between 0 natural regeneration and 50% natural regeneration.

Year	Cost (US $) with 0 NR	Average Income per year (US $)	Cumulative profit (US $)	Cost (US $) with 50% NR	Average Income per year (US $)	Cumulative profit (US $)
1	3,441	471.65	-2,969.38	2,250.83	471.65	-1,779.18
2	724	471.65	-3,221.92	721.72	471.65	-2,029.25
3	0	471.65	-2,750.27	0	471.65	-1,557.60
4	0	471.65	-2,278.62	0	471.65	-1,085.95
5	0	471.65	-1,806.97	0	471.65	-614.30
6	0	349.10	-1,457.87	0	349.10	-265.20
7	0	349.10	-1,108.76	0	349.10	83.91
8	0	349.10	-759.66	0	349.10	433.01
9	0	349.10	-410.56	0	349.10	782.11
10	0	349.10	-61.45	0	349.10	1,131.22
11	0	794.41	732.96	0	794.41	1,925.63
12	0	794.41	1,527.37	0	794.41	2,720.04
13	0	794.41	2,321.78	0	794.41	3,514.45
14	0	794.41	3,116.19	0	794.41	4,308.86
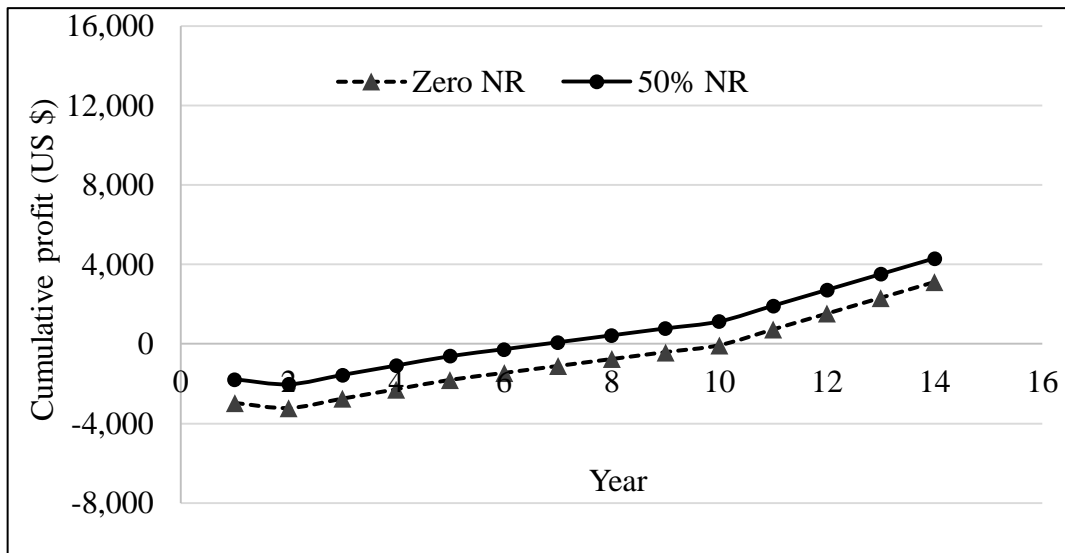
Figure 5.11 The cumulative profit for total (above-ground + below-ground) carbon offset (US $) over years compare between 0 NR and 50% NR (NR = Natural regeneration).

5.7 Species composition and species preference for forest restoration project

The above-ground carbon sequestration of selected framework species in plot R14 calculated in section 4.1.2 was used to predict above-ground carbon sequestration of each scenarios in the future. The stocking density and carbon accumulation (tC/tree) of 8 species by year 15 (2,573 trees/ha) were then used to predict the carbon accumulation in 1 hectare. Predicted above-ground carbon sequestration was calculated based on the restoration project in area of 1 hectare. All 8 species were differently distributed.

By year 15, if every species were to be planted evenly (plan 1), a 1- hectare restoration site would accumulate above-ground carbon 253.1 tC/ha. This plan will be considered as based line plan as there were no dominant species (every species were planted evenly in number of trees or 13% each).

