NEW ALLOMETRIC EQUATIONS FOR TREE BIOMASS AND CARBON CALCULATIONS IN SECONDARY HILL EVERGREEN FOREST IN NORTHERN THAILAND

TITINAN POTHONG

DOCTOR OF PHILOSOPHY
IN ENVIRONMENTAL SCIENCE

GRADUATE SCHOOL
CHIANG MAI UNIVERSITY
APRIL 2019

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A THESIS SUBMITTED TO CHIANG MAI UNIVERSITY IN PARTIAL
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หัวข้อดุษฎีนิพนธ์	สมการอัลโลเมตริกชุดใหม่สำหรับการคำนวณมวลชีวภาพและคาร์บอนของต้นไม้ในป่าดิบเขาทุติยภูมิในภาคเหนือของประเทศไทย
ผู้เขียน	นางสาว ฐิตินันท์ โพธิ์ทอง
ปริญญา	ปรัชญาดุษฎีบัณฑิต (วิทยาศาสตร์สิ่งแวดล้อม)

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	อ.ดร. เดีย พนิตนาถ แชนนอน	อาจารย์ที่ปรึกษาร่วม

บทคัดย่อ

การบุกรุกทำลายป่าและการเสื่อมสภาพของป่าไม้อย่างรวดเร็วในปัจจุบัน มีส่วนทำให้กลไกทางเศรษฐศาสตร์ได้เกิดขึ้น เช่นกลไกการซื้อขายคาร์บอน ซึ่งถือได้ว่าเป็นอีกหนึ่งวิธีการที่มีความสำคัญ และมีส่วนสร้างแรงจูงใจในการช่วยรักษาและฟื้นฟูป่าทุติยภูมิ ดังนั้นการวัดปริมาณการสะสมคาร์บอนที่แม่นยำและมีความน่าเชื่อถือจึงมีบทบาทสำคัญที่มีส่วนทำให้กลไกนี้บรรลุผลตามเป้าหมายได้อย่างสมบูรณ์ การศึกษานี้ได้สร้างสมการอัลโลเมตริกชุดใหม่ที่เฉพาะเจาะจงต่อป่าดิบเขาทุติยภูมิและพื้นที่ป่าของแปลงไร่หมุนเวียนในภาคเหนือของประเทศไทย ที่มีความหลากหลายของชนิดพันธุ์พืชและขนาดต้นไม้ที่แตกต่างจากป่าสมบูรณ์ประเภทอื่น ๆ การพัฒนาสมการอัลโลเมตริกชุดใหม่ได้เก็บจากตัวอย่างต้นไม้ด้วยวิธีการตัดและชั่งตัวอย่าง จากพื้นที่การศึกษา 3 พื้นที่คือ แปลงไร่หมุนเวียนอายุ 4 ปี 7 ปี และป่าทุติยภูมิหลังจากการทำไร่หมุนเวียนโดยมีอายุประมาณ 50 ปี ตัวอย่างต้นไม้ทั้งหมด 136 ต้น (รวมกับต้นไม้ที่มีการแตกหน่อจากต้นเดียวกัน) 23 ชนิด โดยมีขนาดความโตของต้นไม้ (DBH) ตั้งแต่ 1 ถึง 32.9 เซนติเมตร ตัวอย่างต้นไม้จากการอบและบดละเอียดแล้วจะถูกนำส่งเพื่อวิเคราะห์ปริมาณคาร์บอนในเนื้อไม้แต่ละชนิด การศึกษาความหนาแน่นเนื้อไม้ ได้จากการเก็บตัวอย่างจากต้นไม้ 79 ชนิด พบว่า 35 ชนิด ยังไม่มีปรากฏในฐานข้อมูลของ Global Wood Densities database ความหนาแน่นของเนื้อไม้แต่ละชนิดจากการศึกษาในครั้งนี้มีค่าเฉลี่ยอยู่ระหว่าง 0.23 ถึง 0.75 กรัมต่อลูกบาศก์เซนติเมตร ทั้งนี้การสร้างสมการอัลโลเมตริกได้ใช้ข้อมูล ขนาดความโต

ของต้นไม้ (DBH) ความสูง (H) และความหนาแน่นเนื้อไม้ (WD) เป็นตัวแปรอิสระ และค่ามวลชีวภาพของต้นไม้เหนือพื้นดิน (AGB) เป็นตัวแปรตาม ผลจากการการวิเคราะห์ค่าความหนาแน่นเนื้อไม้มีความแตกต่างกันระหว่างชนิดของต้นไม้ ($p < 0.05$) ส่งผลทำให้เมื่อเพิ่มตัวแปรอิสระ ความหนาแน่นเนื้อไม้เข้าไปในสมการในรูปของ DBH^{2}HWD มีความสำคัญที่สามารถทำนายค่าตัวแปรตาม AGB และยังช่วยลดความไม่แน่นอนของการประเมินการสะสมมวลชีวภาพเหนือพื้นดินได้ นอกจากนี้จากการวิเคราะห์ค่าปริมาณคาร์บอนของระหว่างชนิดพบว่ามีความแตกต่างกันในทางสถิติ ($p < 0.05$) ค่าปริมาณคาร์บอนจากการวิเคราะห์โดยเฉลี่ยระหว่างชนิดคือ 44.84% (±1.63) ทั้งนี้จากการใช้สมการอัลโลเมตริกชุดใหม่กับข้อมูล พบว่าสามารถทำนายการสะสมมวลชีวภาพของต้นไม้ได้มากที่สุดอยู่ในแปลงป่าทุติยภูมิ รองลงมาคือแปลงไร่หมุนเวียนอายุ 7 ปี และ 4 ปี ตามลำดับดังนี้คือ 105.3, 38.3 และ 10.3 เมกกะกรัมต่อเฮกตาร์ และค่าการกักกับคาร์บอน คือ 47.7, 17.4 และ 4.6 เมกกะกรัมคาร์บอนต่อเฮกตาร์ ภาพรวมจากการศึกษาในครั้งนี้สามารถช่วยเพิ่มความเข้าใจเกี่ยวกับการเก็บกักคาร์บอนในป่าทุติยภูมิและพื้นที่ไร่หมุนเวียน ซึ่งสามารถนำข้อมูลไปใช้เกิดประโยชน์กับการจัดเตรียมข้อมูลการสะสมคาร์บอนระดับชาติเพื่อเตรียมความพร้อมต่อกลไกเรดด์พลัสและการซื้อขายในตลาดคาร์บอนต่าง ๆ ได้

Dissertation Title New Allometric Equations for Tree Biomass and Carbon Calculations in Secondary Hill Evergreen Forest in Northern Thailand

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Degree Doctor of Philosophy (Environmental Science)

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ABSTRACT

Accelerating deforestation and forest degradation make financial incentives to preserve and regenerate secondary forests, such as carbon credit trading, urgently needed. However, such schemes ultimately rely on the ability to accurately quantify carbon stocks. This study establishes new allometric equations that are specific to secondary forests, within hill evergreen forest and shifting cultivation areas in northern Thailand, a forest type with considerable variation in plant diversity and tree sizes. New allometric equations were developed, using data collected from destructively sampled trees from three sites: 4-year-fallow, 7-year-fallow, and secondary forest (approximately 50 years old). In total, 136 trees (including coppiced trees) from 23 species were harvested, with a diameter at breast height (DBH) ranging from 1 to 32.9 cm. Oven-dried and ground samples were sent for carbon analysis. Wood density data of 79 species, including 35 species currently missing from the Global Wood Densities database was measured. Values ranged from 0.23 to 0.75 g/cm^3. Several models were developed using above-ground biomass (AGB) as a dependent variable, and DBH, total tree height (H), and wood density (WD) as independent variables to create allometric equations. Wood density varied significantly among species ($p < 0.05$). Consequently, including WD combination of DBH^2HWD was strongly related to AGB and reduced biomass estimation uncertainty. Moreover, average carbon concentration also varied significantly among tree species ($p < 0.05$), the average being 44.84% (±1.63). Furthermore, applying the new allometric equation revealed that tree biomass was highest in the secondary forest site, followed by the 7-year-fallow, and the 4-year-fallow, at 105.3, 38.3, and 10.3 Mg/ha, respectively, and above-ground carbon was 47.7, 17.4, and 4.6 Mg C/ha, respectively. This study provides better insights into carbon sequestration in secondary forest and fallows, and may be helpful in preparing baseline data for Thailand’s carbon stocks for REDD+ and other carbon trading schemes.

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LIST OF ABBREVIATIONS

AGB	Above-ground biomass
AGC	Above-ground carbon
DBH	Diameter at breast height
FORRU	Forest Restoration Research Unit
GWD	Global Wood Density database
H	Height
IVI	Importance value index
ha	Hectare
Mg	Megagram = tonne
Mg C	Megagram carbon = tonne carbon
NDVI	Normalized difference vegetation index
NIR	Near infrared band
OLI	Operational Land Imager
R	Red band
REDD+	Reducing emissions from deforestation and forest degradation and enhancing carbon stocks
RFD	Royal Forest Department
SF	Secondary forest
WD	Wood density
4Y	4-year-fallow
7Y	7-year-fallow

ข้อความแห่งการริเริ่ม

1) วิทยานิพนธ์นี้ได้นำเสนอสมการอัลโลเมตริกชุดใหม่ โดยสร้างสมการจากการเก็บตัวอย่างด้วยวิธีการตัดและชั่งตัวอย่าง โดยมุ่งเน้นที่ป่าดิบเขาทุติยภูมิและพื้นที่ป่าที่ถูกพักหลังจากการทำไร่หมุนเวียน ซึ่งยังไม่มีการรายงานเกี่ยวกับสมการอัลโลเมตริกในพื้นที่ป่าประเภทนี้ โดยสมการชุดใหม่ที่ได้จากการศึกษาจะมีการเปรียบเทียบกับสมการอัลโลเมตริกเดิม ที่รู้จักและถูกใช้กันอย่างแพร่หลาย ซึ่งได้ปรากฏอยู่ในรายงานทางวิชาการทั้งในประเทศและต่างประเทศ

2) วิทยานิพนธ์นี้ได้มีการทดสอบความสามารถของการเพิ่มตัวแปรเข้าไปในสมการอัลโลเมตริกเพื่อประเมินสะสมมวลชีวภาพ โดยเฉพาะอย่างยิ่งตัวแปรของความหนาแน่นเนื้อไม้ ซึ่งอาจจะช่วยลดความไม่แม่นยำของการวิเคราะห์ข้อมูล และช่วยเพิ่มความสามารถในการคำนวณค่าการสะสมมวลชีวภาพในป่าประเภทนี้ ให้มีความถูกต้องและแม่นยำเพิ่มมากขึ้น

STATEMENT OF ORIGINALITY

1. This study aims to provide new allometric equations based on the destructive method, focusing on secondary hill evergreen forest and fallow after shifting cultivation, forest types that have received little interest in Thailand. It also compares these new equations with well-known and widely used allometric equations from previous studies, in Thailand as well as in other countries.

2. This study also tests the usefulness of adding more parameters to allometric equations to estimate tree biomass. In particular, adding wood density may reduce the uncertainty of the estimates and also increase accuracy in these types of forest.

CHAPTER 1

Introduction

1.1 Historical background

There is no doubt that the current rise in atmospheric carbon dioxide is mainly caused by anthropogenic activities, such as the combustion of fossil fuels, transportation, agriculture, land use change and loss of forest cover in the tropical forests (IPCC 2007). Carbon dioxide accounts for about 62% of total annual anthropogenic greenhouse gases (GHG) emissions in the period 1970–2010 (IPCC, 2014). Deforestation and forest degradation are accelerating the rate of climate change by increasing carbon dioxide levels in the atmosphere (Vashum and Jayakumar 2012), with 1.1–1.4 Gt C/year coming from forests and other land uses (IPCC, 2014). The situation has drawn the attention of many international organizations. The United Nations Framework Convention on Climate Change (UNFCCC), for example, has created the UN program Reducing Emissions from Deforestation and Forest Degradation (REDD+) with the aim of reducing emissions from deforestation, forest degradation, and other land-use conversions (e.g. agriculture, peatland, trees-outside-forest, agroforest, plantations), plus foster conservation, sustainable management of forests and enhancement of forest carbon stocks. The REDD+ program is designed to provide payment mechanisms for carbon dioxide emitters to compensate developing commissions for their emissions through carbon credits (Minang et al., 2009, UN-REDD, 2011). The Intergovernmental Panel on Climate Change (IPCC), Food and Agriculture Organization (FAO), Center for International Forestry Research (CIFOR), among others, have produced many public reports on climate change, forest carbon and the methods for biomass and carbon estimation in forests. Furthermore, scientists worldwide are also becoming interested in the capacity of forests to sequester carbon, by studying how much carbon dioxide can be absorbed from the atmosphere by trees and associated vegetation (Chave et al., 2005). Several studies estimate current annual sequestration in tropical forests to be in the range of 1.2Gtc – 1.8Gtc, based on data from 2005-2010 (Pan et al., 2011; Grace et al., 2014), which confirms their importance in reducing anthropogenic emissions from the atmosphere.

Furthermore, regenerating secondary forests can sequester large amounts of carbon and play a significant role in mitigating climate change, according to recent studies (Chazdon et al., 2016 and Poorter et al., 2016). However, quantitative data are lacking. Carbon accumulation in forests is measured as a proportion of biomass accumulation, carbon constituting roughly half of wood mass. Estimating biomass accumulation enables assessment of forest productivity as well the carbon storage potential achievable by reforestation or lost when forests are cleared. Forest biomass is assessed by various methods. Forest inventories use relationships among different parts of trees to create allometric equations. Such models use relatively easy-to-measure variables (e.g. diameter at breast height (DBH), height, wood density etc.) to predict difficult-to-measure variables such as biomass (Gibbs et al., 2007). Wood density data are particularly important for accurately estimating tree biomass (Baker et al., 2004; Chave et al., 2014); hence a global wood density (GWD) dataset has been compiled (Chave et al., 2009; Zanne et al., 2009). Biomass and carbon accumulation varies by forest type, fertility, and geographic location, climatic characteristics, different forest management practices, tree specific traits (Chan et al., 2013; Chen et al., 2015; U.S. EPA, 2015). It is now more important than ever to determine accurate forest carbon balance, due to the development of carbon credit trading, which provides financial incentives to both encourage reforestation and discourage deforestation (Nakane, 2001; IPCC, 2006; Chaturvedi et al., 2012). Such financial mechanisms rely on market confidence, which in turn depends on knowing accurately the quantity of carbon in the credits being bought or sold.

Chave et al. (2005) and Chave et al. (2014) compiled the GWD dataset from a wide range of studies in various vegetation types in pantropical forests to validate allometric equations for tropical forest trees using DBH, total tree height, above-ground biomass & wood density data from destructive harvesting. Although the GWD dataset includes some Southeast Asian studies, data from Thailand are scant, with several tree species found in northern Thailand still missing. Furthermore, the allometric equations that are widely used in Thailand lack wood density measurement.

Several studies in Thailand have estimated the biomass of forest ecosystems by using allometric equations and have calculated the content of carbon from biomass. Allometric equations in Thailand have been established only for mixed deciduous forests (MDF) (Ogawa et al., 1965) and dry evergreen forests (DEF) (Tsutsumi et al., 1983) and have yet to be developed for secondary forests, fallow areas and coppiced trees in hill evergreen forests (HEF), which are typical of northern Thailand. Almost all studies in Thailand used Ogawa et al. (1965) and Tsutsumi et al. (1983) to estimate forest biomass. In addition, most allometric equations used in Thailand are for trees larger than DBH 4.5 cm (Ogawa et al., 1965; Tsutsumi et al., 1983) or for other countries >5 cm (Brown 1997; Ketterings et al., 2001; Basuki et al., 2009; Chave et al., 2005; Chave et al., 2014). Smaller trees, which make up a large part of young secondary forests, have received much less attention (Kenzo et al., 2009; Chan et al., 2013), and are not included in the equations developed for Thailand. Consequently, unsuitable equations for biomass estimation may over- or under- estimate forest carbon content and distort carbon credit values. Clearly, new allometric equations, based on a more complete dataset, would be useful. To establish these new allometric equations, some trees species have to be felled, to accurately directly measure biomass and carbon content.

Few allometric equations have been developed for secondary hill evergreen forest, even though such forest dominates mountains above 1000 m elevation, has higher species diversity than almost all other forest types in northern Thailand (Khamyong 2009; Junsongduang et al., 2014) and are mostly classified as A1 protected watersheds. Consequently, the destruction of such forests leads to losses of both carbon and biodiversity and disruption of watershed services such as water supply and soil erosion. Knowledge of carbon accumulation during regeneration of such forest would enable scalable financial incentives to be developed to facilitate their restoration. However, Thailand lacks proper tools and optimal equations for quantifying carbon stocks and the role of secondary forests in carbon storage at the landscape level still poorly understood.

Therefore, this research project aimed to establish new allometric equations that are specific to secondary forests within hill evergreen forest ecosystems in northern Thailand. These allometric equations can be used to accurately estimate tree biomass and carbon in forests and provide alternative criteria for choosing the most appropriate model for each forest type. In addition, this research could satisfy the evaluation requirements of REDD+ and other carbon trading schemes in the future.

1.2 Research objectives

5.1 To develop new allometric equations for secondary forests in northern Thailand and more specific equations that includes multi-stemmed coppicing trees, which are a large component of secondary re-growth, often ignored in existing allometric equations (if DBH< 4.5 cm).

5.2 To determine finer scale relationships among tree part sizes to create new optimal parameters.

5.3 To produce a wood density dataset of secondary forests and shifting cultivation areas in northern Thailand, and compare variations in wood density of species missing from the Global Wood Density (GWD) database with the average wood density of the same genus or family in the GWD, including the effect on biomass calculation.

5.4 To compare biomass accounting from other equations used for Thai forests, and verify data with the results from the new allometric equations developed in this study.

1.3 Usefulness of the research

6.1 New allometric equations for secondary forests and coppiced trees in northern Thailand will be useful for accurately estimating tree biomass and evaluate carbon in forests.

6.2 A more complete wood density dataset will provide important data for estimating tree biomass. Furthermore, wood density of several species that are still missing from the Global Wood Density (GWD) database will be added and may be used in future studies.

6.3 Enhanced ability to evaluate the role of carbon in secondary forests and shifting cultivation fallows, which may have significant implication for forest plantations.

6.4 Increased understanding of the current status of carbon stocks and enhanced ability to predict near-future changes in those carbon stocks by using the allometric equations to calibrate remote-sensing technique for large scale carbon estimation.

6.5 Provide information of biomass and carbon storage of secondary forests in order to prepare baseline data for Thailand’s carbon stocks, which will be useful for the REDD+ and carbon markets that require carbon accounting at an international level.

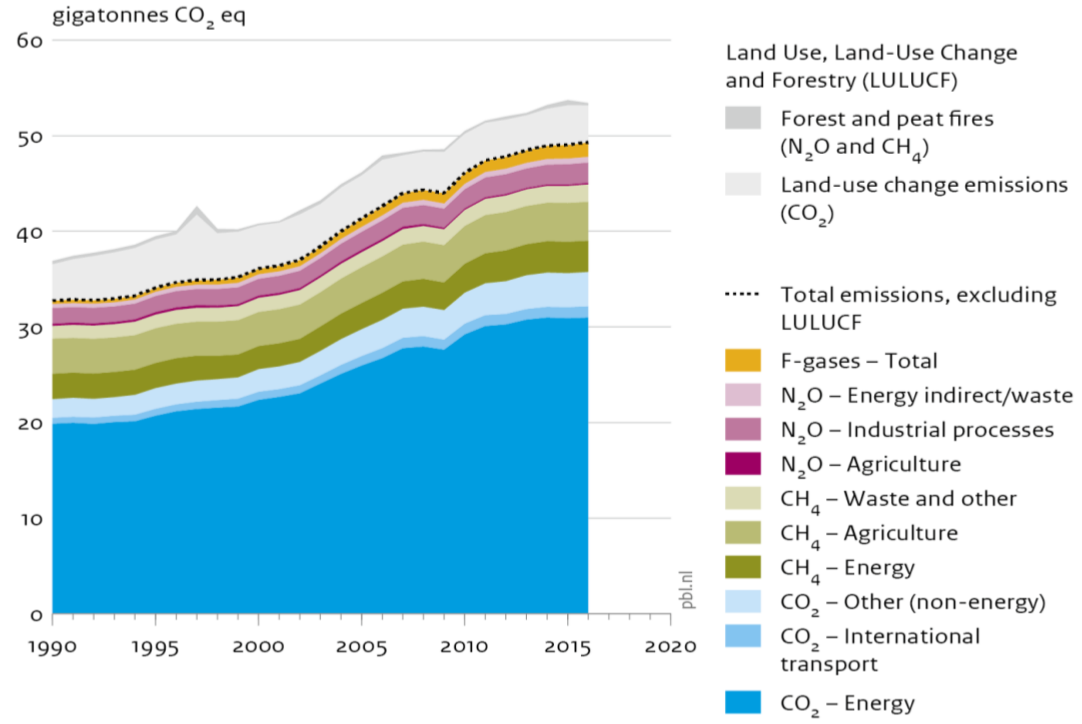
CHAPTER 2

Literature review

2.1 Greenhouse gases emissions

Increasing atmospheric concentrations of greenhouse gases from human activities is creating an ever thicker blanket around the world, absorbing and trapping energy and warming the planet over the last 150 years (IPCC, 2007). Global warming is mainly the result of accelerating emissions of carbon dioxide and other greenhouse gases, due to human activities; population growth, increased and intensified agriculture, deforestation, industrialization and associated energy use from fossil fuel sources (coal and oil), and transportation since 1750 (IPCC, 2014; U.S. EPA, 2018). Carbon dioxide (CO_2) remains the most important gas, accounting for 72% of total anthropogenic greenhouse gas emissions. Secondly, methane (CH_4), mainly from agriculture, contributes 19%, nitrous oxide (N_2O), mostly from industry and agriculture, contributes 6%, and fluorinated gases (F-gases), used in industrial and manufacturing processes, contributes 3%. It is worth noting that these percentages do not include net CO_2 emissions from land use, land-use change, and forestry (LULUCF). Such land-use related emissions are less certain and show large inter-annual variations. When excluding LULUCF and forest and peat fires, the trend in total carbon emissions has remained more or less flat (±0.5%) for the last two years, see Figure 2.1. In contrast, CO_2 emissions from LULUCF show a highly varying pattern that reflects periodically occurring strong El Niño years, in 1997–1998 and 2015–2016 (Figure 2.1) (Olivier et al., 2017).

Moreover, global average concentrations of CO_2 reached 403.3 part per million in 2016, up from 400 ppm in 2015. A higher growth rate was found in 2015 and 2016 compared to the previous years because of a combination of human activities and a strong El Niño event. El Niño increased forest fires due to droughts in tropical regions, which also reduced the capacity of forests to act as “sinks”, and a decreased uptake of CO_2 by vegetation in drought-affected areas. In 2016, CO_2 levels in the atmosphere reached 145% of pre-industrial (before 1750) levels (WMO-No.1212, 2018)



Source: EDGAR v4.3.2 (EC-JRC/PBL 2017); Houghton and Nassikas (2017); GFED 4.1s (2017)

Figure 2.1 Global greenhouse gas emissions per type of gas and source including land use, land-use change and forestry (LULUCF).

Figure 2.2 shows the global carbon cycle and overall CO_2 emissions caused by anthropogenic activities, averaged globally 2007–2016, Emissions from fossil fuels and industry was 9.4 GtC yr^{-1}, and emissions from land-use change, including deforestation was 1.3 GtC yr^{-1}(12%). During the same period, the growth rate in atmospheric CO_2 concentration was 4.7 GtC yr^{-1}, while carbon sinks in the land reservoirs and oceans amounted to 3 GtC yr^{-1} and 2.4 GtC yr^{-1}, respectively. The budget imbalance was about 0.6 GtC yr^{-1}, which was a mismatch calculation between the estimated of emissions and the estimated changes in atmosphere, land, and ocean. Knowledge of trends in the natural carbon cycle is necessary to understand how natural sinks respond to changes in climate, CO_2 and land-use change drivers, as well as permissible emissions for a given climate stabilisation target (Le Quéré et al., 2018).

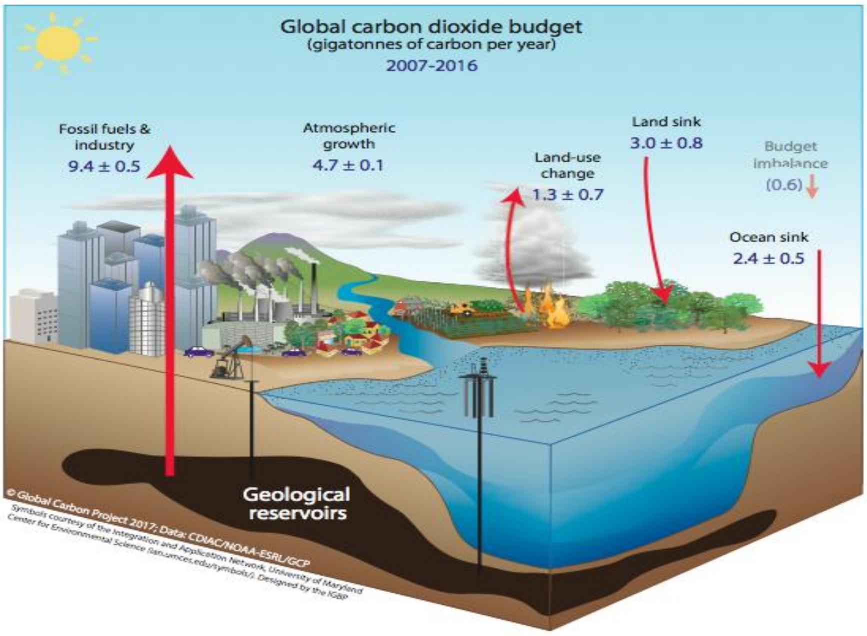


Figure 2.2 An overview of the global carbon cycle caused by anthropogenic activities

Approximately 88% of the anthropogenic carbon emissions 2007-2016 was from fossil fuels and industry, while 12% was from deforestation and other land-use changes. On average only about 44% of these carbon emissions remained in the atmosphere; 28% were removed by the land, and 22% by the ocean; making the unattributed budget imbalance, 5% (shown in light grey in the bottom of the graph, reflecting total emissions) (Figure 2.3) (Le Quéré et al., 2018; WMO-No.1212, 2018).