Plan 2-9 were calculated based on criteria that each species was dominant species or 50% and the other species randomly distributed in restoration site of 1 hectare. The results of plan 2-9 were compared with plan 1 to find the most carbon accumulation plan

with remain biodiversity value. The calculation in plan 2 with the dominant of *E. subambrans* was the highest carbon accumulation at 457.3 tC/ha. On the other hand, in plan 8, though *H. dulcis* was the dominant species but carbon accumulation was the lowest at 172.5 tC/ha. Meanwhile, plan 5, *M. toosendan* was the dominant species but carbon accumulation (256.4 tC/ha) found similar with the base line plan that had no dominant species and every species were planted equally. This suggested that although we plant some species more than other species but it did not affect the carbon accumulation since it did not obviously different from planting equally (Table 5.8).

Therefore, species composition is important factor for maximize carbon accumulation consideration while biodiversity still maintain. However, this modeling calculated based on only 8 species which is not enough for the reality if we want to restore forest with healthy ecological function. Plant species richness observed for ecological restoration site in tropical forest in Australia was around 30 species but if consider for canopy species consideration, there were species richness of around 7 species (Wardell-Johnson *et al.,* 2005). As well as mentioned in FORRU protocol for forest restoration that species richness both introduced and endemic should be around 20-30 species (FORRU, 1993).

Table 5.8 The percentage proportion of all species (randomly distributed) and the total above-ground carbon stock per hectare.

Species	tC/tree	Scenario								
		1	2	3	4	5	6	7	8	9
E. subumbrans	**0.135**	13%	50%	10%	10%	5%	10%	10%	5%	15%
G. arborea	**0.021**	13%	5%	50%	5%	5%	5%	10%	5%	10%
H. trijuga	**0.081**	13%	5%	5%	50%	5%	5%	5%	10%	5%
M. toosendan	**0.061**	13%	15%	10%	5%	50%	5%	5%	5%	5%
N. javanica	**0.052**	13%	10%	5%	5%	5%	50%	5%	10%	5%
P. cerasoides	**0.020**	13%	5%	5%	10%	15%	10%	50%	5%	5%
H. dulcis	**0.015**	13%	5%	5%	5%	10%	5%	10%	50%	5%
B.javanica	**0.010**	13%	5%	10%	10%	5%	10%	5%	10%	50%
% TOTAL		100%	100%	100%	100%	100%	100%	100%	100%	100%
tC/ha		**253.1**	**457.3**	**203.1**	**329.6**	**256.4**	**263.1**	**192.3**	**172.5**	**198.5**

Forest restoration projects should mix slow- and fast-growing trees and not plant only the trees that grow most rapidly. Mixing of pioneer and climax species provides a wider range of ecological products and services, supports natural succession and enables balanced long-term carbon storage by more efficient "canopy packing". A higher variability in tree height in more diverse plots suggested that these effects were facilitated by denser canopy packing due to architectural complementarity between species (Castro-Izaguire et al., 2016). The benefits of pioneer species are that they are fast-growing and can accumulate carbon in a short time. However, they also have short lifetimes which shorten their ability to absorb carbon. When pioneer trees fall, the carbon stored in such trees transfers to the soil and thus increases below-ground carbon storage. Although slow growing trees have lower growth rates, compared with pioneer trees they live longer, so they should absorb more carbon over a longer time period than pioneer species.

From the result of carbon sequestration and photosynthesis rate, the species preference were selected for enhancing carbon stock in interested area. *Gmelina arborea, Erythrina subumbrans* and *Spondias axillaris.* Moreover, *Melia toosendan* and *Bischofia javanica* also show high efficiency of photosynthesis on young leaves.

Therefore, they should be planted in open area or in the beginning of forest restoration. *Gmelina arborea* also showed high efficiency on mature leaves and *Erythrina subumbrans* showed high efficiency on shade leaves. Budiharta et al. (2014) if the objective is to improve the habitat of threatened species, multiple forest types should be restored. The restoration should occur in heterogeneous landscapes in order to maximize the benefits for both carbon storage and biodiversity. Species composition and community structure had significant impacts on both the biomass carbon density and soil organic carbon density of the forest stand. (Hu, et al., 2015). Plantings differed in the composition of the species planted aimed for ecological restoration plantings typically use many more fleshy-fruited species than timber plantations, which will influence their attractiveness to seed dispersing fauna (Wardell-Johnson *et al.,* 2005).

CHAPTER 6

Conclusions

6.1 Overall conclusions

1. The mean value of carbon content in stem wood was 44.67% (± 0.54) with no significant differences among the species or the plots.
2. The percent of relative growth rate of carbon sequestered from year 5 to 14, *Erythrina subumbrans* was the highest species at 38%.
3. Aboveground carbon sequestration increased over time, 13.17, 44.34 and 105.91 tC/ha for year 5, 10 and 14 respectively
4. The carbon cycle in restoration plots approach levels similar to those of mature forest by around 20 years
5. After 18-20 years of restoration, the profit earn from carbon trading will be positive and increase every year since the cost is only invest for the first two years.

6.2 Recommendations for further study

Tree growth and carbon sequestration modeling for future prediction still need to be developed. Data collection over a greater range of plot ages is needed to construct the time period modeling, since this study collected data from only 3 plot ages. This study tried to construct modeling, based on actual measurement, but errors were found because of lack of data such as species-specific tree respiration rates that of leaves, stem and roots; photosynthesis rate of fully mature trees; carbon loss from litter fall of each species; actual roots mass; light availability within, above and below trees crown and cloudiness data for specific area and time.

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LIST OF PUBLICATIONS

1)   Kanlayarat Jantawong, Stephen Elliott and Prasit Wangpakapattanawong, "Above-Ground Carbon Sequestration during Restoration of Upland Evergreen Forest in Northern Thailand", Open Journal of Forestry, Vol. 7, April 10, 2017, pp. 157-171.

Modeling calculation

The example of modeling calculation in *B. javanica*

$LAI_{month} = LAI_{max} *$ % leaves total

Month	Mature	Young	Total	LAI
Jan	95%	5%	100%	4.6
Feb	95%	3%	98%	4.5
Mar	65%	10%	75%	3.5
Apr	98%	2%	100%	4.6
May	100%	0%	100%	4.6
Jun	95%	5%	100%	4.6
Jul	95%	5%	100%	4.6
Aug	100%	0%	100%	4.6
Sep	100%	0%	100%	4.6
Oct	100%	0%	100%	4.6
Nov	100%	0%	100%	4.6
Dec	100%	0%	100%	4.6

Light under-canopy calculation (Beer's law light attenuation);

$$L_i = L_0 \times EXP\left(-LAI_m \times k\right)$$

where;　　　　L_i　　　= Light at any vertical position (i); expressed as a proportion of

light reaching the top of the canopy

L_0　　　= Light at above canopy

LAI_m = Leaf area index of any month

k = Light extinction coefficient; in this case, light extinction coefficient for broadleaf forest was applied which is 0.59 (Zhang et al., 2014).

Example of photosynthesis rate calculation of *B. javanica*

Photosynthesis rate of young leaves (μmol $CO_2/m^2/s$)

= 16.564*ln(light$_{\text{full sun}}$) - 54.41

Photosynthesis rate of mature leaves (μmol CO2/m2/s)

= 5.4229*ln(light$_{\text{under canopy}}$) - 13.148

Date	LAI	PAR above canopy (μmol/m^2/s)	PAR under canopy (μmol/m^2/s)	Photosynthesis rate of young leaves (μmol $CO_2/m^2/s$)	Photosynthesis rate of mature leaves (μmol $CO_2/m^2/s$)
01-Jan	4.6	349.1	23.14	42.58	3.89
02-Jan	4.6	349.1	23.14	42.58	3.89
03-Jan	4.6	349.1	23.14	42.58	3.89
04-Jan	4.6	349.1	23.14	42.58	3.89
05-Jan	4.6	349.1	23.14	42.58	3.89
06-Jan	4.6	349.1	23.14	42.58	3.89
07-Jan	4.6	349.1	23.14	42.58	3.89
08-Jan	4.6	349.1	23.14	42.58	3.89
09-Jan	4.6	349.1	23.14	42.58	3.89
10-Jan	4.6	349.1	23.14	42.58	3.89
11-Jan	4.6	349.1	23.14	42.58	3.89
12-Jan	4.6	349.1	23.14	42.58	3.89
13-Jan	4.6	349.1	23.14	42.58	3.89
14-Jan	4.6	417.86	27.69	45.56	4.86
15-Jan	4.6	417.86	27.69	45.56	4.86

Example of the % leaves in canopy evaluation of *B. javanica*

	% leaves in canopy											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Mature leaves	80%	80%	70%	98%	100%	95%	95%	100%	100%	100%	100%	100%
Young leaves	20%	5%	10%	2%	0%	5%	5%	0%	0%	0%	0%	0%
Total	100%	85%	80%	100%	100%	100%	100%	100%	100%	100%	100%	100%
% young leaves emerging	**20%**	**0%**	**5%**	**0%**	**0%**	**5%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**
% young leaves maturing into mature leaves (increasing mature leaves)	**0%**	**15%**	**0%**	**28%**	**2%**	**0%**	**0%**	**5%**	**0%**	**0%**	**0%**	**0%**
% leaves fall (decreasing mature leaves	**20%**	**15%**	**10%**	**0%**	**2%**	**5%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**