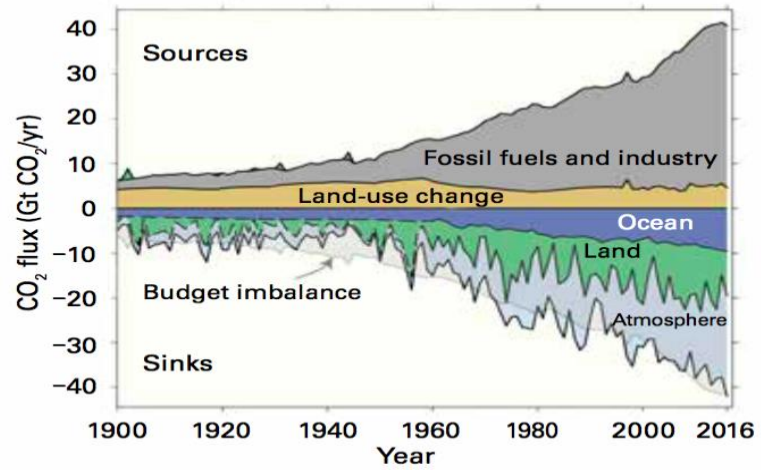


Figure 2.3 The historical global carbon budget, 1900–2016

2.2 Greenhouse gas emissions from deforestation, agriculture and land-use change

Agriculture, forestry, and land use (AFOLU) was are responsible for about one-quarter of all the global greenhouse gas emissions (IPCC, 2014). Emissions from agriculture are increasing with time, due to a growing global human population, rapidly rising meat consumption and higher food production requirements, necessitating dramatic expansion of agricultural land and intensification of farming practices. This has caused biodiversity loss, reduced carbon storage, and soil deterioration (Foley et al., 2011). Slash and burn agriculture causes deforestation which releases CO_2 stored in trees and soils. Currently, agriculture is mainly expanding in the tropical region, where approximately 80% of forests have been replaced by new croplands. Most of the agricultural land expansion comes from forests, woodlands, and savannas, not from previously cleared lands (Gibbs et al., 2010).

Rice and rubber tree plantations are the dominant forms of agriculture in continental Southeast Asia (FAO, 2009). Approximately 60% of the new agricultural land comes from intact forests (open and closed forests), while more than 30% comes from disturbed forests (fragmented forests, e.g., affected by long-fallow shifting cultivation, logging, and fuel wood collection) (Gibbs et al., 2010).

Deforestation is, to a certain extent, being countered with reforestation projects. In continental Southeast Asia, the area of tree plantations increased from approximately 11 million ha to 17.4 million ha between 1980 and 2000, representing a 58% increase (FAO, 2009). In northern Thailand, forest restoration projects have been initiated since the early 1990s (FORRU, 2005).

2.3 REDD+

The introduction of economic drivers may help to slow deforestation and mitigate climate change if they are attractive REDD+ (Reducing Emissions from Deforestation and Forest Degradation and Enhancing Carbon Stocks) is a package of policies and incentives, developed under the UN Framework Convention on Climate Change, to finance forest conservation and restoration, by placing a value on the capacity for forests to absorb atmospheric carbon dioxide and thus mitigate global climate change This powerful international instrument encourages developing countries to contribute to climate mitigation in the forestry sector by providing funding mechanisms to support: (i) reduced emissions from deforestation; (ii) reduced emissions from forest degradation; (iii) conservation of forest carbon stocks; (iv) sustainable forest management and (v) enhancement of forest carbon stocks through land use and land cover change. Such mechanisms encourage developing countries to protect, manage and use their forest resources more wisely. The aim of REDD+ is to make it more valuable to leave forests standing than to cut them down by financially compensating stored and increased forest carbon stocks. This means that developing countries may receive monetary compensation for their standing forests from developed countries, to offset carbon emissions. It is hoped that REDD+ may tip the economic balance in favour of sustainable forest management and reduced net greenhouse gas emissions from the forestry sector (Brofeldt et al., 2014). Other multilateral REDD+ initiatives include the Forest Carbon Partnership Facility (FCPF) and Forest Investment Program (FIP), hosted by The World Bank. According to the FCPF, land use change, land cover change and shifting fallow forests have received more attention during the development of new mechanisms to REDD+ (Chan et al., 2016).

One challenge is to make sure that initiatives also restore biodiversity and preserve forest ecosystems that benefit both local people and wildlife (Elliott et al., 2013). It is also important to take into account how the livelihoods of shifting cultivators might be impacted, if they are prevented from producing food locally, since many of them live under fragile tenure. REDD+ represents a new opportunity for shifting cultivators, but it is not without challenges. The question is how local people can benefit from this mechanism, and how it is best implemented where shifting cultivation has been a tradition for generations. Presently, the number of studies looking at how shifting cultivators may benefit from REDD+ is low. However, shifting cultivators may gain economically from maintaining forests rather than cutting it for cultivation. Clearly, the conditions have to be favourable for all concerned parties for such programs to be attractive (Martz, 2009).

Unlike most other South-East Asian countries, Thailand has been slow to embrace REDD+. The Thai government submitted a Readiness Plan Idea Note (R-PIN) to the Forest Carbon Partnership Facility (FCPF) in 2009, and more recently a Readiness

Preparation Proposal (RPP) (REDD PLUS DNP, 2013) after a series of consultations throughout 2012. Thailand's R-PP submission is currently under review by the FCPF. (USAID LEAF, 2012). In 2010, the government of Thailand decided to participate in the REDD+ partnership, which it followed up with the establishment of a REDD+ Taskforce. In 2013, the REDD+ Taskforce was strengthened for the REDD+ readiness in Thailand by revising the composition of committee members and including more stakeholders from both government and non-government agencies, such as civil society organizations, local forest-dependent communities and private sector organizations, as well as academic and research institutions (REDD PLUS DNP, 2013). According to the last update of the Country Progress Sheets at the FCPF website, Thailand has received a grant of 3.6 million dollars to carry out the REDD+ Readiness phase from 2016-2019 (FCPF, 2017). In Thailand, each sector has established systems for monitoring relevant sector indicators, and the aim is to build a national REDD+ monitoring system that will integrate forestry sector information with that of other relevant sectors. However, national carbon stock change monitoring data does not currently exist. Other existing data have several limitations: inconsistent data across the country; several data custodians; lack of data on some forest resources; lack of tools to accurately estimate carbon in standing trees; and lack of mechanisms for information dissemination, sharing and networking (REDD PLUS DNP, 2013). It is increasingly important to develop methods for monitoring, reporting, and verification of REDD+ (Mohd Zaki et al., 2018).

2.4 Secondary forests and fallow areas

Anthropogenic disturbances by deforestation and degradation have rapidly converted primary forests to secondary forests (Putz and Redford, 2010; Ziegler et al., 2012). Secondary forests have become a very common land-cover type in South-East Asia (Wright, 2005), representing 63% of the total forest cover in 2005 (Kettle, 2010). Over the last 50 years, Thailand has lost about 20% of its total forest cover (RFD, 2017). Although exact data on the extent (surface area) of primary and secondary forest types within northern Thailand are lacking, secondary forests make up by far the larger portion of evergreen forest cover (Santisuk, 1988; Schmidt-Vogt, 2001).

The forest loss in Thailand began with teak logging concessions granted to foreign powers in the late 1800's after the Bowring Treaty. The legal logging concessions were expanded in 1953 (Chalermlarp and Khuan-Arch, 2012) and continued until the Thailand government cancelled the concessions in 1989. Since then, reforestation projects have been started in many areas to recover and increase Thai forests, starting with the nationwide Golden Jubilee projects in 1994 (Chalermlarp and Khuan-Arch, 2012) and reforestation initiatives in northern Thailand by The Forest Restoration Research Unit (FORRU) of Chiang Mai University the same year (Pakkad et al., 2002).

In northern Thailand specifically, forest cover decreased dramatically during the 1970's, mainly due to three factors: i) conversion of forests to agriculture to support a growing population as well as for export, ii) logging of natural forest to fuel economic growth, and iii) farming practices of ethnic hilltribe people, including opium production and shifting cultivation (Suraswadi et al., 2000). Consequently, northern Thailand lost a net total of about 15% of its forests between 1973 and 2017 (RFD, 2017).

Nevertheless, shifting or swidden cultivation in the uplands it has been practiced for centuries and forms the basis of land-use patterns, livelihoods and customs. It involves clearing small areas of forest, followed by cultivation for one or a few years, before abandonment and natural forest regeneration. Long fallow periods allow the forest to regrow and restore productivity to the land (Bruun et al., 2009). This type of cultivation is commonly practiced with short (<5 years), intermediate (5–10) or long (20+years) fallow periods before farmers clear the land and recultivate it (Ziegler et al., 2012). Consequently, a complex mosaic of active fields, interspersed with patches of mature forests and secondary forest of various ages comprise the landscape (McNicol et al., 2015). This system of shifting cultivation is now mainly being replaced by continuous annual cropping or by perennial crops such as rubber, fruit trees, oil palm, timber, or rice field cultivation (Schmidt-Vogt et al. 2009). In 2009, shifting cultivation was practised in more than 5% of the highlands of northern Thailand (Rarkasem et al., 2009). The dominant tree species in fallows or secondary forests in northern Thailand differ substantially from those in mature hill evergreen forests. The dominant species depend on fallow age being mostly light demanding pioneer species during early successional phases, and replaced with shade tolerant species later (Chazdon, 2014). Furthermore, most of the trees in the early stages of succession in shifting cultivation or young fallow fields have very different architecture, traits and biomass allocation compared to trees in undisturbed or logged forests. If disturbance cycles recur many times in the same area, re-sprouts or coppices become a common trait in these ecosystems (Fukushima et al., 2008; McNicol et al., 2015).

Active reforestation or forest restoration may also form another kind of secondary forest, at least temporarily. The well-known framework species method, adopted by Chiang Mai University's Forest Restoration Research Unit (FORRU-CMU), has been used to restore tropical forest ecosystems in Thailand and neighbouring countries. The framework species method of forest restoration involves planting mixtures of 20-30 indigenous tree species that rapidly re-establish forest structure and ecosystem functioning, including both pioneer and climax species (Elliott et al., 2013). Many framework species have been identified as suitable for restoring forest ecosystems in northern Thailand, such as *Archidendron clypearia*, *Balakata baccata*, *Castanopsis acuminatissima*, *C. tribuloides*, *Elaeocarpus lanceifolius Bischofia javanica*, *Erythrina subumbrans*, *Gmelina arborea*, *Heynea trijuga*, *Hovenia dulcis*, *Melia toosendan*, *Nyssa javanica*, *Prunus cerasoides*, *Sapindus rarak*, *Sarcosperma arboretum*, *Spondias axillaris* (FORRU, 2005).

Secondary forests provide important ecological services and economic benefits. They play an essential role in biodiversity conservation (Chan et al., 2016), and have great potential to re-absorb considerable amounts of the CO_2 emitted by deforestation (Kenzo et al., 2009). However, carbon accounting in tropical forests remains uncertain, due to unknown amounts of deforestation and forest degradation (Malhi, 2010), and a limited number of studies of tree biomass estimation and carbon content in secondary forests (Mukul et al., 2016). Again, more accurate methods to estimate above-ground biomass and carbon sequestration in secondary forests and restoration projects are needed, in particular to meet the requirements and activate the pay-out mechanisms of REDD+ (IPCC 2006; Chan et al., 2013).

2.5 Forest classification

The natural forests of northern Thailand have been classified by several systems. Forest areas above 1000 m are classified as hill evergreen forest, based on Royal Forest Department reports (1950, 1962), cited in Maxwell and Elliott, (2001). The secondary forest type, found in the shifting cultivation highland area of Mae Chaem watershed, was classified as hill evergreen forests by Royal Forest Department system (RFD), based on an altitude of over 1000 m. This term has also been used in previous studies (Khamyong et al. 1999; cited in Thomas et al., 2004, Ruankeaw et al., 2004, Junsongdaung et al., 2014).

Maxwell and Elliott (2001) proposed another system for forest classification in Thailand, based on seasonality, vegetational structure, floristic composition, elevation, and developmental state, such as primary, secondary, and tertiary. Forest degradation affects the vegetation: evergreen species are replaced by deciduous species and weeds that may grow at higher elevations than their normal habitat (Maxwell and Elliott, 2001). Consequently, forests above 1000 m that have been disturbed are classified as evergreen scrub (sea level – *c.* 1800m), evergreen + bamboo (eg/bb) and/or deciduous dipterocarp-oak forest (dof) which consist of deciduous species more than 80 percent (1000 – *c.* 2565m) , that may grow where primary forests, such as lowland evergreen, teak forest and bamboo + deciduous seasonal forest (bb/df) or mixed evergreen + deciduous, seasonal forest (mxf), have been disturbed (Maxwell and Elliott, 2001).

Moreover, Santisuk et al. (2012) classified natural forest in Thailand according to climatic, edaphic, elevation and biotic characteristics. As a result, forests in an altitude of 1000 - 1900 meter were classified as lower mountain rain forest. The Fagaceae family, with species such as *Castanopsis* spp. and *Lihocarpus* spp., are commonly found in this forest type. Today, the primary lower montane rain forest have been disturbed in many areas in northern Thailand. Consequently, it is instead classified as secondary lower montane forest, such as lower montane oak forest or lower montane pine-oak forest. The lower montane oak forest mostly consist of tree species in Fagaceae, Taeaceae and Lauraceae, such as *Castanopsis acuminatissima, C. diversifolia, C. tribuloides, Lithocarpus elegans, L. polystachyus, Quercus kingiana, Q. lamellosa, Q. semiserrata*

(Fagaceae), *Anneslea fragrans, Schima wallichii* (Theaceae), *Beilschmiedia gammieana, Phoebe* spp. (Lauraceae), *Helicia nilagirica, Heliciopsis terminalis* (Proteaceae), *Engelhardtia spicata* var. *spicata* (Juglandaceae), *Albizia chinensis* (Leguminosae-Mimosoideae), *Dalbergia cultrata* (Leguminosae- Papilionoideae), *Bauhinia variegata* (Leguminosae–Caesalpinioideae), *Wendlandia tinctoria* (Rubiaceae), *Antidesma acidum, Aporosa villosa, Phyllanthus emblica* (Euphorbiaceae), *Styrax benzoides* (Styracaceae), and *Markhamia stipulata* var. *kerrii* (Bignoniaceae).

2.6 Carbon sequestration

Forest carbon is one of the most important carbon sequestration mechanisms in the terrestrial ecosystems. Forest ecosystems can reduce the effect of greenhouse gas emissions and help mitigate climate change by converting carbon dioxide to organic forms of carbon through the process of photosynthesis, and subsequently transfer carbon into vegetation biomass, detritus and soil pools. This storage of carbon in plant tissue, litter and soil is called biological carbon sequestration. (FAO, 2006; Lorenz and Lal, 2010). The carbon sequestration capacity of forests is enormous – globally, they store more than 650 GtC: 289 GtC in the biomass (44%), 72 GtC in dead wood and litter (11%) and 292 GtC in soil (45%) (FRA 2010). It has been shown that tropical forests absorb and store carbon dioxide more efficiently than other ecosystems (Chave et al., 2005). In addition, tropical forests have the greatest potential to act as sinks for carbon dioxide if appropriately managed (Brown et al., 1997).

Carbon sequestration also transfers atmospheric carbon dioxide into other long-lived pools. According to the IPCC, five carbon pools within terrestrial ecosystems are: above-ground biomass, below-ground biomass, dead mass of litter, woody debris and soil organic matter (IPCC, 2007; Lal, 2008). The above-ground living biomass of trees constitutes the major portion of the total above-ground carbon pool in tropical forest ecosystems, which is also the most important and visible carbon pool of the terrestrial forest ecosystem, as well as the one most directly impacted by anthropogenic factors, such as deforestation and forest degradation (Malhi et al., 2009). Consequently, much of the carbon, lost during deforestation and other land-use changes in tropical forests, is offset by carbon sequestration in secondary forests following agricultural abandonment, as they have the potential to store large fractions (Kenzo et al., 2009; Chazdon, 2014).

Tropical secondary forests play an essential role in the global carbon cycle and in determining a country's carbon storage for the REDD+ scheme in developing countries (Gibbs et al., 2007; Kenzo et al., 2010). Thus, biomass and carbon estimation in above-ground secondary forests or fallow forest is an interesting and highly important step in quantifying carbon stocks in tropical forests (Hashimoto et al., 2004; Gibbs et al., 2007; Ravindranath and Ostwald, 2008). Secondary forests after shifting cultivation can be carbon neutral or positive compared to monocrop tree-based plantations, paddy fields and permanent fields (Takeuchi, 2012; Yuen et al., 2013; Dressler et al., 2015). Also, the capacity to store carbon increases with the fallow age, as large trees provide most of aboveground biomass (Mukul et al., 2016).

As a general rule, when calculating carbon storage, dry biomass can be converted to carbon content by assuming that 50% of the biomass is made up by carbon or half of the dry weight of above-ground living biomass (Brown, 1997; Dixon et al., 1994). In tropical forests, the proportion of carbon in the biomass is about 47% (IPCC, 2006). Occasionally, carbon has been measured with a direct method by burning samples in a carbon analyser (CN analyzer, CHN analysis or CNS Elemental Analyzer) (Tsutsumi et al., 1983; Djomo et al., 2011). These studies showed that the average carbon content in different tree parts was 49.9% in stems, 48.7% in branches and 48.3% in leaves (Tsutsumi et al., 1983). The average carbon content in all wood biomass was 46.53% in moist tropical forest (Djomo et al., 2011), 48.77% in secondary dry dipterocarp forest (Hanpattanakit et al., 2016), and 44.67% in restoration upland evergreen forest (Jantawong et al., 2017).

2.7 Aboveground biomass and carbon sequestration estimation

Biomass estimation methods

2.7.1. Destructive method

There are two major field measurement methods to evaluate biomass. The first one is the destructive method or harvest method, which is the most precise way to estimate biomass and carbon. This method involves harvesting all trees, drying and weighing the biomass of the different components (e.g. stem, branches, leaves, flowers, fruits, roots) and subsequently perform carbon analysis to measure the content of the various components. Although this method determines the biomass accurately for a specific area, it is also more time consuming, labour intensive, expensive, and sometimes illegal (Gibbs et al., 2007, Djomo et al., 2010, Yuen et al., 2016). It is also impossible to use for a large-scale analysis that includes degraded forest containing threatened species (Montès et al., 2000). Usually, the destructive method is used to validate other methods, as well as for developing biomass equations or regression models for estimating biomass on a larger scale (Brown et al., 1989; Usoltsev and Hoffmann, 1997; Basuki et al 2009; Devi and Yadava, 2009).

Many studies have assessed the tree biomass and forest inventory data with the destructive method and then used the data to create allometric equations. There are several existing sets of allometric equations developed for a number of tropical forest types in Southeast-Asia, as well as for some areas where the focus is already on biomass accumulation and carbon content in land-use systems. One example is tropical secondary forest regeneration after the land has been disturbed in shifting/swidden/slash-and-burn cultivation areas. Ketterings et al. (2001) proposed an allometric equation based on 29 trees, including tree height and wood density for calculating the biomass of trees in the mixed secondary forest of Sumatra, Indonesia. Hashimato et al. (2004) developed allometric equations for the dominant pioneer species, other pioneer tree species, and all species combined by harvesting a total of 191 trees. Basuki et al. (2009) developed a regression model in lowland mixed dipterocarp forests in East Kalimantan, Indonesia, by collecting samples from 122 trees and using diameter at breast height (DBH), commercial bole height (CBH), and wood density (WD) as predictors for dry weight of total above-ground biomass (TAGB). Kenzo et al. (2009) created allometric equations for tropical secondary forest in Sarawak, Malaysia, by harvesting 136 individuals, also using DBH and H as predictor parameters. Chan et al., (2013) proposed above-ground allometrics of swidden cultivation fallows in mixed deciduous forests, Myanmar, by harvesting 160 trees, again using DBH and H data to estimate above-ground biomass. McNicol et al., (2015) also proposed models from swidden cultivation fallows in Laos. A total of 150 trees were harvested and the study found that a model including DBH and H was best for estimating the biomass.

Recently, many allometric equations in Vietnam have been developed to estimate forest biomass and support carbon national measuring, reporting, and verification systems. Since Vietnam already participate in the REDD+ program, they need to report the state of their forest resources in the form of a national database (Huy et al., 2016a; Kralicek et al., 2017). Huy et al. (2016b) developed a set of equations based on 222 trees to estimate tree aboveground biomass (AGB) in dipterocarp forests in Vietnam using DBH, H, and WD as input variables. Nam et al. (2016) provided equations for aboveground biomass (AGB) based on 300 trees in evergreen forest the central highland zone of Vietnam. The study used the same input variables and the same parameters as Huy et al. (2016b), which were found to be important parameters for the AGB model. In the same area, Kralicek et al. (2017) created equations from 175 destructive trees for dipterocarp forests and evergreen broadleaf forests in the central highlands of Vietnam, using DBH, H, WD, and adding crown area (CA) as predictor parameters (Goodman et al., 2014; Huy et al., 2016b; Kralicel et al., 2017).

Presently, the wood density (WD) parameter has received much focus in above-ground allometric equations. It has been demonstrated that WD is an important predictor, and that adding it as a model variable improves the quality of AGB estimation (Baker et al., 2004; Chave et al., 2005; Basuki et al., 2009; van Breugel et al., 2011; Chaturvedi et al., 2012; Chave et al., 2014; Nam et al., 2016; Kralicek et al., 2017).

There are some confusion between two terms that have been used in previous ecologist research, namely wood specific gravity (WSG) (Chave et al., 2005; van Breugel et al., 2011; Chaturvedi et al., 2012; Rutishauser et al., 2013; Chave et al., 2014) and basic wood density (WD) (Basuki et al., 2009; Nam et al., 2016; Huy et al., 2016b; Kralicel et al., 2017). Both terms actually refer to the same thing, i.e. oven dry mass (103°C) divided by green volume or saturated volume, not air-dry wood density (g/cm^3) (Chave et al., 2005; Basuki et al., 2009; Kralicel et al., 2017). Since air-dried wood moisture content may vary, it is more practical to use oven-dried wood with 0% moisture content for biomass and carbon accounting (Donegan et al., 2014).

In wood science, however, wood specific gravity is not the same as density. Foresters actually define wood density as the mass (m) of a wood per unit volume (v) (g/m^3, kg/m^3 or lb/ft^3), which can be measured at any moisture content. Some confusion occurs because foresters define specific gravity as the ratio of wood density to the density of water (D_{water}), where volume determined for the same moisture content states and specific gravity is unitless (Williamson and Wiemann, 2010).

$$WD = \frac{m_{dry}}{v_{fresh}}$$

$$WSG = \frac{WD}{D_{water}}$$

As the density of water is 1 g/cm^3 or 1 ton/m^3 in ambient conditions, the WSG and WD would produce the same value, regardless if WD is expressed in g/cm^3 or ton/m^3, as long as they are measured at the same moisture content.

Furthermore, Williamson and Wiemann (2010) also mention a common error in recent publications where samples were not oven dried properly at temperatures below 100°C. They point out that a correct oven drying procedure requires a temperature of 101–105°C since wood contains both free water and bound water, and bound water cannot be driven off at less than 100°C. They also urge researchers to explain or carefully cite the source of their chosen method.

There are two ways to access wood density data. One way is to use direct measurement by collecting wood samples either by coring with an increment borer (Djomo et al., 2011; Nam et al., 2016) or cutting a pie or cylinder shape from a felled tree (Basuki et al., 2009; Kralicek et al., 2017). The basic wood density value is then calculated by using a geometrical method or a water displacement method (Chave, 2006; Donegan et al., 2014). Another way to access wood density values is to simply consult the Global Wood Density Database, which contains data collected from various species from all over the world (Zanne et al., 2009). The Global Wood Density Database contains more than 8412 taxa (1638 genera, 191 families) of trees (Chave et al., 2014), and an online data of international database in Tree Functional Attributes and Ecological Database (http://db.worldagroforestry.org//wd) is also available (Huy et al., 2016a). However, it represents only about 10% of the estimated 100,000 tree species in the world, and the massive majority of tree species that remain unmeasured are tropical (Williamson and Weimann, 2010).

Some studies in Thailand have used the direct method and established sets of allometric equations to estimate above-ground biomass in several forest types. A review from Yuen et al. (2016) gathered all allometric models in South-east Asia. In total, 52 allometric equations were found in Thailand for forests (n=11), mangrove forests (12), economic orchards and tree plantations (25), and bamboo (4). Nevertheless, there is no reported allometric equation based on any secondary forest type in the review, which used the term “swidden fallow of any length”.

The well-known equations of different forest types in Thailand were created by using the relationship between biomass and DBH, H and tree biomass. Allometric equations for multi-species of mixed deciduous forest were created by Ogawa et al. (1965). In this study, a total of 119 trees were harvested, 45 of which were felled at Ping Kong, Chiang Mai Province, and the remaining 74 sampled from a tropical rain forest at Khao Chong, Trang Province of peninsular Thailand. Multi-species and species-specific equations have also been developed for dry evergreen forest in Nakhon Ratchasima, northeast Thailand (Sabhasri et al., 1968). Viriyabuncha et al. (1996) cut 11 trees in both mixed deciduous forest and dry deciduous forest in Kanchanaburi, and created basal area (BA) as a parameter to estimate the biomass. The same study also suggested another equation, for which a total of 50 trees were cut, using BA as a parameter for all broadleaved forest stand, which includes mixed deciduous forest, dry dipterocarp forest, dry evergreen forest, tropical rain forest, and hill evergreen forest all over Thailand.

Another forest model created in Thailand that were not included in the review by Yuen et al. (2016) was created by Ogino et al. (1967), who established allometric equations for deciduous dipterocarp forest in Nakhon Ratchasima by harvesting 25 trees, and for dry evergreen forest in Chaiyaphum Province, northeast Thailand, harvesting a total of 60 trees (Tsutsumi et al., 1983). Recently, allometric equations for secondary dry dipterocarp forest were created by collecting 18 trees from five dominant species in Ratchaburi province in the west of central Thailand (Hanpattanakit et al., 2016).

An alternative method is the partial harvest method or semi-destructive measurement. It is a viable choice when cutting down the whole tree is not allowed and for very large trees that are too difficult to be fully weighed in the field. This method consists of measuring both trimmed fresh biomass and untrimmed fresh biomass to calculate tree volume, density and biomass (Snowdon et al., 2002; Picard et al., 2012; Jantawong et al., 2017).

2.7.2 Non-destructive method

The non-destructive method, estimates the biomass of trees without felling. Use of allometric equations is the most widely used non-destructive method; the favourite of many ecologists and an often-used tool in ecological research for estimating biomass. It was developed from the direct method by creating relationships among various physical parameters of trees, such as the diameter at breast height (DBH), height, crown diameter, species, wood density, etc. to assess forest biomass (Martin et al., 1998; Djomo et al., 2011). Allometric equations have been developed for specific species and for different mixtures of species to assess biomass at specific sites and for large-scale assessments (Vashum and Jayakumar, 2012). Many researchers use non-destructive methods and allometric equations to estimate biomass (Jampanin, 2004; Terakunpisut et al., 2007; Pibumrung, et al., 2008). This method based on tree allometric equations together with forest inventories has been widely used for biomass estimation (Yuen et al., 2016; Lin et al., 2017).