Example of the calculation of leaves area and carbon absorption per day of mature leaves of *B. javanica*

Unit conversion:

Carbon absorbed (gC/m^2/s) = [CO$_2$ absorbed (µmol CO$_2$/m^2/s) * 10^{-6}] * 12

Carbon absorbed (gC/m^2/day) = Carbon absorbed (gC/m^2/s) * 39,600

Mature leaves mass in canopy (kg) = maximum crown mass * ratio of mature leaves

Mature leaves mass in canopy (g) = Mature leaves mass in canopy (kg) * 1,000

$$Area\ of\ mature\ leaves\ in\ canopy\ \left(m^2\right) = \left[\frac{Individual\ mature\ leaf\ area\ \left(cm^2\right)\ \times\ Mature\ leaves\ mass\ in\ canopy\ \left(g\right)}{Individual\ mature\ leaves\ mass\ \left(g\right)}\right]\times 0.0001$$

Carbon absorbed (gC/day) = Carbon absorbed (gC/m^2/day) * Area of mature leaves in canopy (m^2)

Carbon absorbed (kgC/day) = Carbon absorbed (gC/day) / 1,000

Example of calculation in carbon absorbed in mature leaves and area of mature leaves in canopy of *B. javanica*

Date	Max Crown mass	Increase of mature leaves	Increase of young leaves	Mature leaves								
				Carbon absorbed (µmol CO_2/m^2/s)	Carbon absorbed (gC/m^2/s)	Carbon absorbed (gC/m^2/s) (SUN 11-12 HR)	Ratio of mature leaves	Mature leaves mass in canopy (kg)	Mature leaves mass in canopy (g)	Area of mature leaves in canopy (m^2)	Carbon absorbed (gC/day)	Carbon absorbed (kgC/day)
01-Jan	0.90	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
02-Jan	1.03	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
03-Jan	1.17	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
04-Jan	1.30	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
05-Jan	1.43	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
06-Jan	1.57	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
07-Jan	1.70	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
08-Jan	1.83	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
09-Jan	1.97	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
10-Jan	2.10	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
11-Jan	2.23	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
12-Jan	2.37	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
13-Jan	2.50	0.00	0.13	3.89	0.000047	1.85	80%	0.72	720.00	8.34	15.41	0.02
14-Jan	2.63	0.00	0.13	4.86	0.000058	2.31	80%	0.72	720.00	8.34	19.28	0.02

Example of the calculation of total Carbon absorbed and total carbon loss of *B. javanica*

Total Carbon absorbed (kgC) = Carbon absorbed by mature leaves (kgC) + Carbon absorbed by young leaves (kgC)

Carbon allocated to roots (kgC) = Total carbon loss (kgC) * 0.37

Carbon remain for tree growth (kgC) = Total Carbon absorbed (kgC) – Carbon allocated to roots (kgC)

Tree above-ground carbon (kgC) = Tree above-ground carbon of previous day (kgC) + Carbon remain for tree growth (kgC)

% leaves = The relationship between tree mass and percent of leaves mass in a tree

% leaves of *B. javanica* was $y = 0.1773e^{-0.072x}$; where y = %leaves, X = tree mass (kg)

Ratio leaves (kgC) = Tree above-ground carbon (kgC) * % leaves

Litter fall (kgC) = percent of leaves fall in a month * Ratio leaves (kgC)

Ratio leaves remain (kg) = Ratio leaves (kgC) - Litter fall (kgC)