Some studies have developed equations from secondary data by gathering and re-analysing destructive samples from previous studies. A well-known study developed allometric models of 170 trees in tropical forests, based on data collected by several authors, from different tropical countries and at different times, with the tree diameters ranging from 5 to 148 cm (Brown, 1997). Pan-tropic models were created by collecting 27 published and unpublished datasets to develop equations from tropical forests across three continents: America, Asia, and Oceania, based on 2410 trees (Chave et al., 2005). Similarly, 4004 trees from 58 sites, spanning a wide range of climatic conditions and vegetation types (DBH range= 5-212 cm) were used to establish allometric models from undisturbed forests, including a few secondary forests (Chave et al., 2014). Both of these studies include DBH, total tree height and wood density as variable parameters in the equations as well. Even though these equations were based on data gathered from many forests in tropical countries, including a few studies in Southeast Asia, e.g. Cambodia, Indonesia, and Malaysia, no data from Thailand was used. This means that the allometric equations, produced from analysing big dataset, do not yet apply to Thailand.

In previous studies, two different allometric models estimated the total aboveground biomass. The first used aboveground biomass (AGB) directly as a dependent parameter and the set of data, such as DBH, H, WD etc., as independent parameters. The second approach used different components of the trees, such as stem, branches, and leaves, as dependent parameters and, again, DBH, H, WD etc. as independent parameters, which means that total biomass can be derived by adding the biomass from each equation. According to Yuen et al. (2016), the second model should be chosen with care, when establishing allometric equations, since it may introduce correlated errors in the biomass estimates. As a result, instead of doing an ordinary least squares regression (OLS) analysis of the data, a seemingly unrelated regression (SUR) should be used instead, to account for correlated errors.

The following allometric equations have been widely used to estimate tree biomass in tropical forests. The most well-known models, based on big datasets, are Chave et al. (2005) and Chave et al. (2014). The Chave et al. (2014) study added more data from both dry and wet forest types. In the Chave et al. (2005) study, only three dry forest sites that included tree height were analysed.

Allometric equation for dry forest stands (below 1,500 mm/ year, over 5 months of dry season) (Chave et al., 2005):

If height (H) is available;

$$AGB = \exp\,(-2.187 + 0.916 \times \ln(DBH^2HWD)$$

$$\equiv 0.112(DBH^2HWD)^{0.916}$$

Here, the symbol ≡ indicates mathematical identity: both formulas can be used in the biomass estimation procedure.

If the total tree height (H) is not available;

$$AGB = WD \times \exp\,(-0.667 + 1.784\ln(D) + 0.207(\ln(D))^2 - 0.0281(\ln(D))^3)$$

Chave et al. (2014) produced a pantropical model, adding temperature and precipitation variables when height is not available:

If height (H) is available;

$$AGB = 0.0673(DBH^2HWD)^{0.976}$$

If the total tree height (H) is not available;

$$AGB = \exp\,[-1.803 - 0.976E + 0.976\ln(WD) + 2.674\ln(D) - 0.299(\ln(D)^2]$$

Where; E is defined as

$$E = (0.178 \times TS - 0.938 \times CWD - 6.61 \times PS) \times 10^{-3}$$

Where; TS is temperature seasonality, CWD is climatic water deficit, and PS is precipitation seasonality

The two most well-known allometric equations used in Thailand are:

Mixed deciduous forest (Ogawa et al., 1965);

$$W_s = 0.0396(DBH^2H)^{0.9326}$$

$$W_b = 0.003487(DBH^2H)^{1.027}$$

$$\frac{1}{W_l} = \frac{28}{W_s + W_b} + 0.025$$

Tropical rain forest and dry evergreen forest in Thailand (Tsutsumi et al., 1983);

$$W_s = 0.0509(DBH^2H)^{0.919}$$
$$W_b = 0.00893(DBH^2H)^{0.977}$$
$$W_l = 0.0140(DBH^2H)^{0.669}$$

Where; DBH is diameter at breast height (cm), H is total tree height (m), WD is wood density (g/cm^3), AGB is aboveground biomass (kg), W_s, W_b and W_l are the dry weights of the stem, branches, and leaves, respectively, of a tree (kg)

In addition, many studies in Thailand that have assessed carbon sequestration in natural forests by using allometric models to estimate biomass and carbon. Jampanin and Gajaseni (2004) studied carbon sequestration in above-ground biomass in mixed deciduous forest, dry evergreen forest and tropical rain forest at Kaeng Krachan National Park, Thailand. Above-ground biomass was estimated using allometric equations (Ogawa et al., 1965; Tsutsumi et al., 1983), while above-ground carbon sequestration rates were calculated by using a multiplying conversion factor of 50% of biomass. Terakunpisut et al., (2007) also used the same method and equations to estimate biomass and carbon sequestration in different forest ecosystems in Thong Pha Phum National Forest in the west of central Thailand. The greatest potential for carbon sequestration is in mixed deciduous forests, followed by tropical rain forest and dry evergreen forest. Khamyong (2009) evaluated the carbon in several forest types at Doi Suthep-Pui National Park in Chiang Mai, northern Thailand. The study found the highest value in dry evergreen forest, followed by hill evergreen forest, and the lowest in dry dipterocarp forest. Furthermore, Pibumrung et al., (2008) estimated the carbon at various sites, which were based on field data collected in the Nam Yao sub-watershed in northern Thailand. The greatest amount of stored above-ground carbon was found in mature forests, followed by reforestation and agricultural land, respectively. Carbon sequestration varied in different types of forests. Habitat variability caused differences in biomass accumulation, species composition and allometric relationships (Terakunpisut et al., 2007).

Another common non-destructive method to estimate biomass and carbon stocks is to use satellite-based or remote-sensing techniques (Houghton, 2005), such as Light

Detection and Ranging (LiDAR) and optical satellite data such as Landsat. The LiDAR system sends out pulses of laser light and measures the signal return time to directly estimate the height and vertical structure of forests (Patenaude et al., 2004; Fernández-Landa et al. 2017), map the AGB (Mohd Zaki et al., 2016) and estimate timber volume (Abd Rahman et al., 2017). The LiDAR technology enables increasingly detailed and large scale assessments of spatial variation in above-ground biomass, and may be used to map thousands of hectares of forest per day to quantify environmental controls over forest carbon storage (Asner et al., 2009). In addition, Chisholm et al., (2013) have tested an unmanned aerial vehicle (UAV) LiDAR technique for mobile below-canopy forest surveys. Although efficient, the use of airborne LiDAR may be cost-prohibitive (Savage et al., 2018).

As an alternative, freely accessible imagery form Landsat may be used to estimate carbon stocks. Presently, Landsat offers large-scale availability in medium resolution and has been widely used for above-ground biomass or carbon estimation (Lu et al., 2012; Wu et al., 2016; Askar et al., 2018). These datasets facilitate timely biomass or carbon estimation on a regional scale (Gibbs et al., 2007; Wulder et al., 2012). Landsat imagery is enhanced by applying vegetation indices that combine the reflectance and absorption of different wavelength bands. For example, near infrared light (NIR) is reflected by mesophyll tissue inside leaves, while red light is absorbed by chlorophyll (Gasparri et al., 2010). The most commonly used vegetation index is normalised difference vegetation index (NDVI), which shows a good correlation with vegetation data such as tree biomass, green biomass, and chlorophyll content, and may be used to estimate biomass and productivity in both grassland and forest (Gasparri et al., 2010; Zhu et al., 2015). Suitable variables from the multispectral bands are selected for establishing biomass or carbon estimation equations by using multiple regression analysis, which is the most popular for model development (Lu et al., 2012). Gasparri et al. (2010) used spectral data of Landsat 7 ETM+ as independent variables to create a regression model to estimate biomass in subtropical dry forests of Argentina, while Aisyah et al. (2016) used Landsat 8 OLI for above-ground biomass estimation for hill dipterocarp forest in Malaysia. In Thailand, vegetation indices from Landsat 5 TM has been used in combination with biomass and carbon data calculation from field measurements to create the above-ground models for carbon estimation in each forest type of the Mae Tuen Wildlife Sanctuary, Tak province

(Boonsang and Arunpraparat, 2011). However, remote–sensing techniques and allometric models are both important and should be linked together, and calibration with field data is still preferred for more accurate estimation of forest above-ground biomass and carbon stocks (Gibbs et al., 2007; Asner et al., 2010).

CHAPTER 3

Materials and methods

3.1 Materials

3.1.1 Vegetation survey

1) Study area map
2) Compass
3) Global Positioning System (GPS)
4) Measuring tapes
5) DBH tapes
6) Tree calliper
7) Digital clinometers

3.1.2 Wood density

1) Increment borers (core diameter 5.15 mm)
2) Plastic straws
3) Ropes
4) Zip lock bags
5) Paper bags
6) Oven

3.1.3 Field sample preparation for destructive technique

1) Chain saw
2) Hand saw
3) Scales 7 kg and 60 kg
4) Digital scales (2 decimals) 600 g and 2000 g
5) Measurement tape
6) Tree calliper

7) Plastic/paper bags

8) Wax pencil

3.1.4 Biomass

1) Drying room at 6th floor, Science Building 1, Chiang Mai University

2) Oven

3) Digital scales (2 decimals) 600 g and 2000 g maximum

4) Paper box

3.1.5 Carbon content

1) Blender

2) Power jigsaw

3) Sieve 2 mm

4) Zip lock bags

5) CHN Analyser equipment: LECO CHNS-932 and VTF-900

3.2 Study site

The highlands of northern Thailand are characterised by steep mountains with slopes exceeding 35%, interspersed with narrow valleys. The watershed covers most of Mae Cheam district in Chiang Mai province. The highland area of Mae Cheam is well known for its variety of plant species and vegetation types (Thomas et al., 2004; Junsongdaung et al., 2014). For generations, the various high-land ethnic communities have practiced a number of different land-use systems in Mae Cheam watershed, such as paddy fields in the valleys, and shifting cultivation or slash and burn on the slope areas. Today, some of these traditional practices have been replaced with permanent agriculture.

This study was performed at shifting cultivation areas in Ban Ho village (18°27'24.7"N 98°10'51.2"E), Pang Hin Fon Sup-District, Mae Chaem watershed, Chiang Mai Province, Thailand (Figure 3.1). The study sites (60m x 60m at each land use category) were divided into three categories: (4-5 years old) (4Y), (7-8 years old) (7Y), and secondary forest (SF) (approximately 50 years old) (Figure 3.2). The 4Y and 7Y sites were scheduled to be cleared in March 2018 by the local villagers in preparation for rice cultivation (Figure 3.3). Ban Ho village is inhibited by indigenous hill-tribe people from the Lawa ethnic community. For many decades, they have practiced traditional shifting cultivation for their livelihood, mostly with upland rice. This means that they slash and burn existing vegetation, cultivate their crops for one year and then leave the land for natural vegetation succession. The next year, they move to another fallow for the next rotation cycle site. They return to crop in the previously-cropped areas after a few years.

When fallow areas are prepared for cultivation, trees are cut about 1-1.5 m or more above the ground. Some big trees may be left standing as relict emergents because their trunks are too thick or their wood too hard to be easily cut (Figure 3.2 at 7Y site). This is a common characteristic of shifting of cultivation areas. Coppice or sprouting is another regeneration process often found in fallow areas of shifting cultivation (Rerkasem et al., 2009; Wangpakapattanawong et al., 2010). In this study, coppicing trees were frequent in the 4Y and 7Y sites (Figure 3.4).

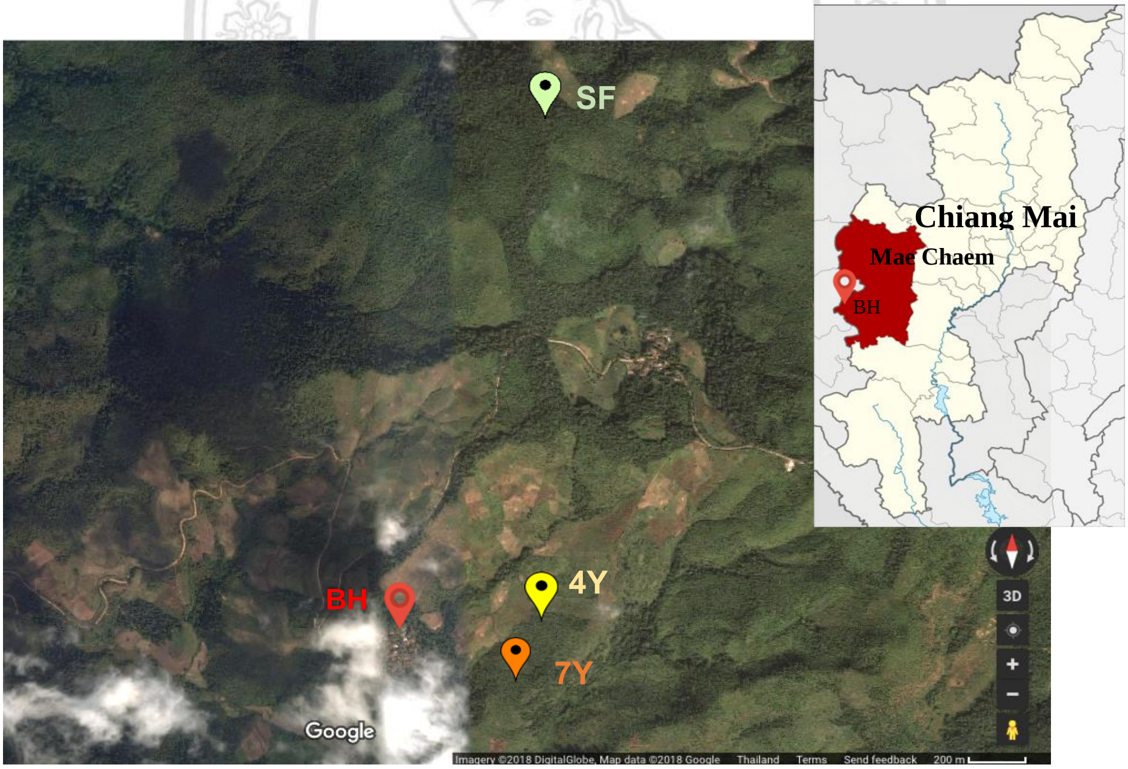


Figure 3.1 The study area in Ban Ho Village (BH), showing the three study sites: 4-year-old-fallow (4Y), 7-year-old-fallow (7Y), and Secondary forest (SF). Map of Chiang Mai province, Thailand, highlighting the district Mae Chaem © 2009 Wikimedia commons. Satellite imagery © 2018 DigitalGlobe.

4-year-old-fallow (4Y), slope 21° W

7-year-old-fallow (7Y), slope 32° W

Secondary forest (SF), slope 28° W

Figure 3.2 The three study sites: 4-year-old-fallow (4Y), 7-year-old-fallow (7Y) and Secondary forest (SF).

Figure 3.3 The 4-year-old-fallow (4Y) and 7-year-old-fallow (7Y) before (top) and during slash and burn (middle), and during cultivation period (bottom).

Figure 3.4 Coppicing stems commonly found in the 4Y and 7Y fallow areas, showing many new stems growing from one stump.

The elevation of the study sites ranged between 1050 to 1270 m above sea level. Based on the elevation, the natural forests of northern Thailand have been classified by several systems. Forest areas above 1000 m are classified as hill evergreen forest, based on Royal Forest Department reports (1950, 1962), cited in Maxwell and Elliott, (2001). The secondary forest type, found in the shifting cultivation highland area of Mae Chaem watershed, was classified as hill evergreen forests by Royal Forest Department system (RFD), based on an altitude of over 1000 m. This term has also been used in previous studies (Khamyong et al. 1999; cited in Thomas et al., 2004, Ruankeaw et al., 2004, Junsongdaung et al., 2014). Furthermore, according to the vegetation, elevation and disturbed history, this forest type could be called as evergreen scrub Maxwell and Elliott, (2001), which also supported by 51 percent of all species in this study were recorded as evergreen species. Moreover, it is known as lower montane oak forest, a secondary regeneration forest after the lower montane forest was disturbed (Santisuk, 2012). However, based on the climate, the forest may also be classified as ‘dry forest’ (precipitation below 1500 mm/year, over 5 months dry season) according to Brown (1997) and Chave et al. (2005). The mean annual temperature is 26.4 °C, while the average annual rainfall in the last decade was 980 mm, ranging from 525 to 1442 mm. These climate data were obtained from Northern Meteorological Centre, Chiang Mai measured in Mae Chaem District (the nearest spot with available data) between 2007 and 2017 (Figure 3.5-3.6).

According to village elders, the fallow rotation period used to be around 10 to 12 years only a few decades ago. As the population density increased in the village, larger cultivation areas were needed for each family and there was not enough land to respect fallow periods of this length. In response to the need for more areas for active cultivation, the fallow rotation period on most fields has been reduced to approximately 4 to 6 years. Some of the shifting cultivation areas have also been changed from rotation crops to permanent commercial cash crops, such as corn or cabbage (Figure 3.7). The same trend is seen in nearby villages, where they have started to grow corn and shortened the fallow periods to maximum 3 years.

In the past, the Secondary forest site (SF) was part of a shifting cultivation area, but approximately 50 years ago the villagers decided to leave this area for fire protection. Since the shifting cultivation stopped, the secondary forest has regenerated. However, the villagers continue to use the forest for their livelihood, e.g. by collecting fire wood, herbs, food, and etc. (data based on interviews of village elders, informants).

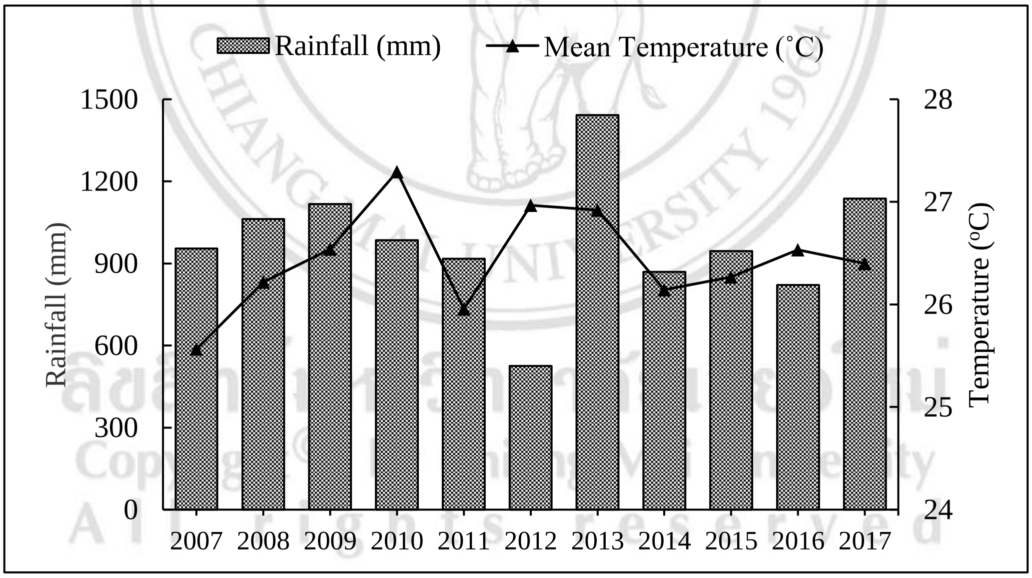


Figure 3.5 The mean annual temperature (°C) and rainfall (mm) 2007-2017, Mae Chaem District, Chiang Mai Province.

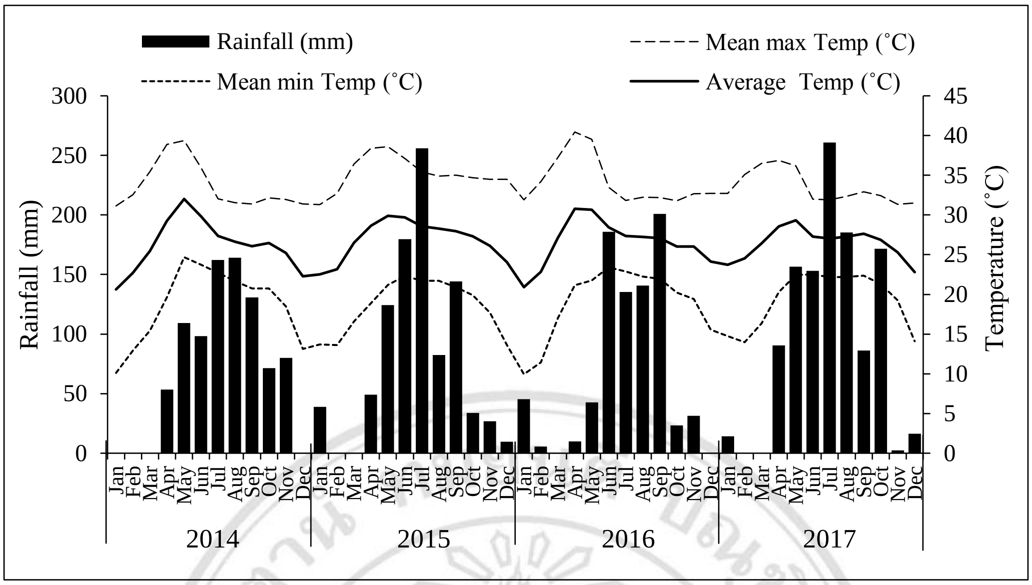


Figure 3.6 Average monthly temperature (°C) and monthly rainfall (mm) 2014-2017, Mae Chaem District, Chiang Mai Province.

Figure 3.7 Ban Ho village area: permanent corn crop and shifting cultivation.

3.3 Sampling design

3.3.1 Tree species composition

Each study site (4Y, 7Y, and SF) was divided into three sampling plots of 20 m x 60 m (1200 m^2), resulting in nine plots in total. The sampling plots of each site were drawn parallel to the contour lines in three positions (lower, middle, upper slopes). diameter at breast height (DBH), and height (H) were recorded for all trees with DBH ≥ 1 cm in each plot. Plant composition was assessed using the Shannon-Wiener index, Shannon-Wiener evenness, species richness, ecological importance value index (IVI), and Sorensen's similarity index.

Shannon-Wiener index

$$H = -\sum_{i=1}^{s}(P_i) \quad P_i$$

Shanon-Wiener evenness

$$E_H = H/H_{max}$$

Evenness Equitability assumes a value between 0 and 1 with 1 being complete evenness.

Where; H = Shannon-Weiner index
S = number of species
P_i = proportion of total sample belonging to ith species
E_H = evenness equitability
H_{max} = InS

Importance Value Index (IVI)

This index is used to determine the overall importance of each species in the community structure. In calculating this index, the percentage values of relative frequency (RF), relative density (RD), and relative dominance (RDo) are summed up together, and this value is designated as the Importance Value Index or IVI of the species (Curtis, 1959).

$$RF = \left(\frac{Frequency\ of\ a\ species}{Sum\ frequency\ of\ all\ species}\right) \times\ 100$$

$$RD = \left(\frac{Number\ of\ individuals\ of\ a\ species}{Total\ number\ of\ individuals}\right) \times\ 100$$

$$RDo = \left(\frac{Total\ basal\ area\ of\ a\ species}{Total\ basal\ area\ of\ all\ species}\right) \times\ 100$$

$$IVI = RF + RD + RDo$$

The value of IVI ranges from 0 to 3.00 (or 300%). By dividing IVI by 3, a number ranging from 0 to 1.00 (or 0-100%) is produced. This value is referred to as the importance percentage. The importance value, or the importance percentage, gives an overall estimate of the influence of importance of a plant species in the community

Sorensen's similarity index

Indices of similarity and dissimilarity were calculated using Sorensen's (1948) formula as follows:

$$Index\ of\ similarity\ (S) = \frac{2C}{A + B}$$

Where; A = Number of species in the community A

B = Number of species in the community B

C = Number of common species in both communities.

3.3.2 Aboveground biomass

i) Selection of trees for harvesting

Trees were selected for harvesting using three different criteria. First, according to plant data analysis, individual trees of all tree species representing up to 50 percent of the accumulated IVI values from plant data analysis in each study site were randomly selected and harvested in different DBH class sizes. Second, three of the tree species that were presented in each study site were harvested. Third, all species belonging to the FORRU framework species grouping found at any study site were selected for harvesting.

Field sample preparation

ii) destructive method

The method for this study part was applied from Viriyabuncha (2003); Walker et al. (2012); Picard et al. (2012), based on a reasonable choice for more optimal and efficient work in the field. The overall procedure of the destructive method is explained in Figure 3.8.

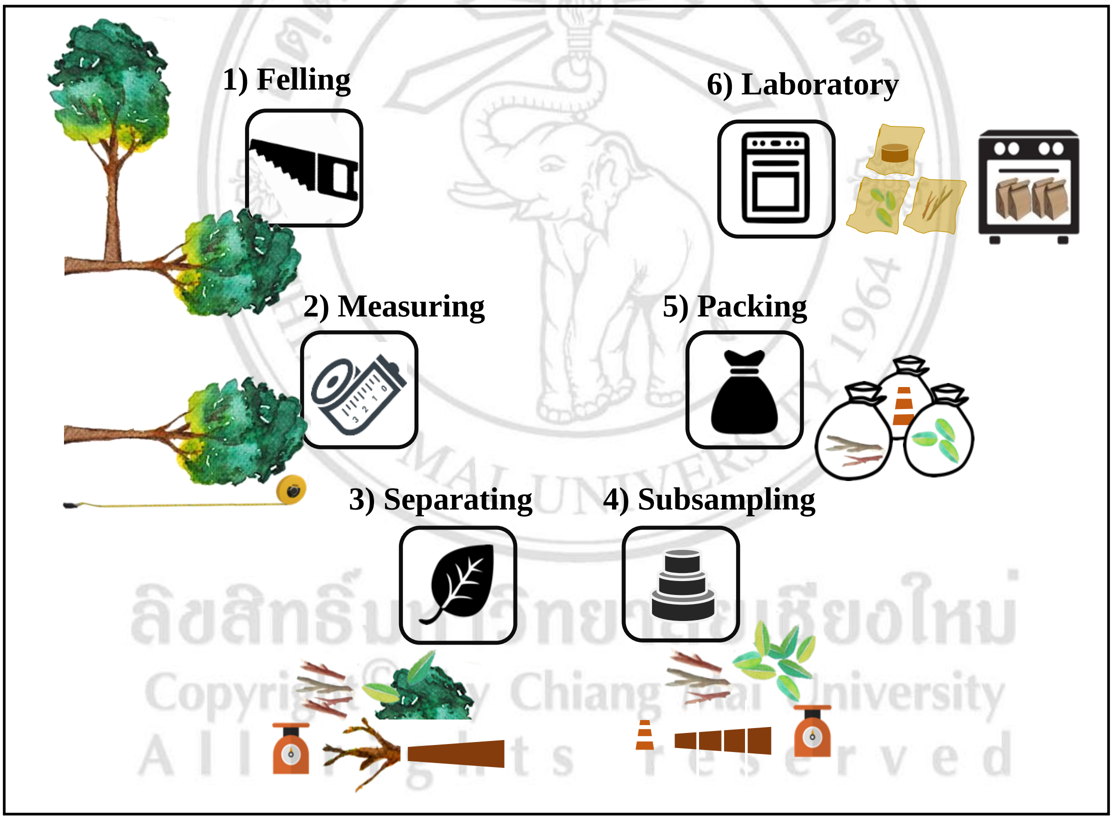


Figure 3.8 Aboveground biomass measurement in 6 steps. 1) felling of selected trees, 2) profile measurement of felled trees, 3) stripping of leaves, separating stem, branches, and weighing, 4) cross cutting stem, subsampling and weighing all samples, 5) packing and labelling, and 6) laboratory measurements.

1. Felling

According to the three criteria above, individual trees were randomly selected and harvested in five different DBH class sizes; class I: DBH<4.5 cm, class II: 4.5<DBH≤10 cm, class III: 10<DBH≤20 cm, class IV: 20<DBH≤40 cm, and class V: 40<DBH≤60 cm. At the 4Y site, the trees were cut starting from Class I, while the trees in the 7Y and SF sites started from Class II. The trees were cut at ground level, as close to the soil as possible. The trees were harvested from March 2015 to October 2016. Permission for cutting the trees was obtained from Chiang Mai Provincial Offices for Natural Resources and Environment in the form of personal communication.

Care was taken when trees were felled to prevent them from getting jammed or lose any part. This made the process very time-consuming. (Figure 3.9).

Figure 3.9 Tree felling in the field. On the left, a small tree is cut using a hand saw (big trees were cut with a chain saw). On the right, even with an experienced crew, some trees were challenging to be harvested.

2. Measuring

After cutting down each tree, the following tree parameters were measured (Figure 3.10):

a) Total height of felled tree (Ht in m)

b) Diameter at ground level (D_0 in cm)

c) Diameter at breast height (DBH at 1.3 meters in cm)

d) Diameter at first branch (D_b in centimetres)

After measuring stem profiles, each log was labelled at every meter (Figure 3.10), starting from the base (D_0) and all the way up to the top of the tree stem, including stem, branches, and leaves. For the straight trees, the main stem could easily be identified. For stems that were very twisted or branched, the largest diameter at each fork in the trunk had to be identified to choose and label the main stem according to the principal axis. All branched axes on the main stem were considered to be branches. Some pictures from the field work can be found in Figure 3.11.

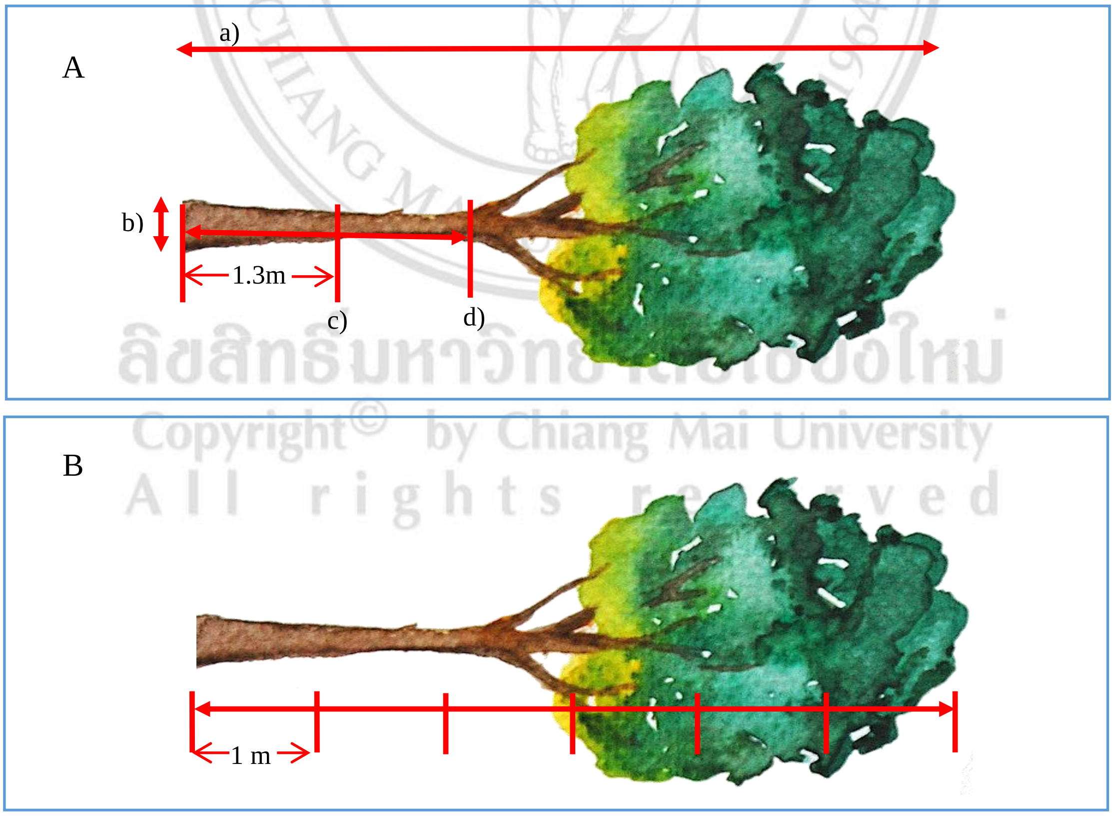


Figure 3.10 (A) Location of measurements following cutting down of tree, (B) Labelling at every meter from base to the top.

Figure 3.11 Measurement the tree profile in the field.

3. Separating and weighing

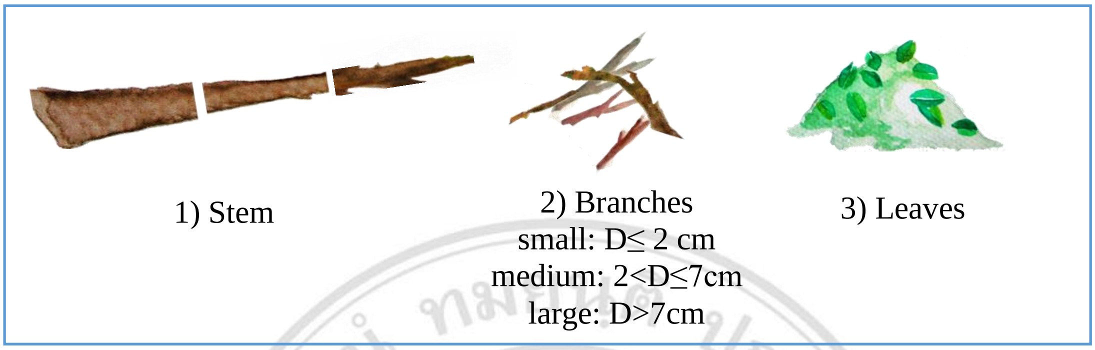
After measuring the tree profiles at one metre intervals, the tree was separated into three parts; 1) stem, 2) branches, and 3) leaves (Figure 3.12).

1) Stem circumferences were measured at every meter. Cross-cutting into one metre logs started from the base (D_0) and continued to the top of tree stem, following the main stem (Figure 3.13). Any branch and leaf on the one metre logs were removed and separated from the main logs. The logs were then labelled and the fresh weight of each log were recorded (Figure 3.14).

2) Branches removed from the main logs were divided according to tree height profile and labelled. The branches were split into three diameter (D) groups (Class 1: small branches $D \leq 2$ cm, Class 2: medium branches $2<D\leq7$ cm, and Class 3: big branches $D>7$ cm) (Figure 3.14). The fresh weight of each group was recorded for all the tree branches.

3) All tree leaves were fresh weighed and recorded according to the tree height profile.

Each sample was weighed using spring scales with a capacity of 7 and 60 kg and an accuracy of 20 and 100g, respectively. A digital scale (2 decimal) was used for samples that were too small or light for an accurate reading on one of the mechanical scales.


1) Stem

2) Branches
small: D≤ 2 cm
medium: 2<D≤7cm
large: D>7cm

3) Leaves

Figure 3.12 Separating trees into stem, branches and leaves


Figure 3.13 Cutting stem in one metre logs in the field.

Figure 3.14 (A) Stripping leaves and removing branches from stem onto tarpaulin, (B) collecting and labelling the one metre logs, (C) separating branches according to stem profile and stem classes, and (D) recording the fresh weight of all samples.

4. Subsampling

Every one-metre stem log was cross-cut at the base to create 3-5 cm thick discs at one-metre intervals along the stem (Figure 3.15-3.16). For trees taller than 10 m, disc samples were collected for every two metres for practical reasons (too heavy to bring back to the laboratory, limited drying room and oven space). The discs were freshly weighed and recorded, and disc dimensions (diameter and thickness) were measured to estimate volume (Figure 3.17). All the disc samples were labelled and prepared for transport to laboratory.

After recording the fresh weights of the branches, all the branches in each class were carefully mixed and a subsample of no less than 800 g for each diameter class was drawn for further analysis. Similarly, all the leaves were carefully mixed and subsampled. Leaf subsamples of approximately 800 g or more were drawn and packed for transportation. To avoid sampling bias, all the subsamples were taken by the same person. For smaller trees where the individual tree part weighed less than 800 g, all harvested parts were brought back for further analysis (Figure 3.18).

The same method was used for the coppiced trees by considering each coppice as an individual stem. Subsamples of all parts were collected in the field.

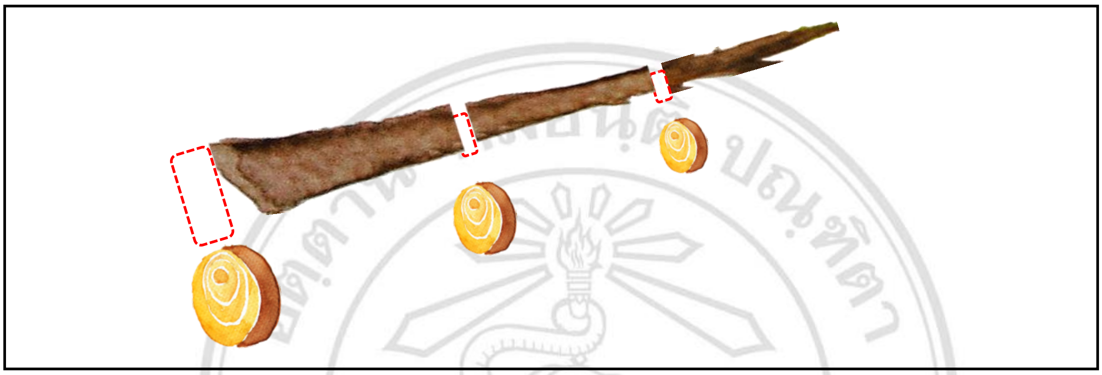


Figure 3.15 Taking disc samples from different part of stem.

Figure 3.16 Cross-cutting discs (left and middle). On the right, labelled disc.

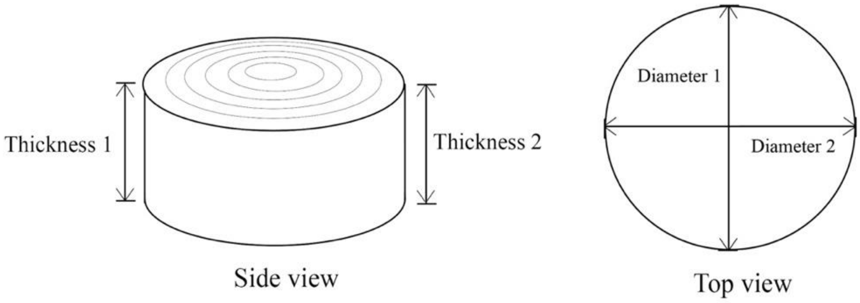


Figure 3.17 Measuring disc dimensions for volume estimation.

5. Packing

All stem, branch, and leaf subsamples were labelled, packed into plastic bags and brought back to the laboratory (Figure 3.19). When it was not possible to return collected subsamples to the laboratory immediately, the subsample bags were left open to allow air drying and avoid mould growth and rotting (Figure 3.20).

Figure 3.18 Mixing branches and leaves before subsampling, and fresh weighing subsamples (discs, branches, and leaves).

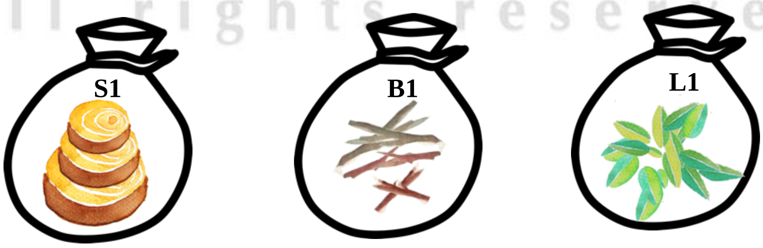


Figure 3.19 Placing the subsamples in plastic bags and labelling to make sure that tree samples were not mixed up.

Figure 3.20 Air-drying samples before returning to laboratory.

iii) Laboratory measurement

6. Drying and weighing samples

All the fresh subsamples of stems, branches and leaves were air-dried in a drying room for approximately one week before discs, branches, and leaves were packed separately into carefully labelled paper bags in preparation for oven-drying (Figure 3.21). The leaf samples were oven-dried at 70°C until reaching constant weight (at least 48 hours), while woody samples were dried at 105°C to constant weight (one to two weeks, depending on sample size). Subsequently, each dried sample was weighed and recorded. After weighing, all the dried samples were stored in labelled paper boxes awaiting the next step, i.e. carbon analysis (Figure 3.22).

The recorded dry weights represented the biomass of the individual subsamples. These values were converted to biomass for the individual trees using the following formulae:

Stem dry weight (Ws)

$$\text{Dried log}_i = \frac{\text{Dried disc sample}_i \text{ x Fresh log}_i}{\text{Fresh disc sample}_i}$$

$$\text{Ws}_i \text{ (kg)} = \text{Sum of Dried log}_i$$

Small branch dry weight (Wsb)

$$Wsb_i\ (\text{kg}) = \frac{\text{Dried small branch sample}_i \times \text{Fresh small branch}_i}{\text{Fresh small branch sample}_i}$$

Medium branch dry weight (Wmb)

$$Wmb_i\ (\text{kg}) = \frac{\text{Dried medium branch sample}_i \times \text{Fresh medium branch}_i}{\text{Fresh medium branch sample}_i}$$

Big branch dry weight (Wbb)

$$Wbb_i\ (\text{kg}) = \frac{\text{Dried big branch sample}_i \times \text{Fresh big branch}_i}{\text{Fresh big branch sample}_i}$$

All branch dry weight per tree (Wb)

$$Wb\ (\text{kg/tree}) = Wsb+Wmb+Wbb$$

Leaves dry weight (Wl)

$$Wl_i\ (\text{kg/tree}) = \frac{\text{Dried leaves sample}_i \times \text{Fresh leaves}_i}{\text{Fresh leaves sample}_i}$$

The total dry weight of a tree or aboveground biomass (AGB) was obtained by summing the dry biomass of the stem (Ws_i), branches (Wb_i), and leaves (Wb_i);

$$AGB_i\ (\text{kg/tree}) = Ws_i+Wb_i+Wl_i$$

Figure 3.21 Air-drying samples in laboratory.(A) air-drying samples in the drying room, (B) packing samples in paper bags, (C) packed and labelled samples, ready to be oven dried.

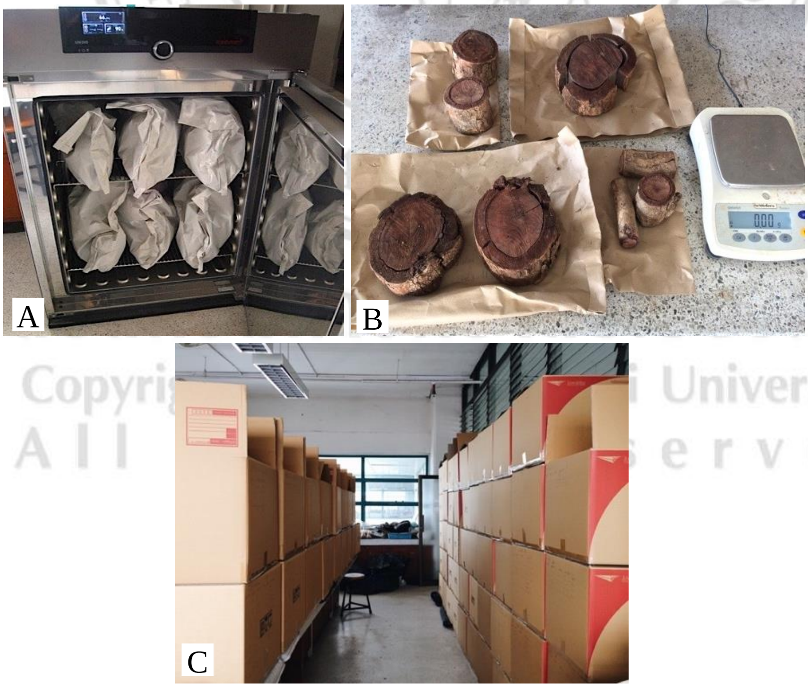


Figure 3.22 (A) oven-drying samples, (B) weighing and recording each dried disc samples, and (C) storing dried samples in paper boxes at 6th floor, Science Building (SCB1), Chiang Mai University.

3.3.3 Wood density

Wood density samples were collected using two methods: increment borer and disc samples.

i) WD field measurement

Increment borer

An increment borer (diameter = 5.15 mm) was used to collect 1 core samples from every tree species in 7Y and SF by collecting the core samples approximately deep half of the tree . However, this method was not practical for the 4Y site since the tree diameters were too small to use an increment borer. The trees in each of the three sites were divided according to diameter size into five DBH classes: class I: DBH≤ 4.5 cm, class II: 4.5≤DBH≤10 cm, class III: 10<DBH≤20 cm, class IV: 20<DBH≤40 cm, and class V: 40<DBH≤ 60 cm. Three core samples were collected in Class II for each tree species, as well as three core samples within Class III-V (sampling method depended on trees at the study sites). All the core samples were immediately placed in plastic straws, labelled and brought back to laboratory (Figure 3.23).

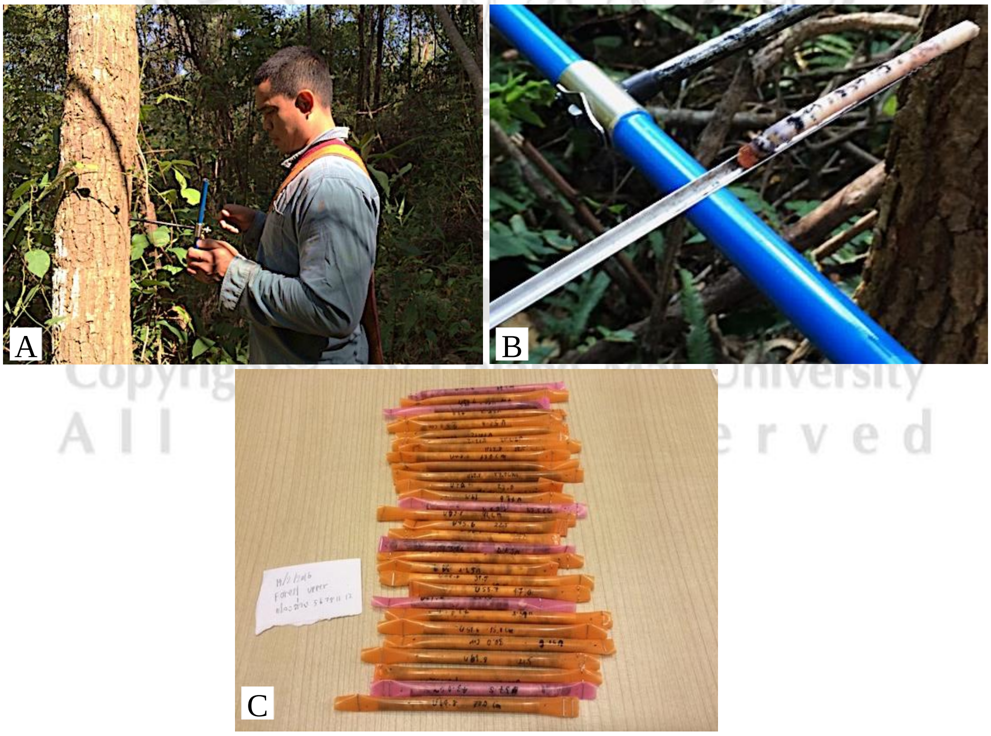


Figure 3.23 Collecting WD samples in the field. Using increment borer (A and B). Storing core samples in plastic straws (C).

Disc

Disc subsamples collected from the three sites using the destructive method (see 4 Subsampling) were also used to calculate WD. Discs from selected tree species were collected and fresh disc dimensions (Figure 3.17) were measured in the field. Due to insufficient tree diameters, only the disc method was used to collect wood samples in the 4Y site.

ii) WD laboratory measurement

Increment borer

Wood density measurement and calculation followed Chave (2006) and Donegan et al. (2014). Each core sample was measured and fresh core volume was calculated assuming a regular cylindrical shape by the following formula;

$$V_{fresh} = \frac{\pi}{4} D^2 L$$

Where V_{fresh} is green volume (cm^3)

D is diameter of sample (cm)

L is length of sample (cm)

Disc

As mentioned above, fresh disc dimensions were measured in the field. The fresh disc dimension data (see Figure 3.17) were used to calculate disc volume by the following equation:

$$Volume = \pi \times \left(\frac{D_1 + D_2}{2} \Big/ 2 \right)^2 \times \left(\frac{T_1 + T_2}{2} \right)$$

Where; Volume = volume of disc sample (cm^3)

D_1 = first diameter of sample (cm)

D_2 = second diameter of sample (cm)

T_1 = first thickness of sample (cm)

T_2 = second thickness of sample (cm)

In the laboratory, all the wood samples were air dried in a drying room and subsequently oven dried at 105°C to constant weight (core samples app. 48 hours; disc samples app. 1 week). After weighing the dried discs, wood density was calculated as:

$$WD = \frac{m_{dry}}{v_{fresh}}$$

Where; WD is wood density (g/cm^3)
m_{dry} is oven-dried mass (g)
V_{fresh} is green volume (cm^3)

iii) WD calculation

Average WD for each species was calculated and the results from the two methods were compared. Next, the WD data from this study were compared with the Global Wood Density database (GWD). Wood density data from this study were then used as predictor parameter for allometric model development.

3.3.4 Carbon analysis

After oven drying, three randomly chosen dried disc, branch, and leaf samples from each destructive tree was ground and sieved. Approximately 150 mg of each sample was prepared. Tree discs were ground with a power jigsaw (Figure 3.24). The ground discs from each tree were mixed and weighed to create three separate samples to allow for replication. Randomly chosen dried branches in different class sizes were ground using a power jigsaw. Three samples were chosen from each class. Finally, dried leaf and fruit samples were randomly chosen and pulverized with a blender (Figure 3.25). Again, three ground samples of each destructive tree were prepared. All the ground samples were collected in zip lock bags, labelled, and sent for carbon analysis using an elemental analyser: LECO CHNS-932 and VTF-900 at Scientific Equipment Center, Kasetsart University, Bangkok, Thailand. After receiving the results of the carbon analysis, the carbon concentration of each tree was calculated from biomass data from this study, and compared with the carbon content from previous studies.

Figure 3.24 Grinding disc and branch samples. (A) Grinding disc samples using a power jigsaw. (B) Ground disc samples. (C) Grinding branch samples. (D) 150 mg ground disc samples in each zip lock bag.

Figure 3.25 (A) Grinding leaves and fruits samples using blender. (B) Leaves, and fruits samples 150 mg in zip lock bags.

3.3.5 Model development and validation

i) Model development and selection

The power equation is a mathematical function and logarithmic transformation using a natural logarithm, and is regularly used to fit an allometric equation with ordinary least squares regression (OLS) (Basuki et al., 2009; Djomo et al., 2010; Picard et al., 2012; Done et al., 2016; Nam et al., 2017).

The power equation:

$$Y = a X^{b} + \varepsilon$$

The transformation of natural logarithm:

$$\ln Y = \ln a + b \ln X + \varepsilon$$

Where; Y is the response variable (dry biomass) in kg
X is the predictor variable (DBH, H… etc.)
a is the y-intercept of the line, b its slope
ε is the regression error.

In this study, several allometric models were developed, based on common equations from previous studies, including relationships such as aboveground biomass (AGB) to diameter at breast height (DBH), height (H), wood density (WD) from forest inventory data. First, models were developed with AGB as a dependent variable and DBH as the only independent variable. Next, H or WD variables were added. Both H and WD were added to the model. Then, combination variables DBH^2H or DBH^2HWD, which have been tested and commonly used in previous studies, were added to the model.

Mixed-species (all trees) allometric models were developed and the best-fit model and variables were selected based on the coefficients of determination (R^2), P-values, residual standard error of the estimate (RSE), average deviation (S%), and Akaike Information Criterion (AIC). The regression model with the highest R^2, lowest RSE, S% AIC and fewest parameters is regarded as the best-fitting model (Basuki et al., 2009; Chave et al., 2005; 2014; Djomo et al., 2010; Huy et al., 2016b; Lin et al., 2017; Nam et al., 2016). The transformation introduced a systematic bias in the calculation which was adjusted by the correction factor (CF) when back-transforming the calculation into biomass (Chave et al., 2005; Basuki et al 2009; van Breugel et al., 2011; Picard et al., 2012; Nam et al., 2016).

Table 3.1 Allometric model description in previous studies.