Date	Total Carbon absorbed (kgC)	Carbon allocated to roots (kgC)	Carbon remain for growth (kgC)	Tree carbon (kgC)	% leaves	Ratio leaves (kgC)	litter fall (kgC)	Ratio leaves remain (kgC)
01-Jan	0.04	0.02	0.03	8.93	9%	0.83	0.17	0.67
02-Jan	0.04	0.02	0.03	8.96	9%	0.83	0.17	0.67
03-Jan	0.04	0.02	0.03	8.98	9%	0.83	0.17	0.67
04-Jan	0.04	0.01	0.03	9.01	9%	0.83	0.17	0.67
05-Jan	0.04	0.01	0.02	9.03	9%	0.83	0.17	0.67
06-Jan	0.04	0.01	0.02	9.06	9%	0.83	0.17	0.67
07-Jan	0.04	0.01	0.02	9.08	9%	0.83	0.17	0.67
08-Jan	0.04	0.01	0.02	9.11	9%	0.83	0.17	0.67
09-Jan	0.04	0.01	0.02	9.13	9%	0.83	0.17	0.67
10-Jan	0.04	0.01	0.02	9.15	9%	0.83	0.17	0.67
11-Jan	0.04	0.01	0.02	9.18	9%	0.83	0.17	0.67
12-Jan	0.04	0.01	0.02	9.20	9%	0.83	0.17	0.67
13-Jan	0.03	0.01	0.02	9.22	9%	0.83	0.17	0.67
14-Jan	0.04	0.01	0.02	9.24	9%	0.83	0.17	0.67
15-Jan	0.04	0.01	0.02	9.27	9%	0.83	0.17	0.67

APPENDIX B

Forest restoration cost calculation

The detailed calculation of total cost for forest restoration in 1 ha with zero regenerants.

(Seedlings/saplings/live tree stumps) per hectare	0	per hectare
Therefore, the recommended number of trees to plant is	3,086	per hectare
Distance from nursery to restoration site and return	30	km
Distance from home-based to restoration site and return	30	km
Current price of 1 liter of diesel fuel	26	THB per liter
Enter the average fuel efficiency of the vehicles to be used in kilometers per liter	12	kilometers per liter
The daily labour rate	310	THB per day
Salary of project staff/supervisors	18,000	THB per month
The total area to be restored	1.00	hectares
Enter the annual inflation rate (forecasted for the next 2 years) here	3	% per year

	1st year (THB)	2nd year (THB)	Total (THB)
Total cost	**148,734**	**38,272**	**187,007**

	#Units	Units	Cost/Unit	Costs		TOTAL	Details
				1st year	2nd year		
Pre-planting site survey							
Vehicle hire	1	Vehicle	1,700	1,700	0	1,700	Enter zero units if use own vehicle
Fuel	30	Km	2	65	0	65	
Equipment	1	Set	300	300	0	300	
Project management staff inputs - supervision data analysis	2	Days work	818	1,636	0	1,636	

	#Units	units	Cost/Unit	Costs		TOTAL	Details
				1st year	2nd year		
Site preparation - weeding spraying							
Weed slashing labour	19	days work	310	5,813	0	5,813	Assuming labourers bring their own tools. Slash weeds down to 10-20 cm, 6 weeks before tree planting.
Herbicide spraying labour	1	days work	465	465	0	465	Spray glyphosate on new weed shoots 3 weeks before tree planting.
Glyphosate	3	gallon	550	1,375	0	1,375	2.5 gallon per hectare (@550 PER GALLON)
Supervision weeding/spraying vehicle hire	1	vehicles	1,700	3,400	0	3,400	Two trips weed slashing and herbicide application.
Supervision weeding/spraying vehicle fuel	30	km	2	130	0	130	
Project management staff inputs - training, supervision, payments, accounting.	2	days work	818	1,636	0	1,636	
	#Units	units	Cost/Unit	Costs		TOTAL	Details

	1st year	2nd year		

Site preparation - weeding spraying							
Seedling transfer to site - labour	2	days work	310	638	0	638	
Seedling transfer to site - pickup truck hire	6	trip	300	1,852	0	1,852	500 trees per 1 load, cost is per trip. Usually we employ local villagers with their own pick-up trucks. They charge per trip, which renegotiated each year.
Seedling transfer to site - pickup truck fuel	185	km	0	0	0	0	Enter zero units - if villagers include petrol in their "per trip" charge.

	#Units	units	Cost/Unit	Costs		TOTAL	Details

	#Units	units	Cost/Unit	Costs		TOTAL	Details
				1st year	2nd year		
Tree Planting							
Planting stock	3,086	tree	18	55,548	0	55,548	Saplings 30-50 cm tall in 9 x 2.5" plastic bags. Cost includes local seed collection, pre-germination treatments, potting and standing down in the nursery with weeding, watering and fertilizer application for 6-18 months depending on species. Does not include delivery to the panting site. On the basis of a team of 3 persons producing 20,000 trees per year.
Staking, hole digging, planting, fertilizer application and garbage clearance - Labour	51	days work	310	15,944	0	15,944	Planting rate is about 60 trees per person per day.
	#Units	units	Cost/Unit	Costs		TOTAL	Details
				1st year	2nd year		