No.	**Input variable**	**Model**	**Source**
I	DBH	ln(AGB) = *a* + *b* ln(DBH)	Brown et al., 1997
II		ln(AGB) = *a* + *b* ln(DBH) + *c* (ln(DBH))^2	IPCC, 2003
III	DBH and H	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(H)	Basuki et al., 2009
IV	DBH and WD	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(WD)	Djomo et al., 2010
V	DBH^{2}H	ln(AGB) = *a* + *b* ln(DBH^{2}H)	Djomo et al., 2010
VI	DBH^{2}H and WD	ln(AGB) = *a* + *b* ln(DBH^{2}H) + *c* ln(WD)	Djomo et al., 2010
VII	DBH^{2}HWD	ln(AGB) = *a* + *b* ln(DBH^{2}HWD)	Chave et al., 2005,2014
VIII	DBH, H and WD	ln(AGB) = *a* + *b* ln(DBH)+ *c* ln(H) + *d* ln(WD)	Chave et al., 2005

where; model: '*a*', '*b*', '*c*', and '*d*' are the coefficient values of the allometric regression models. DBH, H, WD indicate diameter at breast height, tree height and wood density, respectively.

$$S\% = \frac{100}{n}\sum_{i=1}^{n}\frac{|\hat{y}_i - y_i|}{y_i}$$

Where S% is the average deviation, $\hat{y}_i$ is observed dry weight of tree i, y_i is the predicted dry weight of tree i, and n is number of observations. The best fit regression is the one with the lowest S% (Basuki et al., 2009; Chave et al., 2005).

ii) Model validation and comparison

The destructive dataset was randomly split 200 times into training data (80%) used for model development and validating data (20%) used for model testing. The cross-validation statistics were computed for each iteration of randomly selected data, and averaged over the 200 realizations. The models were validated and compared by validation of percent bias (Bias), root mean square percentage error (RMSE) and mean absolute percent error (MAPE), three measures used to forecast error. Bias may be positive or negative, and indicates the tendency to either overestimate or underestimate AGB. RMSE is the standard deviation of the residuals, and measures how spread out the data is around the line of best fit. MAPE, finally, measures the percentage accuracy of a forecast, and is calculated as the average absolute percent error for each time period minus actual values divided by actual values. Smaller values of all these indicators are preferred. After model selection, validation, and comparison, the final parameters of the selected models were fitted with the entire dataset (Huy et al., 2016a; Kralicek et al., 2017). All statistical analyses (regressions and tests) in this study were performed R version 3.5.2 (R Core Team 2018).

$$\text{Bias (\%)} = \frac{1}{R}\sum_{r=1}^{R}\frac{100}{n}\sum_{i=1}^{n}\frac{y_i - \hat{y}_i}{y_i}$$

$$\text{RMSE (\%)} = \frac{1}{R}\sum_{r=1}^{R} 100\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{y_i - \hat{y}_i}{y_i}\right)^2}$$

$$\text{MAPE (\%)} = \frac{1}{R}\sum_{r=1}^{R}\frac{100}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i}$$

Where R is number of resampling (200); n is number of trees per resampling r, and y_i and $\hat{y}_i$ are observed and predicted biomass for the ith tree in each resampling data set.

CHAPTER 4

Results

4.1 Tree species composition

Rarefaction curve showed the expected species richness with standard deviation by sampling individuals within 36 plots or 3600 m^2. The species richness still increased in the Secondary forest (SF) site. The rarefaction curve showed more stable numbers in the 7-year-fallow (7Y) and the 4-year-fallow (4Y). The highest number of the individuals was shown in the 4Y, followed by the SF, and the lowest number was found in the 7Y site (Figure 4.1). A total of 86 genera, 47 families, and 118 species (including 1 bamboo species; *Gigantochloa albociliata*) were recorded in the three study sites (10,800 m^2). In total, 1,840 trees and 3,612 individual all stems with DBH $\geq$ 1 cm were found. The numbers of trees species, trees and total basal area increased with the age of the fallow, the highest being in the secondary forest (SF) site. The same trend was also observed for trees with DBH $\geq$ 4.5 cm. However, stem density (stems/ha) showed the opposite pattern, with the highest values found in the youngest 4Y site and the lowest in SF. Except for DBH $\geq$ 4.5 cm, the highest number of stems were found in the 7Y, followed by SF and 4Y, respectively (Table 4.1).

The Shannon-Wiener and Shannon evenness indices showed the greatest diversity value in the SF site, while the lowest diversity was found in the 4Y site. Both diversity indices increased with the fallow age. Percentage similarity (Sørensen’s index) between paired-plot showed more similarity between the 4Y and the 7Y sites. Percentage of similarity was lower than between the fallow sites and the SF.

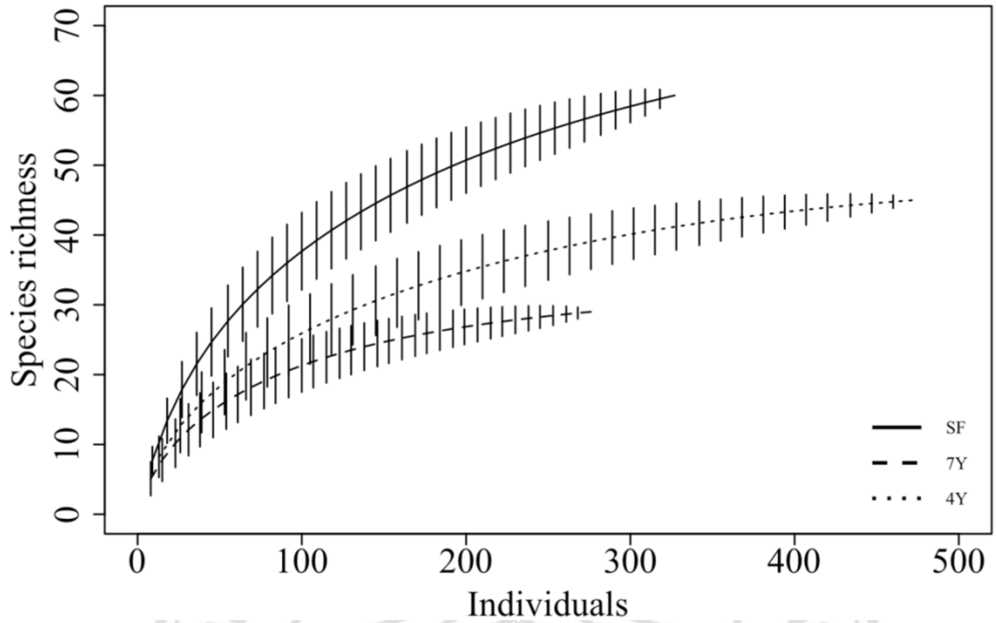


Figure 4.1 Rarefaction curves showing the expected species richness with standard deviations of the 4-year-fallow (4Y), the 7-year-fallow (7Y), and the Secondary forest (SF).

Table 4.1 Vegetation composition at the study sites.

Study site		4-year-fallow (4Y)	7-year-fallow (7Y)	Secondary forest (SF)
Elevation (m)		1090	1120	1254
DBH ≥1 cm	No. of species	43	44	80
	No. of trees	470	678	692
	All individual stems	1791	1045	776
	Coppice	1321	367	84
	Density (stems/ha)	4975	2903	2156
	Basal area (m^2/ha)	4.05	10.99	24.94
	Shannon-Wiener diversity	2.8	2.99	3.74
	Shannon Evenness	0.74	0.79	0.85
DBH ≥4.5 cm	No. of species	21	30	60
	No. of tree	79	278	327
	All individual stems	196	435	353
	coppice	117	157	26
	Density (stems/ha)	544	1208	981
	Basal area (m^2/ha)	1.65	10.09	24.51
	Shannon-Wiener diversity	2.09	2.40	3.52
	Shannon Evenness	0.69	0.71	0.86
Sørensen’s index (%)	4Y	-	55	36
	7Y		-	29
	SF			-

Aporosa villosa had the highest Importance Value Index (IVI) in the 4Y, *Quercus kingiana* in the 7Y and *Castanopsis tribuloides* in the SF. Moreover, *Lithocarpus polystachyus* was found in every site with high IVI values. Fagaceae was the most common family, represented by *Lithocarpus polystachyus* in all sites, *Quercus kingiana* in the 7Y, and *Castanopsis diversifolia*, and *C. tribuloides* in the SF. The number of tree, basal area and IVI values of each species in every study site showed in Appendix A. Table 4.2 present the species that accounted for at least 50% of the cumulative relative IVI score in each site All of them were selected for allometric model development.

Table 4.2 Relative Importance Value Index (%IVI) of the dominant species, and relative cumulative IVI in 4-year-fallow (4Y), 7-year-fallow (7Y), and Secondary forest (SF)

Site	**Species name**	**Thai name**	**Family**	**%IVI**	**Cumulative %IVI**	**Rank**
4Y	*Aporosa villosa*	เหมือดโลด	Phyllanthaceae	17.9	17.9	1
	Lithocarpus polystachyus	ก่อนก	Fagaceae	17.4	35.3	2
	Phyllanthus emblica	มะขามป้อม	Phyllanthaceae	8.9	44.2	3
	Ilex umbellulata	เน่าใน	Aquifoliaceae	6.1	50.4	4
7Y	*Quercus kingiana*	ก่อแดง	Fagaceae	39.4	39.4	1
	Lithocarpus polystachyus	ก่อนก	Fagaceae	9.3	48.6	2
	Dalbergia cultrata	กระพี้เขาควาย	Leguminosae	6.8	55.4	3
SF	*Castanopsis tribuloides*	ก่อใบเลื่อม	Fagaceae	10.5	10.5	1
	Schima wallichii	ทะโล้	Theaceae	9.9	20.4	2
	Castanopsis diversifolia	ก่อแป้น	Fagaceae	9.4	29.8	3
	Lithocarpus polystachyus	ก่อนก	Fagaceae	8.3	38.0	4
	Canarium subulatum	มะกอกเกลื้อน	Burseraceae	5.4	43.4	5
	Albizia chinensis	กางหลวง	Leguminosae	3.8	47.2	6
	Helicia nilagirica	เหมือดคนตัวผู้	Proteaceae	3.7	50.9	7

The IVI values in the 4Y include trees with DBH ≥ 1 cm, while trees with a DBH ≥ 4.5 cm were analysed for the 7Y and the SF.

The highest number of stems was found in the smallest DBH class (1-10 cm), the number decreased with increasing DBH class (Figure 4.2). A majority of the stems had a DBHs of 1-10 cm in 4Y site, and 1-20 cm in the 7Y site. As expected, the highest range, with a DBH between 1–60 cm, was found in the SF site. A small number of trees with DBHs of 20-60 cm, had survived from previous slash and burn, were found in the 4Y and the 7Y sites; the number and species of these trees are shown in Table 4.3.

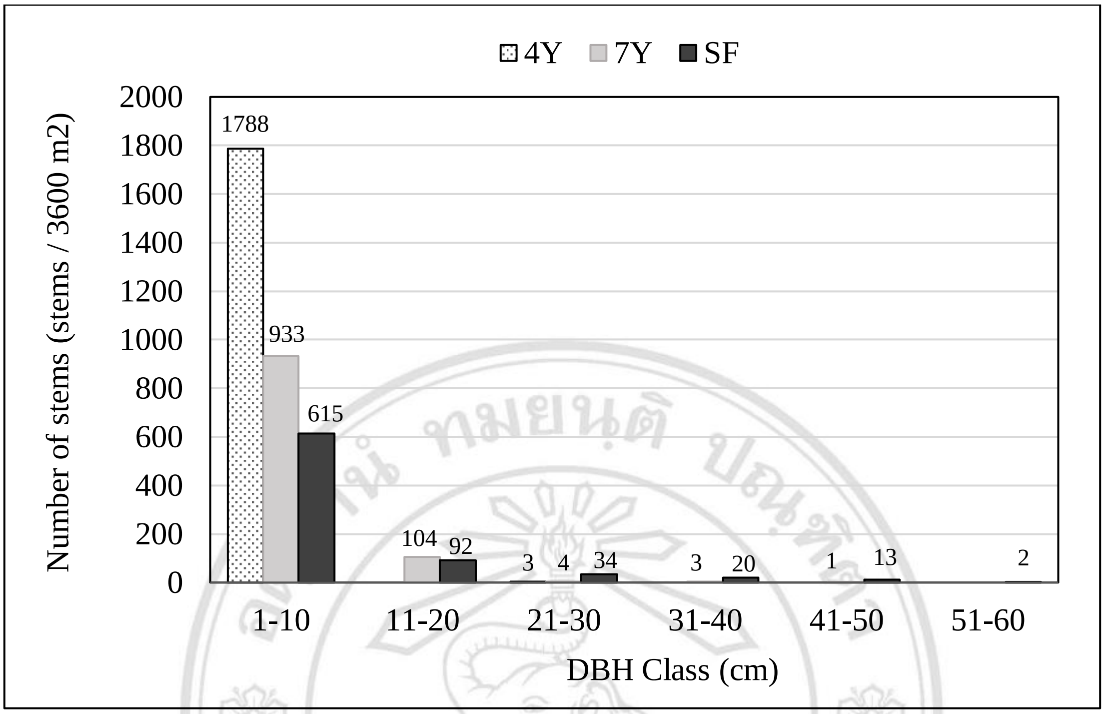


Figure 4.2 The distribution between DBH class size (cm) and number of trees (stems/3600 m^2) in the 4-year-fallow (4Y), the 7-year-fallow (7Y), and the Secondary forest (SF).

Table 4.3 The species name and number (n) of trees left standing in the 4-year-fallow (4Y) and the 7-year-fallow (7Y)

DBH Class	Site	Species name	Thai name	n
20-30 cm	4Y	*Schima wallichii*	ทะโล้	2
		Eugenia fruticosa	หว้าขี้กวาง	1
	7Y	*Quercus kingiana*	ก่อแดง	3
		Erythrina subumbrans	ทองหลางป่า	1
30-40 cm	7Y	*Quercus kingiana*	ก่อแดง	2
		Lithocarpus polystachyus	ก่อนก	1
40-50 cm	7Y	*Quercus kingiana*	ก่อแดง	1

Basal area decreased with DBH size class in the 4Y and the 7Y sites, following the pattern of the number of stems. However, in the SF sites, the basal area was low in the smallest DBH class, but initially increased with the DBH class. In the SF site, the highest basal area was found in the DBH class 41-50 cm, after which it dropped following the stem pattern (Figure 4.3).

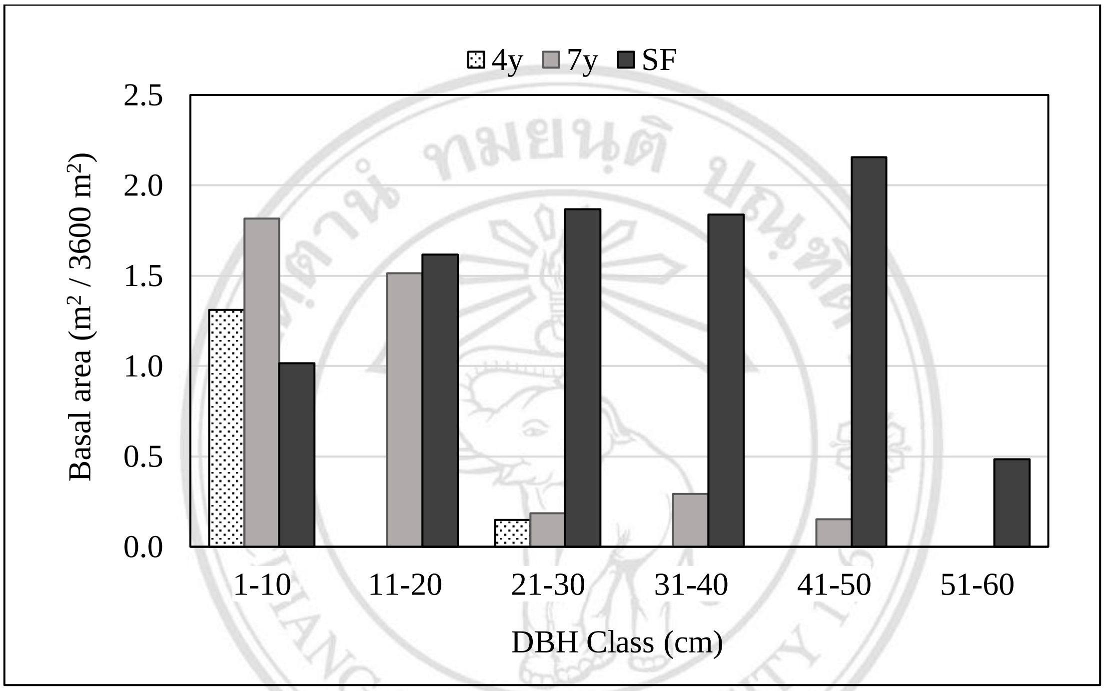


Figure 4.3 The distribution between DBH class size (cm) and basal area (m^2/3600m^2) in the 4-year-fallow (4Y), the 7-year-fallow (7Y), and the Secondary forest (SF).

4.2 Above-ground biomass

4.2.1 Harvested tree species

Harvested trees were selected from three different groups according to the plant diversity analysis; i) the IVI group – dominant species, that comprised cumulatively 50% of IVI (Table 4.2), ii) the S group – species present in all three study sites (Table 4.4), and iii) the F group – confirmed framework species, which are the list of species FORRU restoration method involves planting mixtures of 20 - 30 indigenous forest tree species that include both pioneer and climax species by following characteristics: i) high survival rate, ii) rapid growth, iii) dense, spreading crowns and iv) attractiveness to seed-dispersing wildlife. When these tree species planted on deforested land, help to re-establish the natural mechanisms of forest regeneration and accelerate biodiversity recovery (FORRU, 2005). Some framework species found in this study showed in Table 4.5.

Table 4.4 Tree species present all sites (S group).

S	Species name	Thai name	Family
1	*Aporosa villosa*	เหมือดโลด	Phyllanthaceae
2	*Canarium subulatum*	มะกอกเกลื้อน	Burseraceae
3	*Castanopsis acuminatissima*	ก่อเดือย	Fagaceae
4	*Eugenia fruticosa*	หว้าขี้กวาง	Myrtaceae
5	*Lithocarpus polystachyus*	ก่อนก	Fagaceae
6	*Phoebe lanceolata*	ตองหอม	Lauraceae
7	*Phyllanthus emblica*	มะขามป้อม	Phyllanthaceae
8	*Schima wallichii*	ทะโล้	Theaceae
9	*Styrax benzoides*	กำยาน	Styracaceae
10	*Wendlandia tinctoria*	แข้งกวาง	Rubiaceae

Table 4.5 Confirmed framework tree species (F group) (FORRU, 2005).

F	**Species name**	**Thai name**	**Family**
1	*Archidendron clypearia*	มะขามแป	Leguminosae
2	*Castanopsis acuminatissima*	มะกอกเกลื้อน	Burseraceae
3	*Castanopsis tribuloides*	ก่อใบเลื่อม	Fagaceae
4	*Erythrina subumbrans*	ทองหลางป่า	Leguminosae
5	*Eugenia fruticosa*	หว้าขี้กวาง	Myrtaceae
6	*Ficus fistulosa*	ชิ้งขาว	Moraceae
7	*Ficus hispida*	มะเดื่อปล้อง	Moraceae
8	*Heynea trijuga*	จางจืด	Meliaceae
9	*Quercus semiserrata*	ก่อกระดุม	Fagaceae
10	*Sapindus rarak*	มะซัก	Sapindaceae
11	*Sarcosperma arboreum*	มะยาง	Sapotaceae

For the IVI species, trees to harvest were determined based on DBH class. In the 7Y and the SF sites, three trees of each IVI species were collected in the DBH 4.5-10 cm class. This class was chosen because it contained a high number of individuals to facilitate replication, while making the harvesting process relatively uncomplicated. Three trees of each species in the DBH class were cut where density was highest. Finally, one tree per species in each of the bigger classes were harvested. However, the 4Y site contained only trees in the two smallest DBH classes. Also, the large amount of small coppicing trees made it difficult to select trees to harvest by considering the DBH classes, as in the 7Y and the SF sites. Therefore, the trees in the 4Y site were selected only from the two first DBH classes, with coppices included in both these 2 classes. Subsequently, 3 trees of each IVI species were collected, including every coppice of the selected trees. Furthermore, one tree of each species in the S and F groups were harvested at each study site.

After identifying which tree species to harvest, individual trees were randomly selected using the number assigned to each tree in the plant inventory data and a random number generator (at www.random.org). In some cases, a randomly selected tree could not be harvested (because it had died, fallen, been damaged by fire or been felled since the inventory, or it was simply too big to handle with the available infrastructure). In these cases, the next number on the list was selected, or when this was not possible, the best available alternative of that species was chosen. Harvested tree species, numbers of trees, and coppice samples from the different study sites are shown in Table 4.6-4.8.

Table 4.6 Number of destructively sampled trees (N) and total number of destructive trees including coppicing (numbers in parentheses) in 4-year-fallow

Group	**Family**	**Species name**	**Thai name**	**N**
1/S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	3 (16)
2/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	3 (14)
3/S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	3 (17)
4	Aquifoliaceae	*Ilex umbellulata*	เน่าใน	3 (7)
S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	1
S	Lauraceae	*Phoebe lanceolata*	ตองหอม	1
S	Theaceae	*Schima wallichii*	ทะโล้	1 (4)
S	Styracaceae	*Styrax benzoides*	กำยาน	1
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	1 (2)
S/F	Fagaceae	*Castanopsis acuminatissima*	ก่อเดือย	1 (2)
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	1 (4)
F	Moraceae	*Ficus fistulosa*	ชิ้งขาว	1 (3)
F	Moraceae	*Ficus semicordata*	มะเดื่อปล้องขาว	1 (2)
Total	10 Families	13 species		21(74)

Trees were harvested from three groups. The number (1, 2 and 3) signifies the rank in the IVI group, S consists of species present at every site, while F indicated framework tree species (FORRU, 2005).

Table 4.7 Number of destructively sampled trees (N) and total number of destructive trees including coppicing (numbers in parentheses) in 7-year-fallow.

Group	**Family**	**Species name**	**Thai name**	**N**
1	Fagaceae	*Quercus kingiana*	ก่อแดง	7 (8)
2/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	4 (5)
3	Leguminosae	*Dalbergia cultrata*	กระพี้เขาควาย	4 (4)
S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	1
S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	1
S/F	Fagaceae	*Castanopsis acuminatissima*	ก่อเดือย	1 (2)
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	1
S	Lauraceae	*Phoebe lanceolate*	ตองหอม	1
S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	1
S	Theaceae	*Schima wallichii*	ทะโล้	1 (2)
S	Styracaceae	*Styrax benzoides*	กำยาน	1 (2)
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	1
F	Fagaceae	*Quercus semiserrata*	ก่อกระดุม	1
Total	9 Families	13 species		25(30)

Trees were harvested from three groups. The number (1, 2 and 3) signifies the rank in the IVI group, S consists of species present at every site, while F indicated framework tree species (FORRU, 2005).

Table 4.8 Number of destructively sampled trees (N) in Secondary forest.

Group	**Family**	**Species name**	**Thai name**	**N**
1/F	Fagaceae	*Castanopsis tribuloides*	ก่อใบเลื่อม	4
2/S	Theaceae	*Schima wallichii*	ทะโล้	2
3	Fagaceae	*Castanopsis diversifolia*	ก่อแป้น	4
4/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	4
5/S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	4
6	Leguminosae	*Albizia chinensis*	กางหลวง	1
7	Proteaceae	*Helicia nilagirica*	ชิ้งขาว	4
S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	1
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	1
S/F	Lauraceae	*Phoebe lanceolata*	ตองหอม	1
S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	1
S	Styracaceae	*Styrax benzoides*	กำยาน	1
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	1
F	Leguminosae	*Archidendron clypearia*	มะขามแป	1
F	Sapindaceae	*Sapindus rarak*	มะซัก	1
F	Sapotaceae	*Sarcosperma arboreum*	มะยาง	1
Total	12 Families	16 species		32

Trees were harvested from three groups. The number (1, 2 and 3) signifies the rank in the IVI group, S consists of species present at every site, while F indicated framework tree species (FORRU, 2005).

In total, 78 trees (136 stems) representing 23 species, 19 genera, and 14 families were harvested and measured for aboveground biomass estimation in the three study sites. Tree diameter ranged from 1-32.9 cm and height from 2.1-19.3 cm. (Table 4.9). The most harvested species was *Lithocarpus polystachyus* (23 samples), followed by *Phyllanthus emblica* (19 samples) and *Aporosa villosa* (18 samples). In contrast, only one tree was harvested of *Albizia chinensis, Archidendron clypearia, Quercus semiserrata, Sapindus rarak, Sarcosperma arboretum* (Figure 4.4). The destructive samples, classified by DBH classes and H classes, is shown in Figure 4.5- 4.6.

Table 4.9 All destructive tree species from three study sites, number of trees (T), number of coppices (C), total stem samples (trees and coppices), DBH range in cm, and height (H) in cm

Species	Family	Tree (T)	Coppice (C)	Total (T+C)	DBH range (cm)	H range (cm)
Albizia chinensis	Leguminosae	1		1	21.6	19.3
Aporosa villosa	Phyllanthaceae	5	13	18	1.4-15.2	2.1-11.3
Archidendron clypearia	Leguminosae	1		1	5.9	5.9
Canarium subulatum	Burseraceae	6		6	2.7-30.9	3.8-15.1
Castanopsis acuminatissima	Fagaceae	2	2	4	5.1-11.1	4.1-7.3
Castanopsis diversifolia	Fagaceae	4		4	5.1-11.5	5.9-14.6
Castanopsis tribuloides	Fagaceae	4		4	4.8-15.3	6.5-16.5
Dalbergia cultrata	Leguminosae	4		4	5.2-10.8	5.0-8.9
Eugenia fruticosa	Myrtaceae	3	3	6	10.8-15.1	2.2-8.7
Ficus fistulosa	Moraceae	1	2	3	1.3-1.9	3.1-3.3
Ficus semicordata	Moraceae	1	1	2	2.1-3.3	3.9-4.0
Helicia nilagirica	Proteaceae	4		4	5.1-19.1	5.9-13.4
Ilex umbellulata	Aquifoliaceae	3	4	7	1-4.1	2.3-4.8
Lithocarpus polystachyus	Fagaceae	11	12	23	1-18.1	2.3-16.8
Phoebe lanceolata	Lauraceae	3		3	3.6-12.6	3.8-15.5
Phyllanthus emblica	Phyllanthaceae	5	14	19	1.8-13.1	3.3-10.7
Quercus kingiana	Fagaceae	7	1	8	6.9-32.9	4.9-13.6
Quercus semiserrata	Fagaceae	1		1	10.8	8.7
Sapindus rarak	Sapindaceae	1		1	16.2	15.5
Sarcosperma arboreum	Sapotaceae	1		1	6.1	7.2
Schima wallichii	Theaceae	4	4	8	2.2-17.8	3.9-17.0
Styrax benzoides	Styracaceae	3	1	4	4.1-10.5	5.3-8.2
Wendlandia tinctoria	Rubiaceae	3	1	4	1.4-8.5	2.8-11.7
23	**14**	**78**	**58**	**136**	**1-32.9**	**2.1-19.3**

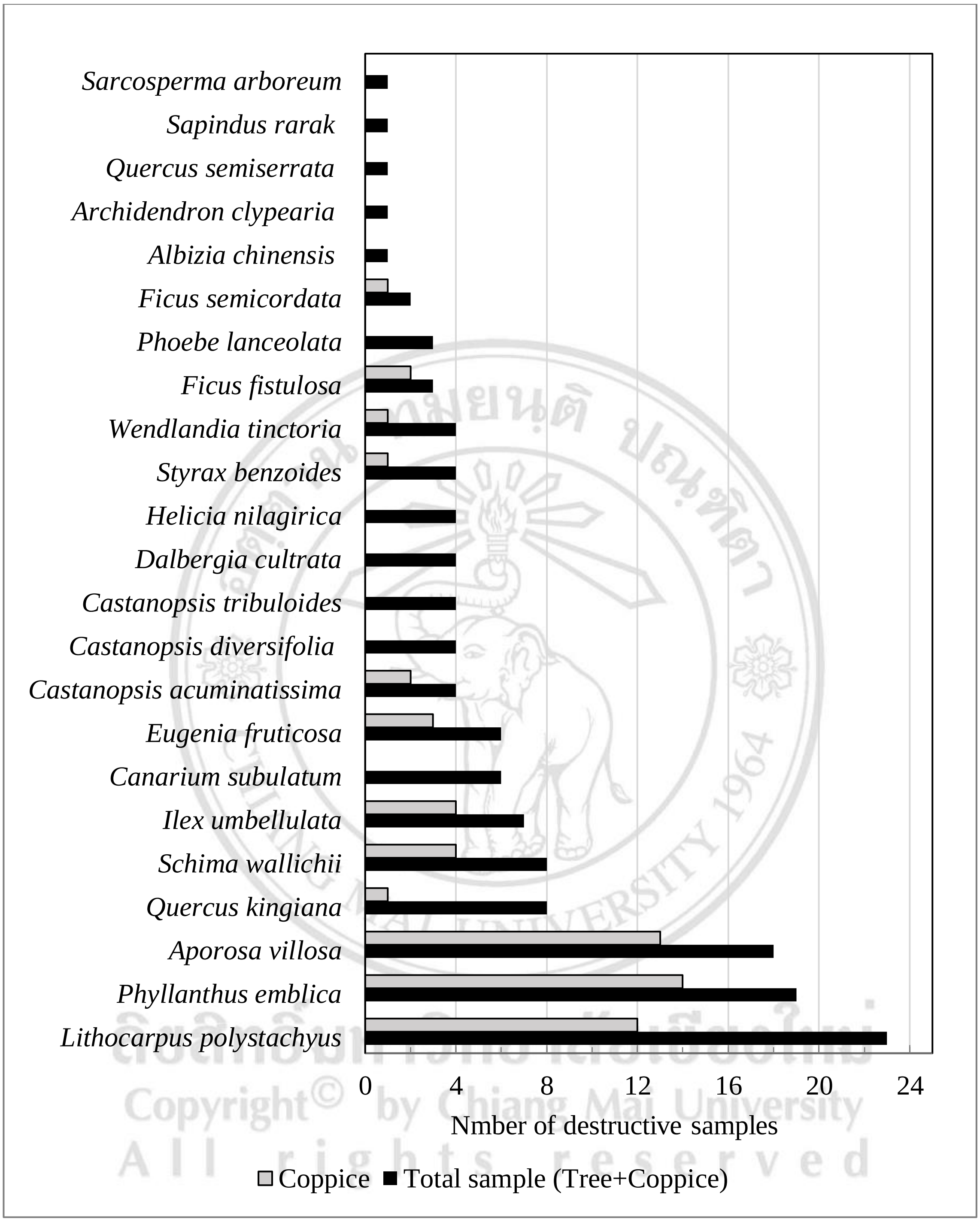


Figure 4.4 Total number of destructive samples for the different tree species

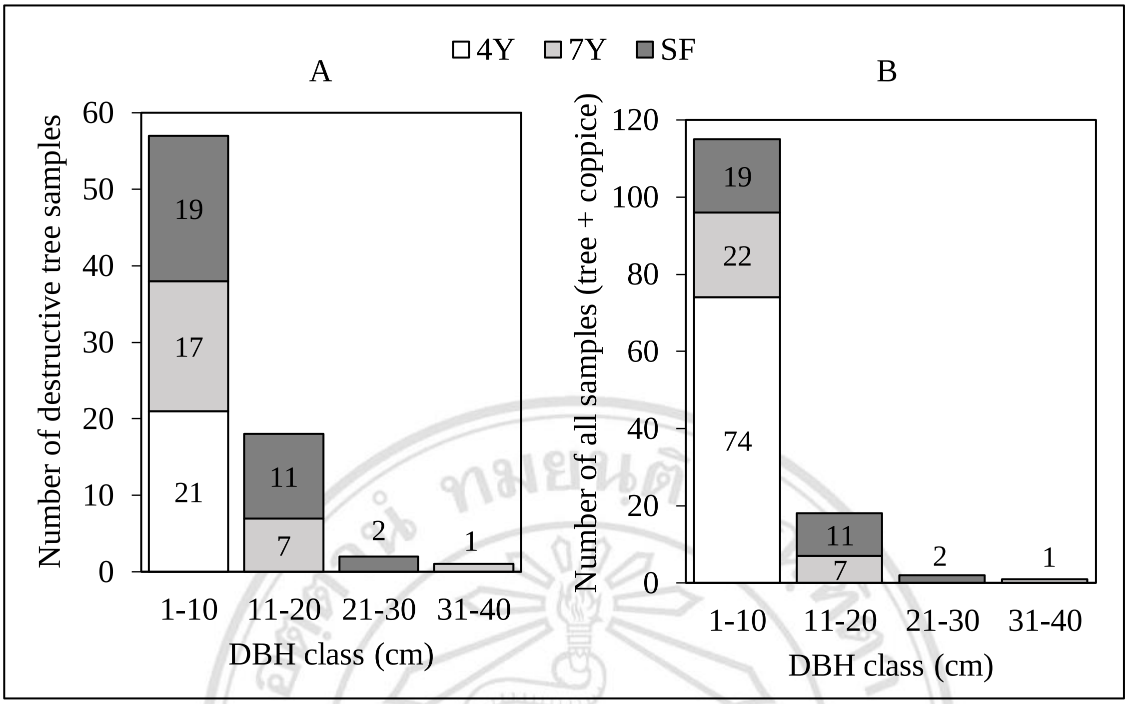


Figure 4.5 A) Distribution of destructive tree samples by DBH class (n = 78), and B) All individual stems including coppice tree (n = 136).

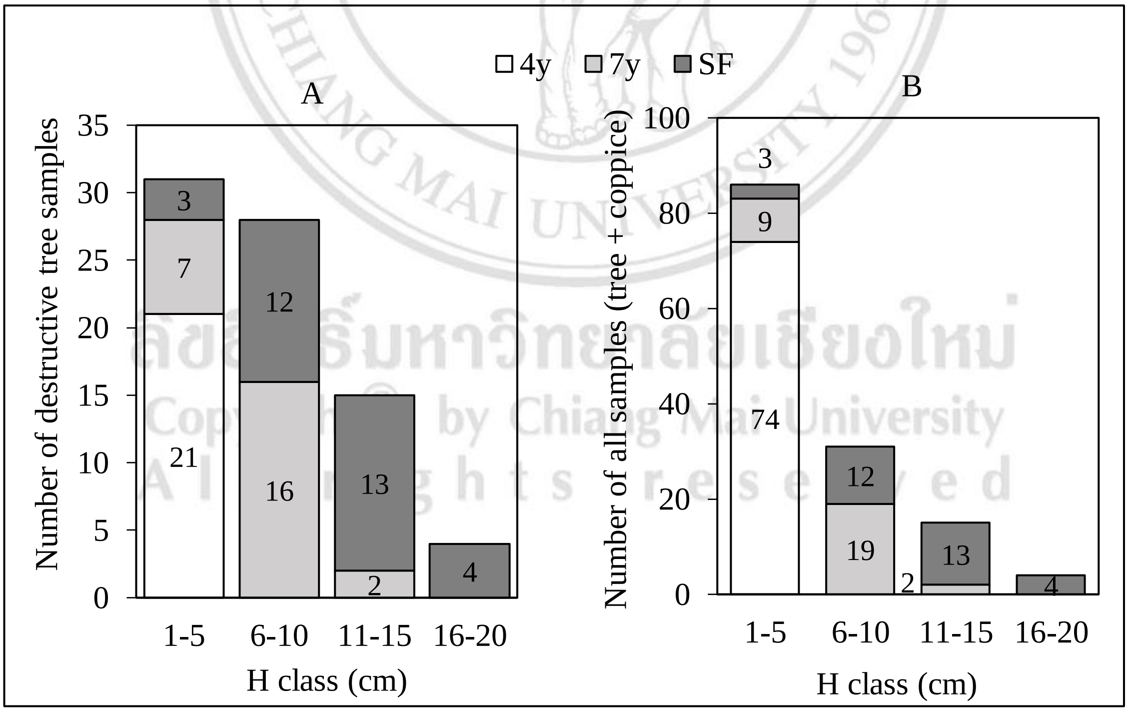


Figure 4.6 A) Distribution of destructive tree samples by height (H) class (n = 78), and B) All individual stems including coppice trees (n = 136).

4.2.2 Biomass allocation among tree parts averaging across species and plots

The highest proportion of biomass was found in stems (Ws), containing more than 40% of the total biomass in every DBH class (ranging from 45-78%). This was followed by branches (Wb), while the lowest biomass proportion was found in leaves (Wl). The highest percentage of the biomass was observed in stems with diameters 11-30 cm. Branch biomass had a similar proportion in the three DBH classes (I-III), after which it increased until reaching about 53% in the largest class. Meanwhile, leaves showed the opposite pattern, with the highest proportion found in the smallest DBH class and decreased from 12% to 2% with larger diameters (Figure 4.7). In addition, average biomass of different tree parts for the all species in each DBH class are shown in Appendix B.

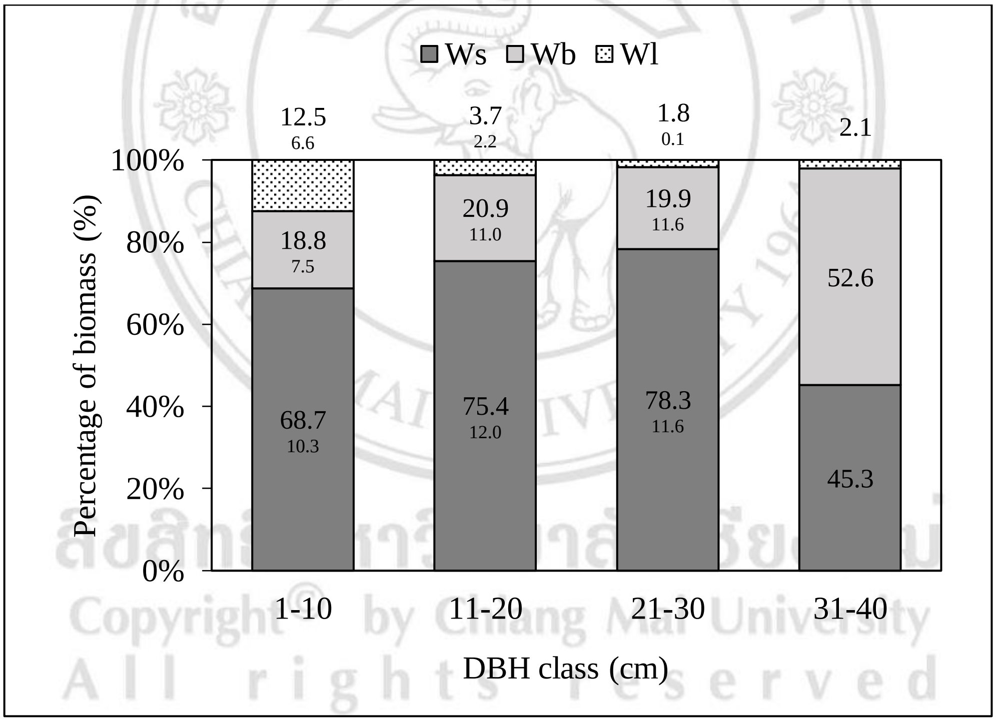


Figure 4.7 Above-ground biomass proportion of tree components across diameter classes. The larger numbers show mean values of all tree species, the smaller numbers below show standard deviations.

4.3 Wood density

Initially, 81 tree species were set to be collected, but 2 species in the inventory, *Dalbergia ovata* and *Lepisanthes tetraphylla*, died before the collection. Then, in total, 883 wood density samples (244 core and 639 discs) were collected from 79 species. Of these 79 species, 44 were included in the Global Wood Density Database (GWD) (Zanne et al., 2009), while 35 species (44%) were missing from the GWD. For 32 of these missing species, the genera were represented in the GWD. However, the genera of two species; was not found in the GWD, *Craibiodendron crepidioides,* and *Schoepfia fragrans* were not found either in the GWD and Tree Functional Attributes and Ecological Database.

Overall, the average wood density of all species in this study was 0.51±0.11g/cm^3. The species had the highest average wood density in this study was *Quercus kerrii* (0.68 g/cm^3) while *Bombax anceps* (0.19 g/cm^3) had the lowest. WD could not be collected for some species at the 7Y and SF sites with a DBH < 4.5 cm, since no disc samples were collected from trees in that DBH class and species at the 4Y site, which were not harvested (Appendix C-1). Differences in wood density, between increment borer and disc samples, was not significantly different within species for most species, except for: *Aporosa villosa, Dalbergia cultrata, Eugenia fruticosa, Lithocarpus polystachyus,* and *Phyllanthus emblica* (Independent Samples t-Test, $p < 0.05$) (Table 4.10). Furthermore, Duncan's Multiple Range tests showed significant differences in mean WD between some species (when $n \geq 3$) ($p < 0.05$). The lowest value of mean WD was found in *Ficus* spp. and the highest was found in *Flacourtia indica* (Figure 4.8, Appendix C-2).

Average wood density values of all species from destructive samples was 0.52±0.09 g/cm^3, ranging from 0.23 to 0.75 g/cm^3 and derived from direct measurement of 136 stems, were included for model development (Appendix D). Subsequently, biomass was estimated for all vegetation in the study (in total 117 species) by applying average wood density data of the 79 tree-specific species from this study and 23 species from GWD. Genus-level data was used for the 15 species missing from the GWD (Appendix C-1).

Table 4.10 Comparison of wood density (WD) (mean±SD) using in, different methods between increment borer and disc samples methods. Means sharing the same superscript are not significantly different from each other ($p < 0.05$), n is number of borer (one sample per trees), and N is number of discs (multiple samples per tree).

No.	Species name	Increment borer		Disc	
		WD (g/cm^3)	n	WD (g/cm^3)	N
1	*Albizia chinensis*	0.34±0.08 ^{a}	3	0.42±0.05 ^{a}	6
2	*Aporosa villosa*	0.60±0.06 ^{a}	10	0.50±0.08 ^{b}	60
3	*Archidendron clypearia*	0.38±0.05 ^{a}	3	0.43±0.03 ^{a}	5
4	*Canarium subulatum*	0.44±0.03 ^{a}	6	0.40±0.09 ^{a}	32
5	*Castanopsis acuminatissima*	0.60±0.11 ^{a}	6	0.58±0.12 ^{a}	20
6	*Castanopsis diversifolia*	0.63±0.09 ^{a}	6	0.56±0.09 ^{a}	29
7	*Castanopsis tribuloides*	0.61±0.06 ^{a}	6	0.60±0.07 ^{a}	24
8	*Dalbergia cultrata*	0.57±0.04 ^{a}	7	0.52±0.05 ^{b}	25
9	*Eugenia fruticosa*	0.59±0.03 ^{a}	7	0.47±0.08 ^{b}	24
10	*Helicia nilagirica*	0.54±0.03 ^{a}	6	0.53±0.07 ^{a}	30
11	*Lithocarpus polystachyus*	0.72±0.06 ^{a}	12	0.64±0.11 ^{b}	107
12	*Phoebe lanceolata*	0.51±0.06 ^{a}	7	0.52±0.10 ^{a}	17
13	*Phyllanthus emblica*	0.61±0.09 ^{a}	3	0.50±0.07 ^{b}	69
14	*Quercus kingiana*	0.64±0.08 ^{a}	7	0.57±0.09 ^{a}	43
15	*Sarcosperma arboreum*	0.57±0.06 ^{a}	4	0.53±0.03 ^{a}	7
16	*Schima wallichii*	0.54±0.01 ^{a}	4	0.53±0.06 ^{a}	43
17	*Styrax benzoides*	0.59±0.02 ^{a}	7	0.58±0.08 ^{a}	26
18	*Wendlandia tinctoria*	0.57±0.07 ^{a}	12	0.53±0.10 ^{a}	15

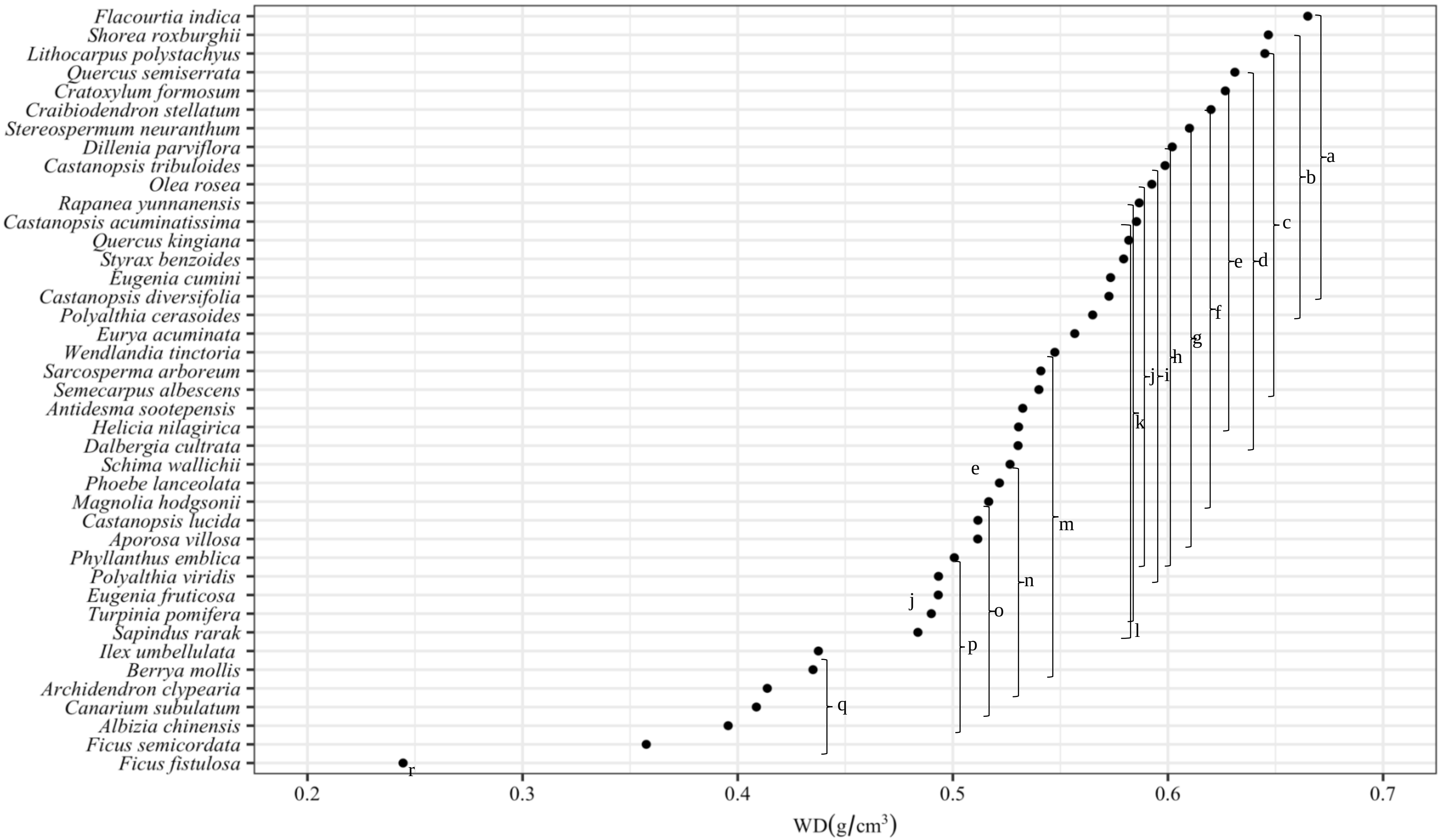


Figure 4.8 Average of wood density (g/cm3) between tree species of all WD samples of each species (n≥3).

4.4 Data analysis

4.4.1 Relationship between parameters

The scatterplot matrix showing the histograms, kernel density overlays, create a smooth curve given a set of data, absolute correlations and significance asterisks (p<0.05*, p<0.01**, p<0.001***) for the relationship between parameters of above-ground biomass (AGB), stem diameter at breast height (DBH), tree height (H), wood density (WD) for all the 136 destructive samples are shown in Figure 4.9 The three parameters of AGB, DBH, and H had strong significant correlations, and the correlation between WD with the other parameter are quite low.

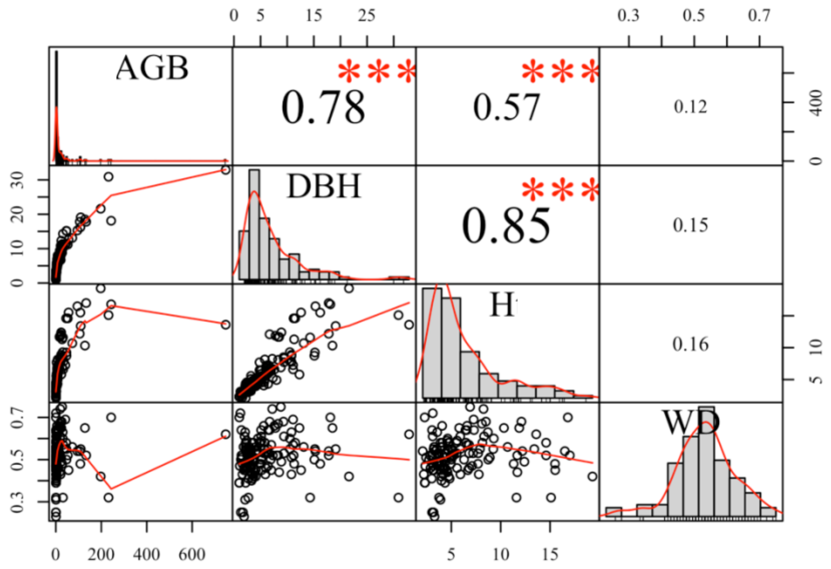


Figure 4.9 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for 136 trees against the variables of DBH, H, and WD. Correlations are significant at p < 0.05.

Moreover, the relationship between parameters of the tree species which contained the destructive samples more than 10 individual trees; *Lithocarpus polystachyus*, *Phyllanthus emblica*, *Aporosa villosa*, *Quercus kingiana*, *Schima wallichii*, *Ilex umbellulata*, *Canarium subulatum*, and *Eugenia fruticosa* are shown in Figures 4.10- 4.17 The relationships between AGB and DBH, AGB and H, DBH and H are highly significant in every species. Although, the correlations of WD and the other parameters showed the opposite results, excepted for *Lithocarpus polystachyus* that had the higher correlations between DBH and WD, H and WD, and for *Quercus kingiana* it was also shown to be significant between H and WD.

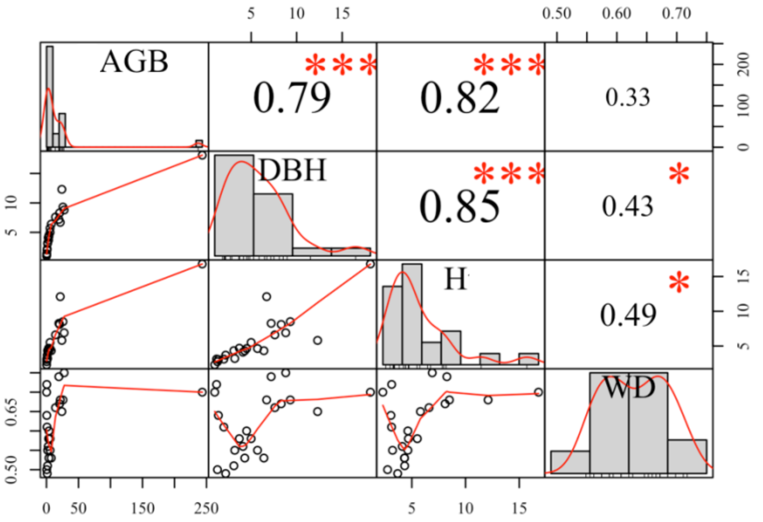


Figure 4.10 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks ($p<0.001$***, $p<0.01$**, $p<0.05$*) for the relationship of above-ground biomass (AGB) for *Lithocarpus polystachyus* (n=23, DBH = 1.0-18.1 cm), against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

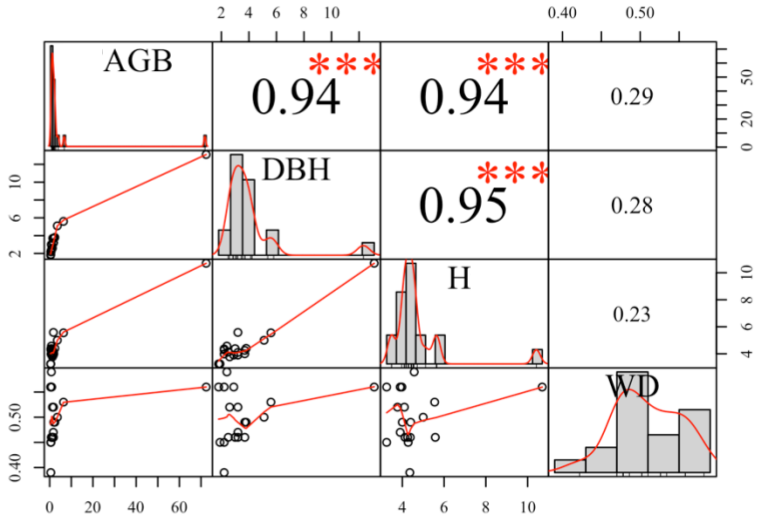


Figure 4.11 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Phyllanthus emblica* (n=19, DBH = 1.8-13.1 cm), against the variables of DBH, H, and WD. Correlations are significant at p < 0.05.

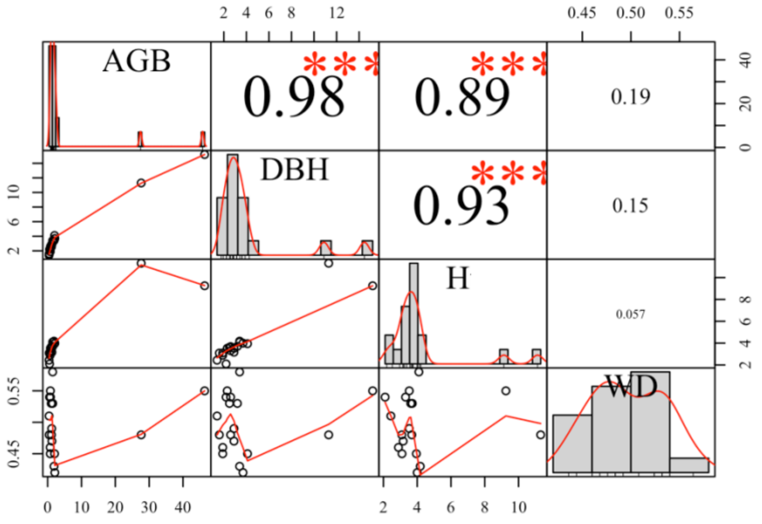


Figure 4.12 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Aporosa villosa* (n=18, DBH = 1.4 -15.2 cm), against the variables of DBH, H, and WD. Correlations are significant at p < 0.05.