Tree Planting							
Organic Fertilizer	3.1	sack (50 kg)	450	1,406	0	1,406	450 THB per 50kg bag organic fertilizer. 6.25 bags per hectare. Apply 100gm to both planted trees and natural regenerants: totally 3,100 trees per hectare
Buckets & cups for fertilizer, gloves and box cutters	2	set	340	680	0	680	4 sets per hectare
Baskets	2	basket	80	123	0	123	1 basket carries 20 trees x 100 times, before falling apart.
Bamboo poles	3,086	pole	0.5	1,543	0	1,543	This price varies enormously from place to place from 0.25 to 2 THB.
Hoes	4	hoe	0	0	0	0	Enter zero UNITS if planters bring their own.
Food and drink for planters	51	person	60	3,086	0	3,086	
	#Units	**units**	**Cost/Unit**	**Costs**		**TOTAL**	**Details**
				1st year	**2nd year**		
Tree Planting							

Item	#Units	units	Cost/Unit	Costs	TOTAL	Details
Vehicle hire for project staff, VIP's etc. - planting event	2	vehicle	1,800	3,600	0	3,600	Assume that most of the planters are local and will come with their own transport. Therefore, we budget for only 4 vehicles for project staff and VIP's sponsors etc.
Fuel for transportation of project staff VIP's etc. to planting event.	60	km	2	130	0	130	
Project management staff inputs - training, supervision, payments, accounting.	6	days work	818	4,909	0	4,909	
Ceremonial items, e.g. banner, gifts, T-shirts, sound equipment etc.		misc.		0			**Add cost as required**

	#Units	**units**	**Cost/Unit**	**Costs**		**TOTAL**	**Details**
				1st year	**2nd year**		

Plot maintenance for 2 years							
Tree maintenance - weeding and fertilizer application, to both planted trees and natural regenerants - LABOUR	19	days work	310	17,438	17,961	35,398	3 times in first rainy season and 3 times in 2nd rainyseason
Fertilizer	3.1	sack (50 kg)	450	4,219	4,345	8,564	450 THB per 50kg bag organic fertilizer. 6.25 bags per hectare. Apply 100gm to both planted trees and natural regenerants: totally 3,100 trees per hectare. 3 times in the 1st raint season and 3 times in the 2nd rainy season.
Supervision weeding/fertilizer application vehicle hire	1	vehicle	1,600	4,800	4,944	9,744	ENTER ZERO UNITS IF USE OWN VEHICLE. 3 times in rainy season and 3 times in 2nd rainy season.
Supervision weeding/fertilizer application vehicle fuel	30	km	2	195	201	396	
	#Units	units	Cost/Unit	Costs		TOTAL	Details
				1st year	2nd year		
Plot maintenance for 2 years							

	#Units	units	Cost/Unit	Costs		TOTAL	Details
Project management staff inputs - training, supervision, payments, accounting.	2	days work	818	4,909	5,056	9,965	3 times x 2 staff in 1st rainy season and same in 2nd rainy season

	#Units	units	Cost/Unit	Costs		TOTAL	Details
				1st year	**2nd year**		
Seedling monitoring for 2 years							
Labour	1	days work	310	319	164	483	Assuming 5% of trees are labeled and monitored
Supervision monitoring - vehicle hire	1	vehicle day	1,600	3,200	1,648	4,848	enter zero units if use own vehicle
Supervision weeding/fertilizer application - vehicle fuel	30	km	2	130	67	197	
	#Units	**units**	**Cost/Unit**	**Costs**		**TOTAL**	**Details**
				1st year	**2nd year**		
Seedling monitoring for 2 years							

Project management staff inputs - training, supervision, payments, accounting.	4	days work	818	6,545	3,371	9,916	In Y1 twice - baseline and end rainy. In Y2 once - end rainy.
Equipment and materials	1	set	500	1,000	515	1,515	Spare labels, gloves, stationary etc.
Fire prevention program for a year		misc.		0	0		Fire break cutting, fire patrols/warning system and fire suppression teams. Costs for these items vary hugely from site to site, according to size/shape and remoteness of plots and local fire risk factors. Please calculate after negotiation with local villagers and forestry officials and add costs of 2 years fire prevention.
Fencing		misc.		0			Livestock exclusion

CURRICULUM VITAE

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Publication   Kanlayarat Jantawong, Stephen Elliott and Prasit
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