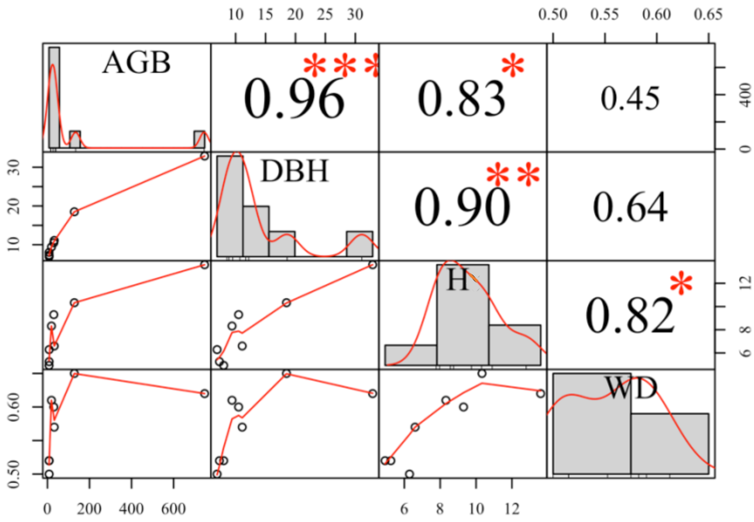


Figure 4.13 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Quercus kingiana* (n=8, DBH = 6.9-32.9 cm), against the variables of DBH, H, and WD. Correlations are significant at p < 0.05.

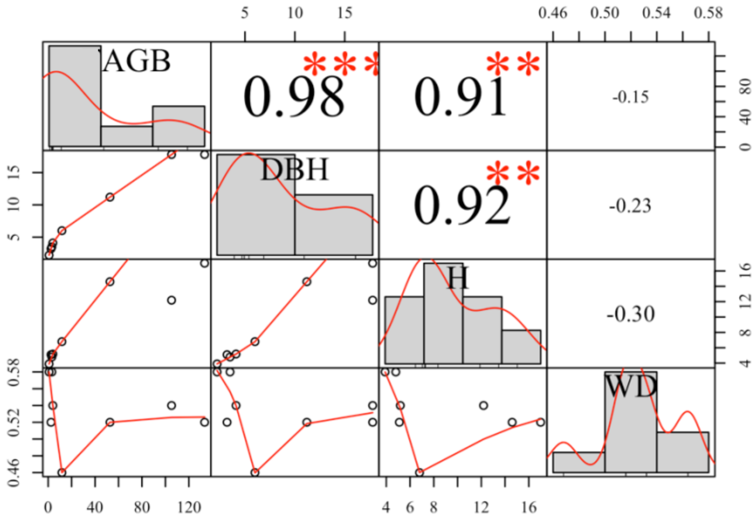


Figure 4.14 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Schima wallichii* (n=8, DBH = 2.2-17.8 cm), against the variables of DBH, H, and WD. Correlations are significant at p < 0.05.

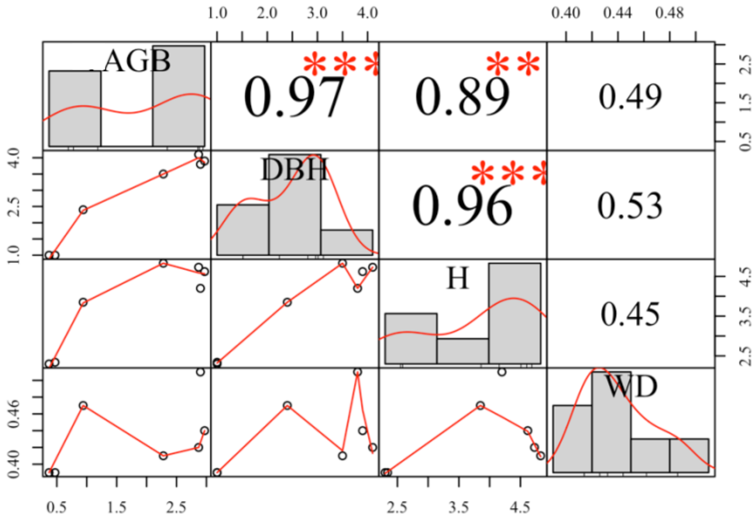


Figure 4.15 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Ilex umbellulata* (n=7, DBH = 1.0-4.1 cm*)*, against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

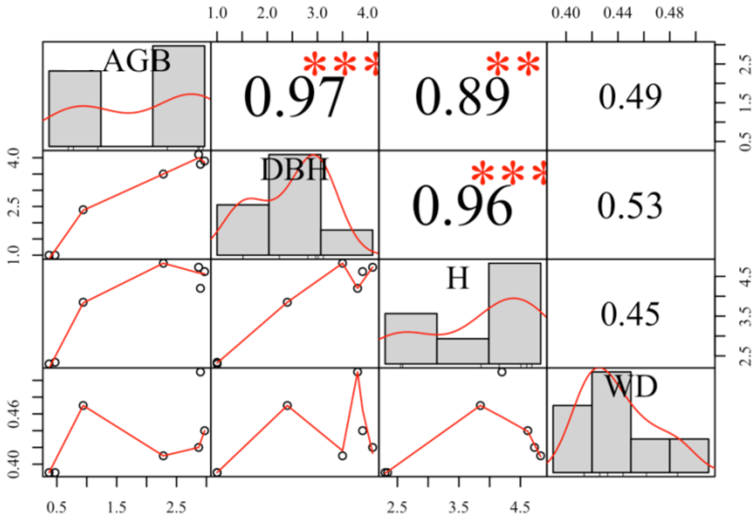


Figure 4.16 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Canarium subulatum* (n=6, DBH = 2.7-30.9 cm), against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

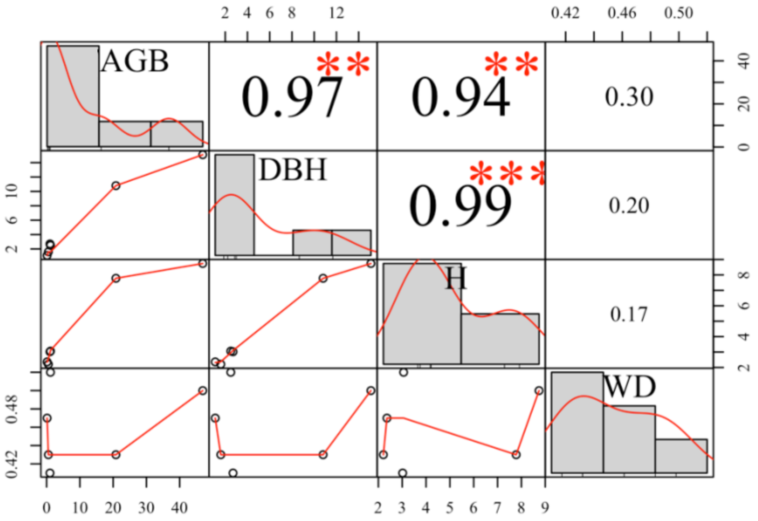


Figure 4.17 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Eugenia fruticosa* (n=6, DBH= 1.1-15.1 cm), against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

4.4.2 Model validation and comparison

All destructive data from 136 trees were randomly split 200 times into training data and validating data. Eighty percent of the observed data (109 trees) were used for model development, while 20% (27 trees) were used for model validation. The same sets were used for validating and comparing all 8 common models. Cross-validation statistics were also computed for each realization of randomly selected data. The averaged validation statistic over the 200 realizations and %Bias, %RMSE and %MAPE are presented in Table 4.11. The Bias of all models ranged from -4.85% to -6.66%, RMSE ranged from 29.62% to 38.30%, and MAPE ranged from 22.02% to 29.33%. Model VI-VIII shared the same variables (DBH, H, and WD), and model VII showed the lowest values of Bias, RMSE, and MAPE, with fewer parameters requiring estimation.

Table 4.11 Model validation and comparison between eight common models. Cross-validation statistics were computed for each realization of randomly selected validation data, and averaged over the 200 realizations; N=109.

No.	**Model**	**Bias (%)**	**RMSE (%)**	**MAPE (%)**
I	$\ln(AGB) = a + b \ln(DBH)$	-6.66	37.22	29.33
II	$\ln(AGB) = a + b \ln(DBH) + c (\ln(DBH))^2$	-6.19	38.30	28.27
III	$\ln(AGB) = a + b \ln(DBH) + c \ln(H)$	-6.27	35.29	26.24
IV	$\ln(AGB) = a + b \ln(DBH) + c \ln(WD)$	-5.46	33.26	25.72
V	$\ln(AGB) = a + b \ln(DBH^2H)$	-6.35	35.56	26.17
VI	$\ln(AGB) = a + b \ln(DBH^2H) + c \ln(WD)$	-4.91	29.88	22.16
VII	$\ln(AGB) = a + b \ln(DBH^2H \cdot WD)$	-4.85	29.62	22.02
VIII	$\ln(AGB) = a + b \ln(DBH) + c \ln(H) + d \ln(WD)$	-4.89	29.83	22.30

AGB: above-ground biomass, DBH: stem diameter at breast height, H: tree height, WD: wood density

4.4.3 Model development and selection

Eight common allometric models were fitted with data from 136 harvested individual trees to establish relationships between measured AGB and DBH, H, and WD as predictor variables. Adjusted R^2 exceeded 0.9 in all models. The lowest adjusted R^2 value was 0.959 in the model I (DBH only). Adding H or WD into the equations increased R^2 slightly, while RSE, AIC, and %S decreased. In contrast, the highest R^2, 0.972, was found in model VI-VII, which provided a better fit by adding WD together with DBH and H. The best fit model was model VII, which had the highest adjusted R^2, a low average deviation (S%) of 21.64 and the lowest RSE and AIC values of 0.298 and 61.3, respectively. The relationship between AGB and the parameter of independent variables of all models and all regression coefficients used were statistically significant ($p < 0.001$) (Table 4.12).

Table 4.12 Comparison of different allometric equations for estimating aboveground biomass (AGB) with different input variables (entire dataset, 136 trees).

Model No.		Parameter estimated				Adj. R^2	RSE	AIC	S%
		a	*b*	*c*	*d*				
I	$\ln(AGB) = a + b\ln(DBH)$	-2.032	2.275			0.959	0.365	115.5	29.19
II	$\ln(AGB) = a + b\ln(DBH) + c(\ln(DBH))^2$	-1.618	1.603	0.209		0.966	0.333	92.1	27.11
III	$\ln(AGB) = a + b\ln(DBH) + c\ln(H)$	-2.571	1.832	0.721		0.966	0.334	92.7	25.69
IV	$\ln(AGB) = a + b\ln(DBH) + c\ln(WD)$	-1.473	2.227	0.723		0.965	0.337	95.3	25.52
V	$\ln(AGB) = a + b\ln(DBH^2H)$	-2.675	0.869			0.966	0.334	91.8	25.78
VI	$\ln(AGB) = a + b\ln(DBH^2H) + c\ln(WD)$	-2.069	0.850	0.768		0.972	0.299	63.0	21.61
VII	$\ln(AGB) = a + b\ln(DBH^2H\cdot WD)$	-2.003	0.847			0.972	0.298	61.3	21.64
VIII	$\ln(AGB) = a + b\ln(DBH) + c\ln(H) + d\ln(WD)$	-2.008	1.761	0.756	0.761	0.972	0.300	64.4	21.71

DBH indicate stem diameter at breast height, H: tree height, WD: wood density, Parameter estimated; a, b, c and d are the coefficients estimated of regression model, Adj R^2 is the coefficient of determination, RSE: residual standard error of the estimate, AIC: Akaike Information Criterion, and S%: average deviation. All regression coefficients used were statistically significant in all models ($p < 0.001$

The allometric relationship between AGB and DBH^2HWD based on model VII is shown in Figure 4.18. The best fit equation for AGB estimation in this study was:

$$ln(AGB) = -2.003 + 0.847ln(DBH^2HWD)$$

$$\text{or } AGB = \exp(-2.003 + 0.847ln(DBH^2HWD))$$

$$\text{or } AGB = 0.134\ (DBH^2HWD)^{\ 0.847}$$

However, the destructive trees with highest residual error was found in a *Canarium subulatum* tree (DBH = 30.9 cm, H=15.1 m) in the SF site, and two coppices were *Ilex umbellulata* with DBHs of 1 cm and H were 2.30 cm, and 2.34 cm, respectively.

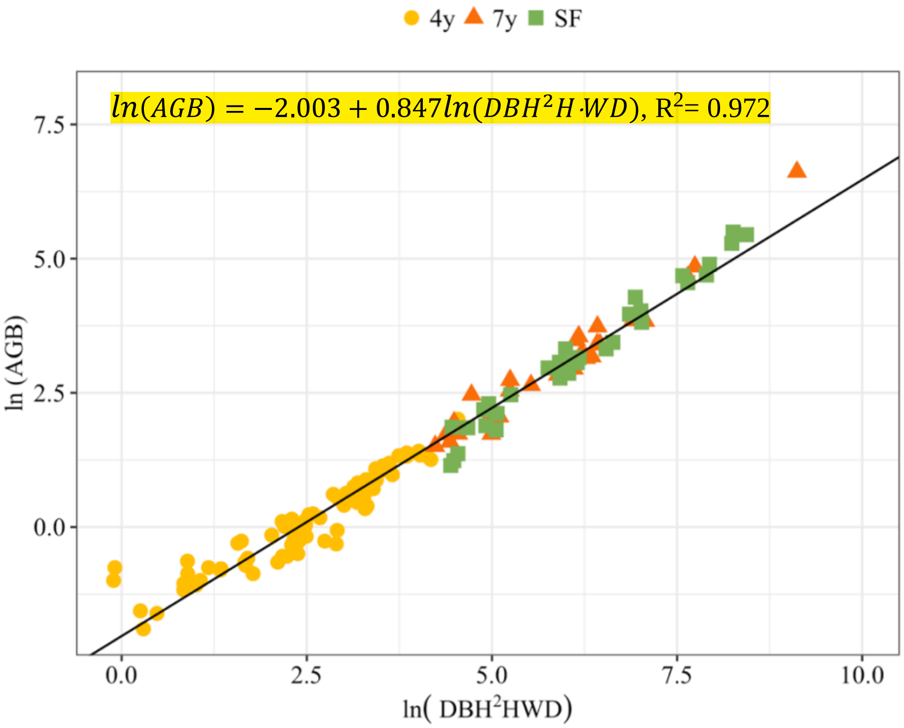


Figure 4.18 Relationship between the natural log transformation of above-ground biomass values observed in this study (AGB) and the best-fit explanatory variable $DBH^2H{\cdot}WD$ (N=136)

Moreover, allometric equation for species-specific of *Lithocarpus polystachyus*, *Phyllanthus emblica*, and *Aporosa villosa*, which were harvested from more than 10 samples were tested by following the eight general models. The AGB estimation equation of *Lithocarpus polystachyus* from 23 harvested individual trees showed the best fit on Model VII with DBH^2HWD as a parameter with (R^2= 0.99) is shown in Table 4.13 and Figure 4.19 The best fit equation for species-specific AGB estimation of *Lithocarpus polystachyus* was:

$$ln(AGB) = -1.912 + 0.846ln(DBH^2H{\cdot}WD)$$

$$\text{or } AGB = \exp(-1.912 + 0.846ln(DBH^2H{\cdot}WD))$$

$$\text{or } AGB = 0.147\ (DBH^2H{\cdot}WD)^{\ 0.846}$$

Table 4.13 Comparison of different allometric equations for estimating aboveground biomass (AGB) with different input variables of *Lithocarpus polystachyus* (23 individual trees).

Model No.		Parameter estimated				Adj. R^2	RSE	AIC	S%
		a	*b*	*c*	*d*				
I	$\ln(AGB) = a + b\ln(DBH)$	-1.682	2.186			0.957	0.360	22.3	26.84
II	$\ln(AGB) = a + b\ln(DBH) + c\,(\ln(DBH))^2$	-1.345	1.430	0.282*		0.967	0.316	17.0	22.78
III	$\ln(AGB) = a + b\ln(DBH) + c\ln(H)$	-2.756	1.468	1.311		0.990	0.168	-11.9	11.87
IV	$\ln(AGB) = a + b\ln(DBH) + c\ln(WD)$	-0.736	2.102	1.677		0.971	0.296	14.0	19.35
V	$\ln(AGB) = a + b\ln(DBH^2H)$	-2.414	0.864			0.987	0.198	-5.4	14.08
VI	$\ln(AGB) = a + b\ln(DBH^2H) + c\ln(WD)$	-1.865	0.843	0.922**		0.991	0.163	-13.2	12.10
VII	$\ln(AGB) = a + b\ln(DBH^2H{\cdot}WD)$	-1.912	0.846			0.992	0.160	-15.1	12.02
VIII	$\ln(AGB) = a + b\ln(DBH) + c\ln(H) + d\ln(WD)$	-2.241	1.524	1.148	0.674*	0.992	0.152	-15.6	11.95

DBH indicate stem diameter at breast height, H: tree height, WD: wood density, Parameter estimated; a, b, c and d are the coefficients estimated of regression model, Adj R^2 is the coefficient of determination, RSE: residual standard error of the estimate, AIC: Akaike Information Criterion, and S%: average deviation. Significance of the parameter estimate is indicated with ‘*’ for $P < 0.05$; ‘**’ for $P < 0.01$, for ‘ ’ for $P < 0.001$.

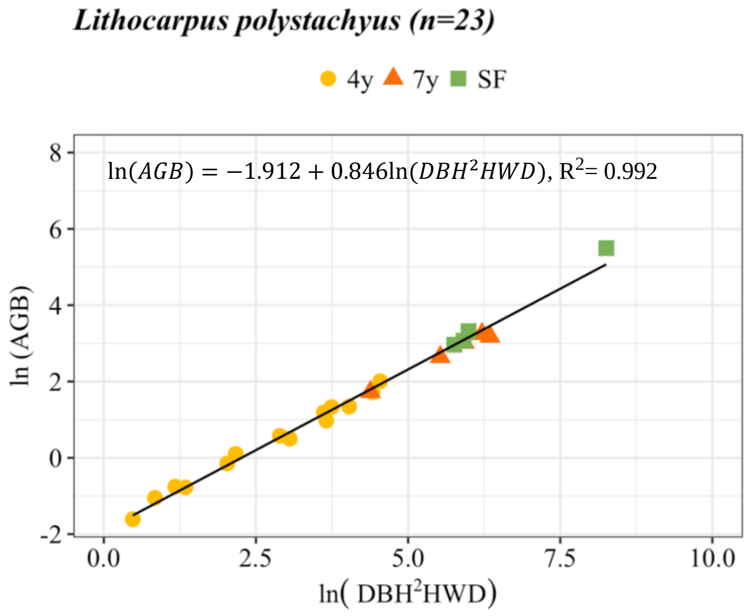


Figure 4.19 Species-specific relationship between the natural log transformation of above-ground biomass values observed in this study (AGB) and the best-fit explanatory variable DBH^2HWD of *Lithocarpus polystachyus*

However, the species specific models of *Phyllanthus emblica* (n=19) (Table 4.14, Figure 4.20), and *Aporosa villosa* (n=18) (Table 4.15, Figure 4.21) showed the best fit on model II, which contained only DBH as a parameter, had the highest adjusted R^2, the lowest RSE and AIC. The best fit equation for species-specific AGB estimation of *Phyllanthus emblica* was:

$$ln(AGB) = -1.743 + 1.327ln(DBH) + 0.393(ln(DBH))^2),\ R^2 = \ 0.962$$

$$\text{or } AGB = \exp(-1.743 + 1.327ln(DBH) + 0.393(ln(DBH))^2)$$

and equation for species-specific of *Apososa villosa* was:

$$ln(AGB) = -1.277 + 1.056ln(DBH) + 0.318(ln(DBH))^2),\ R^2 = \ 0.985$$

$$\text{or } AGB = \exp(-1.743 + 1.327ln(DBH) + 0.393(ln(DBH))^2)$$

Table 4.14 Comparison of different allometric equations for estimating aboveground biomass (AGB) with different input variables of *Phyllanthus emblica* (19 individual trees).

Model No.		Parameter estimated				Adj. R^2	RSE	AIC	S%
		a	*b*	*c*	*d*				
I	ln(AGB) = *a* + *b* ln(DBH)	-2.505	2.510			0.952	0.257	6.2	34.00
II	ln(AGB) = *a* + *b* ln(DBH) +*c*(ln(DBH))^2	-1.743	1.327*	0.393*		0.962	0.229	2.8	30.19
III	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(H)	-2.963	2.269	0.494^{ns}		0.952	0.257	7.1	30.80
IV	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(WD)	-2.010	2.474	0.648^{ns}		0.953	0.255	7.1	29.62
V	ln(AGB) = *a* + *b* ln(DBH^{2}H)	-3.418	1.003			0.952	0.258	6.3	30.60
VI	ln(AGB) = *a* + *b* ln(DBH^{2}H) + *c* ln(WD)	-2.840	0.987	0.738		0.954	0.254	6.5	24.11
VII	ln(AGB) = *a* + *b* ln(DBH^{2}HWD)	-2.644	0.980			0.956	0.247	4.7	23.37
VIII	ln(AGB) = *a* + *b* ln(DBH)+ *c* ln(H) + *d* ln(WD)	-2.470	2.213	0.530^{ns}	0.688^{ns}	0.953	0.2543	6.9	25.32

DBH indicate stem diameter at breast height, H: tree height, WD: wood density, Parameter estimated; a, b, c and d are the coefficients estimated of regression model, Adj R^2 is the coefficient of determination, RSE: residual standard error of the estimate, AIC: Akaike Information Criterion, and S%: average deviation. Significance of the parameter estimate is indicated with 'ns' for $p > 0.05$ (on-significant), '*' for $P < 0.05$; '**' for $P < 0.01$, for ' ' for $P < 0.001$.

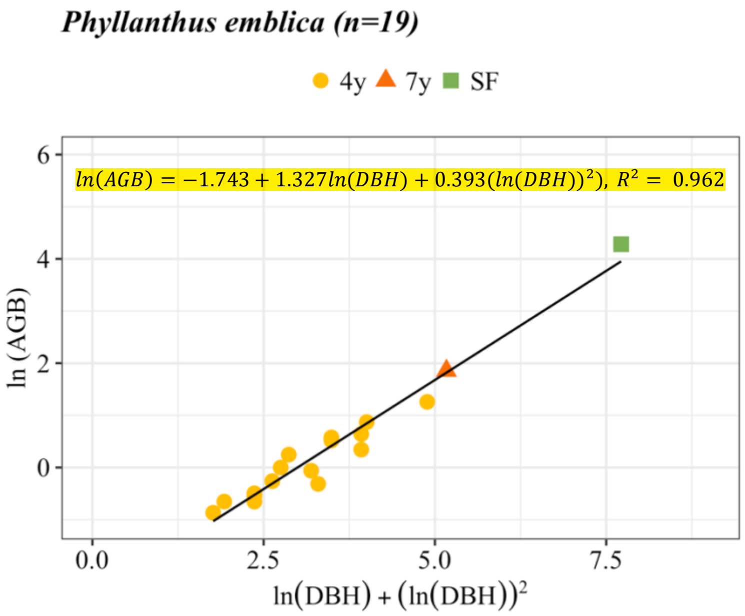


Figure 4.20 Species-specific relationship between the natural log transformation of above-ground biomass values observed in this study (AGB) and the best-fit explanatory variable DBH, DBH^2 of *Phyllanthus emblica*

Table 4.15 Comparison of different allometric equations for estimating aboveground biomass (AGB) with different input variables of *Apososa villosa* (18 individual trees).

Model No.		Parameter estimated				Adj. R^2	RSE	AIC	S%
		a	*b*	*c*	*d*				
I	ln(AGB) = *a* + *b* ln(DBH)	-1.871	2.041			0.972	0.209	-1.3	29.92
II	ln(AGB) = *a* + *b* ln(DBH) + *c*(ln(DBH))^2	-1.277	1.056**	0.318**		0.985	0.152	-11.9	32.97
III	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(H)	-2.428	1.493	0.878**		0.982	0.167	-8.6	26.83
IV	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(WD)	-2.299	2.048	-0.596^{ns}		0.972	0.208	-0.7	36.16
V	ln(AGB) = *a* + *b* ln(DBH^{2}H)	-2.368	0.779			0.983	0.162	-10.4	27.13
VI	ln(AGB) = *a* + *b* ln(DBH^{2}H) + *c* ln(WD)	-2.677	0.780	-0.431^{ns}		0.983	0.162	-9.6	32.69
VII	ln(AGB) = *a* + *b* ln(DBH^{2}HWD)	-1.799	0.771			0.976	0.195	-3.8	17.79
VIII	ln(AGB) = *a* + *b* ln(DBH)+ *c* ln(H) + *d* ln(WD)	-2.704	1.520	0.842**	-0.417^{ns}	0.982	0.168	-7.7	32.37

DBH indicate stem diameter at breast height, H: tree height, WD: wood density, Parameter estimated; a, b, c and d are the coefficients estimated of regression model, Adj R^2 is the coefficient of determination, RSE: residual standard error of the estimate, AIC: Akaike Information Criterion, and S%: average deviation. Significance of the parameter estimate is indicated with ‘ns’ for $p > 0.05$ (on-significant), ‘*’ for $P < 0.05$; ‘**’ for $P < 0.01$, for ‘ ’ for $P < 0.001$.

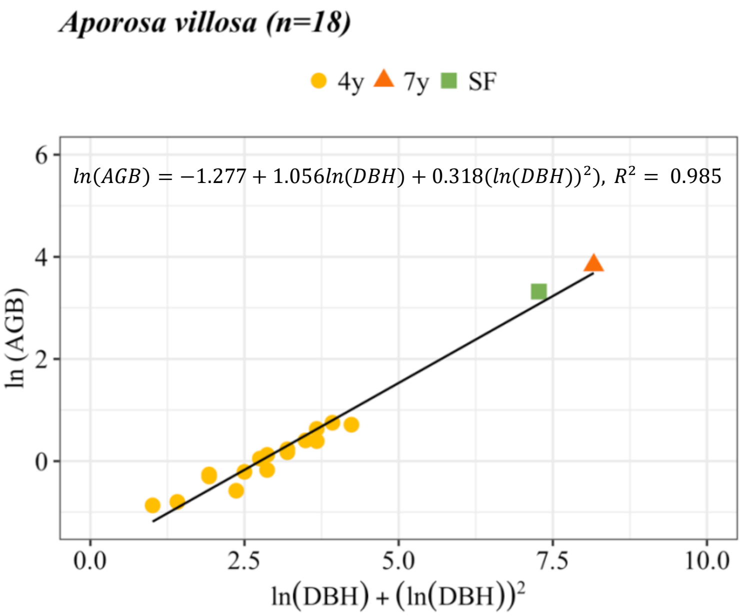


Figure 4.21 Species-specific relationship between the natural log transformation of above-ground biomass values observed in this study (AGB) and the best-fit explanatory variable DBH, DBH^2 of *Apososa villosa*

4.4.4 Carbon content

Carbon concentration in dry wood mass was analysed in 899 samples from 23 destructive tree species. The highest average carbon (%) was found in *Archidendron clypearia*, 46.67% (±1.89), while the lowest value was seen in *Ficus fistulosa*, 39.43% (±3.87). Overall, the average carbon content was 44.84 % (±1.63) (Appendix E). Moreover, significant differences between the species-specific average carbon content was observed by applying Duncan's Multiple Range test, $p < 0.05$ (Figure 4.22)

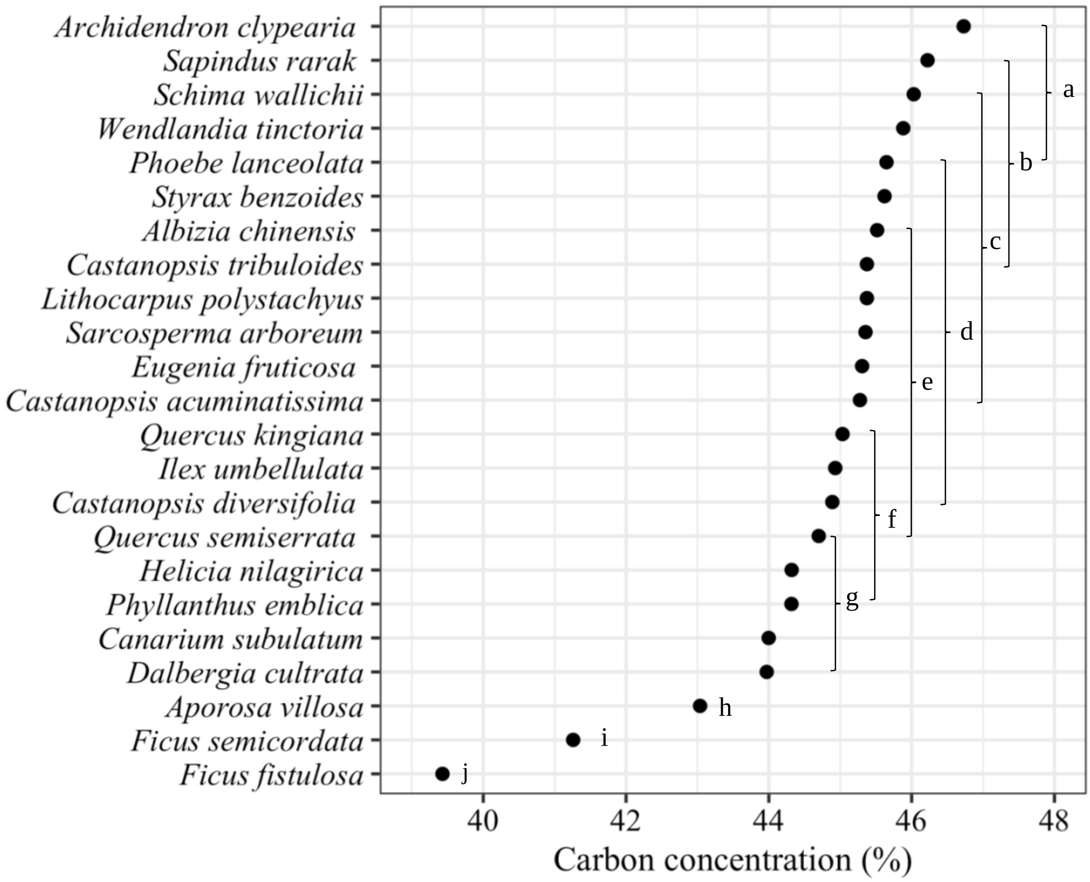


Figure 4.22 Average carbon concentration (%) differences among destructive tree species. Bars not sharing the same superscript are significantly different ($p < 0.05$).

4.4.5 Applying the allometric model and carbon content for above-ground biomass (AGB) estimation and above-ground carbon (AGC) sequestration

Aboveground biomass accumulation was estimated by applying the vegetation data, recorded in the beginning of this study, to the best-fit allometric equation (Model VII) as a function of DBH^2HW. Even though a bamboo species (*Gigantochloa albociliata*) found only in the 7-year-follow site, a bamboo-specific allometric equation was used to calculate biomass based on a mixed bamboo species model, which included *Gigantochloa* sp. (Yuen et al., 2017); $AGB = 0.269D^{2.017}$, where AGB in kg and D is culm DBH in cm. This equation is based on 65 bamboo samples collected in Chiang Mai Province, Thailand, with a culm DBH ranging from 2 to 7.5 cm.

Species specifics carbon concentration analysis results were used for the 23 species found in the inventory data. For the remaining species, the average carbon content across species was used. Only bamboo species using carbon factor of 50% (following Smith et al., 2010, cited in Yuen et al., 2017). Above-ground carbon (AGC) values were then evaluated by multiplying above-ground biomass (AGB) by the carbon factor.

Biomass increased 10 fold from 4Y to mature SF. In 3600 m^2, the 4Y had accumulated 3.7 Mg above-ground biomass, corresponding to 6.7% of total above-ground biomass. This increased to 13.8 Mg in the 7Y, or 24.9% of total above-ground biomass, including bamboo biomass of 0.9 Mg. Unsurprisingly, the highest amount was found in the secondary forest site, 37.9 Mg or 68.4% of total above-ground biomass. Moreover, the SF site sequestered the highest amount of carbon (17.2 Mg C/ha), followed by the 7Y site at 6.3 Mg C/ha, and 4Y site at 1.7 Mg C/ha.

Per hectare, the highest AGB and AGC values were recorded in the SF site (105.3 Mg/ha and 47.7 Mg C/ha), followed by the 7Y site (38.3 Mg/ha and 17.4 Mg C/ha). Being the youngest study site, the 4Y site had accumulated AGB at 10.3 Mg/ha and AGC at 4.6 Mg/ha. In average, the three sites in this study are estimated to accumulate 51.3 Mg/ha of biomass and 23.2 Mg C/ha carbon (Table 4.16, Figure 4.23).

Table 4.16 Above-ground biomass (AGB) and above-ground carbon (AGC) accumulation among study site per ha.

	Type	AGB (Mg/ha)				AGC (Mg C/ha)			
		4Y	7Y	SF		4Y	7Y	SF	
Tree	DBH ≥1-4.5 cm	5.6	2.5	1.1		2.5	1.2	0.5	
	DBH ≥ 4.5 cm	4.7	33.3	104.2		2.1	15.0	47.1	
Bamboo	*G. albociliata*	-	2.50	-		-	1.3	-	
	Total	10.3	38.3	105.3		4.6	17.4	47.7	
	Average				51.3				23.2

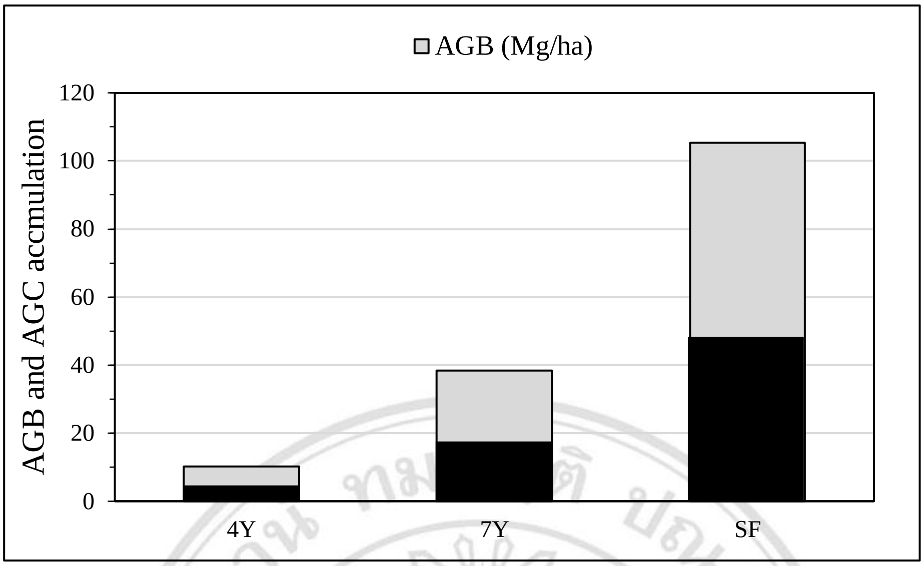


Figure 4.23 Accumulation of above-ground biomass (AGB) and above-ground carbon (AGC) per ha (including bamboo).

4.4.6 Above-ground biomass (AGB) accumulation in the selected destructive tree species

Using the newly developed equation, the selected tree species in the 4Y site was estimated to contain up to 75% of all biomass in the site. *Lithocarpus polystachyus* had the largest biomass (2.72 Mg/ha), largest BA (0.91 m^2/ha), and second highest stem density (747 stems/ha), followed by *Schima wallichii* (1.52 Mg/ha) with lower BA and stem density values. *Aporosa villosa* had the third largest biomass in the 4Y site, although it had a higher BA than *S. Wallichii* and the highest stem density of all species. Moreover, the FORRU framework tree species *Castanopsis acuminatissima*, *Eugenia fruticose, Ficus semicordata* and *Ficus fistulosa* stored about 4.2% of all biomass in this site (Table 4.17).

Table 4.17 Above-ground biomass (AGB), basal area (BA) and stem density of the destructive species in the 4-year-fallow (4Y).

Group	Family	Species name	Thai name	AGB (Mg/ha)	AGB (%)	BA (m^2/ha)	Stems/ha
IVI/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	2.72	26.511	0.91	747
S	Theaceae	*Schima wallichii*	ทะโล้	1.52	14.782	0.44	106
IVI/S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	1.44	14.038	0.75	1297
IVI/S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	0.65	6.328	0.31	533
S	Styracaceae	*Styrax benzoides*	กำยาน	0.47	4.598	0.16	147
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	0.35	3.393	0.17	89
IVI	Aquifoliaceae	*Ilex umbellulata*	เน่าใน	0.33	3.221	0.19	328
S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	0.11	1.073	0.05	83
S/F	Fagaceae	*Castanopsis acuminatissima*	ก่อเดือย	0.07	0.692	0.02	19
S	Lauraceae	*Phoebe lanceolata*	ตองหอม	0.04	0.407	0.02	25
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	0.02	0.205	0.01	31
F	Moraceae	*Ficus semicordata*	มะเดื่อปล้องขาว	0.01	0.094	0.01	11
F	Moraceae	*Ficus fistulosa*	ชิ้งขาว	0.00	0.015	0.00	8
	Sum of all species			7.74	75.359	3.03	3425
	Total data in 4Y			10.27	100	4.05	4975

In the 7-year-fallow, *Quercus kingiana* contained by far the highest amount of AGB of the selected species, 57% of the total biomass in the site, followed by *Lithocarpus polystachyus* (8.7%). Together, the selected species accounted for 85% of the total biomass accumulation in 7Y site, with the FORRU species (*Castanopsis acuminatissima, Eugenia fruticose, Quercus semiserrata, Erythrina subumbrans*) accounting for 4.7% (Table 4.18).

In the secondary forest, the highest AGB accumulation of the selected destructive species was 21.1 Mg/ha, recorded in *Schima wallichii,* which also had the highest BA but not the highest stem density. It was followed by *Castanopsis diversifolia* and *C.tribuloides* with 19.6 Mg/ha and 15.1 Mg/ha, respectively. The selected species were estimated to store 83% of all biomass in the SF site. Many FORRU trees species were found in SF site, and one of them are also part of the most dominant species. Consequently, 22.4% of the total biomass in SF site was stored in FORRU species (Table 4.19).

Table 4.18 Above-ground biomass (AGB), basal area (BA) and stem density of the destructive species in the 7-year-fallow (7Y).

Group	Family	Species name	Thai name	AGB (Mg/ha)	AGB (%)	BA (m^2/ha)	Stems/ha
IVI	Fagaceae	*Quercus kingiana*	ก่อแดง	20.5	57.0	5.8	511
IVI/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	3.1	8.7	1.0	144
S	Styracaceae	*Styrax benzoides*	กำยาน	1.5	4.3	0.4	456
IVI	Leguminosae	*Dalbergia cultrata*	กระพี้เขาควาย	1.3	3.5	0.4	175
S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	1.0	2.9	0.4	372
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	0.9	2.6	0.3	42
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	0.9	2.4	0.3	172
S/F	Fagaceae	*Castanopsis acuminatissima*	ก่อเดือย	0.4	1.1	0.1	14
S	Theaceae	*Schima wallichii*	ทะโล้	0.3	0.9	0.1	11
F	Leguminosae	*Erythrina subumbrans*	ทองหลางป่า	0.2	0.7	0.1	3
F	Fagaceae	*Quercus semiserrata*	ก่อกระดุม	0.1	0.4	0.0	6
S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	0.1	0.3	0.1	25
S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	0.1	0.3	0.0	72
S	Lauraceae	*Phoebe lanceolata*	ตองหอม	0.1	0.2	0.0	14
	Sum of all species			30.6	85.3	9.2	2016.7
	Total data in 7Y site (without bamboo)			35.9	100.0	11.0	2903

IVI species, S is species present at every site, while F is FORRU framework tree species.

Table 4.19 Above-ground biomass (AGB), basal area (BA) and stem density of the destructive species in the Secondary forest (SF).

Group	Family	Species name	Thai name	AGB (Mg/ha)	AGB (%)	BA (m^2/ha)	Stems/ha
IVI/S	Theaceae	*Schima wallichii*	ทะโล้	21.1	20.0	4.7	69
IVI	Fagaceae	*Castanopsis diversifolia*	ก่อแป้น	19.9	18.9	4.0	86
IVI/F	Fagaceae	*Castanopsis tribuloides*	ก่อใบเลื่อม	15.1	14.3	3.3	103
IVI/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	7.0	6.6	1.5	139
IVI	Leguminosae	*Albizia chinensis*	กางหลวง	6.1	5.7	1.7	25
IVI/S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	5.0	4.7	1.5	42
S/F	Fagaceae	*Castanopsis acuminatissima*	ก่อเดือย	3.3	3.1	0.7	39
F	Meliaceae	*Heynea trijuga*	จางจืด	1.9	1.8	0.5	3
IVI	Proteaceae	*Helicia nilagirica*	ชิ้งขาว	1.9	1.8	0.8	36
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	1.8	1.7	0.5	39
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	1.4	1.3	0.4	56
S/F	Lauraceae	*Phoebe lanceolata*	ตองหอม	0.7	0.7	0.2	150
S	Styracaceae	*Styrax benzoides*	กำยาน	0.6	0.5	0.1	28
S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	0.4	0.4	0.2	25
F	Sapotaceae	*Sarcosperma arboreum*	มะยาง	0.3	0.3	0.1	14
F	Sapindaceae	*Sapindus rarak*	มะซัก	0.3	0.3	0.1	3
F	Leguminosae	*Archidendron clypearia*	มะขามแป	0.3	0.3	0.1	61
S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	0.1	0.1	0.0	6
	Sum of all species			87.0	82.5	20.6	922
	Total data in SF site			105.4	100	24.9	2156

CHAPTER 4

Results

4.1 Tree species composition

Rarefaction curve showed the expected species richness with standard deviation by sampling individuals within 36 plots or 3600 m^2. The species richness still increased in the Secondary forest (SF) site. The rarefaction curve showed more stable numbers in the 7-year-fallow (7Y) and the 4-year-fallow (4Y). The highest number of the individuals was shown in the 4Y, followed by the SF, and the lowest number was found in the 7Y site (Figure 4.1). A total of 86 genera, 47 families, and 118 species (including 1 bamboo species; *Gigantochloa albociliata*) were recorded in the three study sites (10,800 m^2). In total, 1,840 trees and 3,612 individual all stems with DBH ≥ 1 cm were found. The numbers of trees species, trees and total basal area increased with the age of the fallow, the highest being in the secondary forest (SF) site. The same trend was also observed for trees with DBH ≥ 4.5 cm. However, stem density (stems/ha) showed the opposite pattern, with the highest values found in the youngest 4Y site and the lowest in SF. Except for DBH ≥ 4.5 cm, the highest number of stems were found in the 7Y, followed by SF and 4Y, respectively (Table 4.1).

The Shannon-Wiener and Shannon evenness indices showed the greatest diversity value in the SF site, while the lowest diversity was found in the 4Y site. Both diversity indices increased with the fallow age. Percentage similarity (Sørensen’s index) between paired-plot showed more similarity between the 4Y and the 7Y sites. Percentage of similarity was lower than between the fallow sites and the SF.

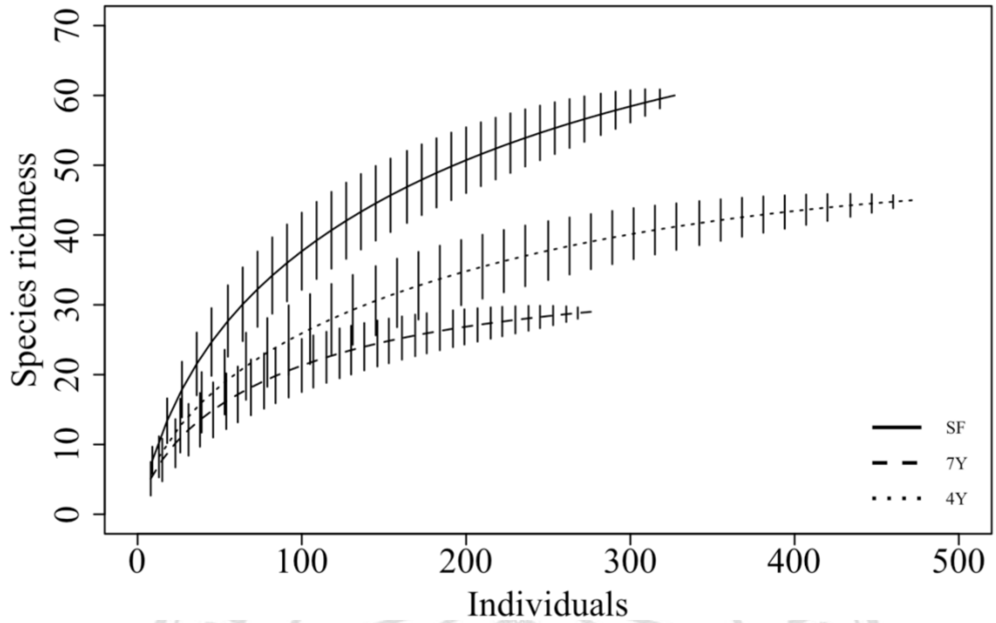


Figure 4.1 Rarefaction curves showing the expected species richness with standard deviations of the 4-year-fallow (4Y), the 7-year-fallow (7Y), and the Secondary forest (SF).

Table 4.1 Vegetation composition at the study sites.

Study site		4-year-fallow (4Y)	7-year-fallow (7Y)	Secondary forest (SF)
Elevation (m)		1090	1120	1254
DBH ≥1 cm	No. of species	43	44	80
	No. of trees	470	678	692
	All individual stems	1791	1045	776
	Coppice	1321	367	84
	Density (stems/ha)	4975	2903	2156
	Basal area (m^2/ha)	4.05	10.99	24.94
	Shannon-Wiener diversity	2.8	2.99	3.74
	Shannon Evenness	0.74	0.79	0.85
DBH ≥4.5 cm	No. of species	21	30	60
	No. of tree	79	278	327
	All individual stems	196	435	353
	coppice	117	157	26
	Density (stems/ha)	544	1208	981
	Basal area (m^2/ha)	1.65	10.09	24.51
	Shannon-Wiener diversity	2.09	2.40	3.52
	Shannon Evenness	0.69	0.71	0.86
Sørensen's index (%)	4Y	-	55	36
	7Y		-	29
	SF			-

Aporosa villosa had the highest Importance Value Index (IVI) in the 4Y, *Quercus kingiana* in the 7Y and *Castanopsis tribuloides* in the SF. Moreover, *Lithocarpus polystachyus* was found in every site with high IVI values. Fagaceae was the most common family, represented by *Lithocarpus polystachyus* in all sites, *Quercus kingiana* in the 7Y, and *Castanopsis diversifolia*, and *C. tribuloides* in the SF. The number of tree, basal area and IVI values of each species in every study site showed in Appendix A. Table 4.2 present the species that accounted for at least 50% of the cumulative relative IVI score in each site All of them were selected for allometric model development.

Table 4.2 Relative Importance Value Index (%IVI) of the dominant species, and relative cumulative IVI in 4-year-fallow (4Y), 7-year-fallow (7Y), and Secondary forest (SF)

Site	**Species name**	**Thai name**	**Family**	**%IVI**	**Cumulative %IVI**	**Rank**
4Y	*Aporosa villosa*	เหมือดโลด	Phyllanthaceae	17.9	17.9	1
	Lithocarpus polystachyus	ก่อนก	Fagaceae	17.4	35.3	2
	Phyllanthus emblica	มะขามป้อม	Phyllanthaceae	8.9	44.2	3
	Ilex umbellulata	เน่าใน	Aquifoliaceae	6.1	50.4	4
7Y	*Quercus kingiana*	ก่อแดง	Fagaceae	39.4	39.4	1
	Lithocarpus polystachyus	ก่อนก	Fagaceae	9.3	48.6	2
	Dalbergia cultrata	กระพี้เขาควาย	Leguminosae	6.8	55.4	3
SF	*Castanopsis tribuloides*	ก่อใบเลื่อม	Fagaceae	10.5	10.5	1
	Schima wallichii	ทะโล้	Theaceae	9.9	20.4	2
	Castanopsis diversifolia	ก่อแป้น	Fagaceae	9.4	29.8	3
	Lithocarpus polystachyus	ก่อนก	Fagaceae	8.3	38.0	4
	Canarium subulatum	มะกอกเกลื้อน	Burseraceae	5.4	43.4	5
	Albizia chinensis	กางหลวง	Leguminosae	3.8	47.2	6
	Helicia nilagirica	เหมือดคนตัวผู้	Proteaceae	3.7	50.9	7

The IVI values in the 4Y include trees with DBH ≥ 1 cm, while trees with a DBH ≥ 4.5 cm were analysed for the 7Y and the SF.

The highest number of stems was found in the smallest DBH class (1-10 cm), the number decreased with increasing DBH class (Figure 4.2). A majority of the stems had a DBHs of 1-10 cm in 4Y site, and 1-20 cm in the 7Y site. As expected, the highest range, with a DBH between 1–60 cm, was found in the SF site. A small number of trees with DBHs of 20-60 cm, had survived from previous slash and burn, were found in the 4Y and the 7Y sites; the number and species of these trees are shown in Table 4.3.

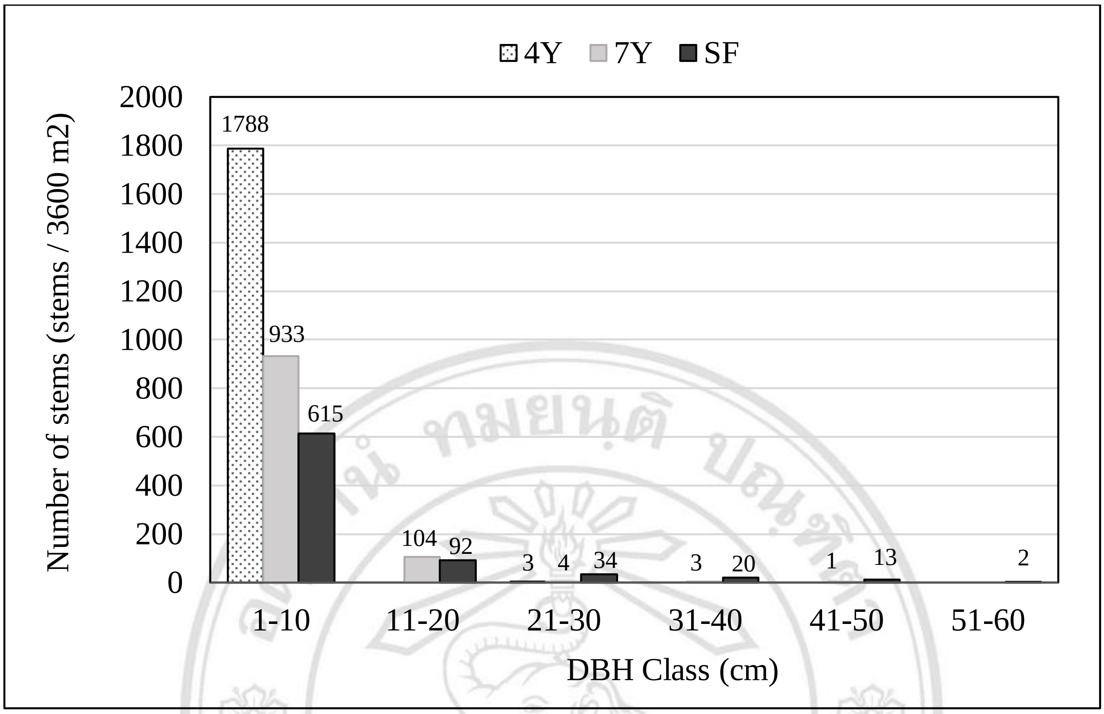


Figure 4.2 The distribution between DBH class size (cm) and number of trees (stems/3600 m^2) in the 4-year-fallow (4Y), the 7-year-fallow (7Y), and the Secondary forest (SF).

Table 4.3 The species name and number (n) of trees left standing in the 4-year-fallow (4Y) and the 7-year-fallow (7Y)

DBH Class	Site	Species name	Thai name	n
20-30 cm	4Y	*Schima wallichii*	ทะโล้	2
		Eugenia fruticosa	หว้าขี้กวาง	1
	7Y	*Quercus kingiana*	ก่อแดง	3
		Erythrina subumbrans	ทองหลางป่า	1
30-40 cm	7Y	*Quercus kingiana*	ก่อแดง	2
		Lithocarpus polystachyus	ก่อนก	1
40-50 cm	7Y	*Quercus kingiana*	ก่อแดง	1

Basal area decreased with DBH size class in the 4Y and the 7Y sites, following the pattern of the number of stems. However, in the SF sites, the basal area was low in the smallest DBH class, but initially increased with the DBH class. In the SF site, the highest basal area was found in the DBH class 41-50 cm, after which it dropped following the stem pattern (Figure 4.3).

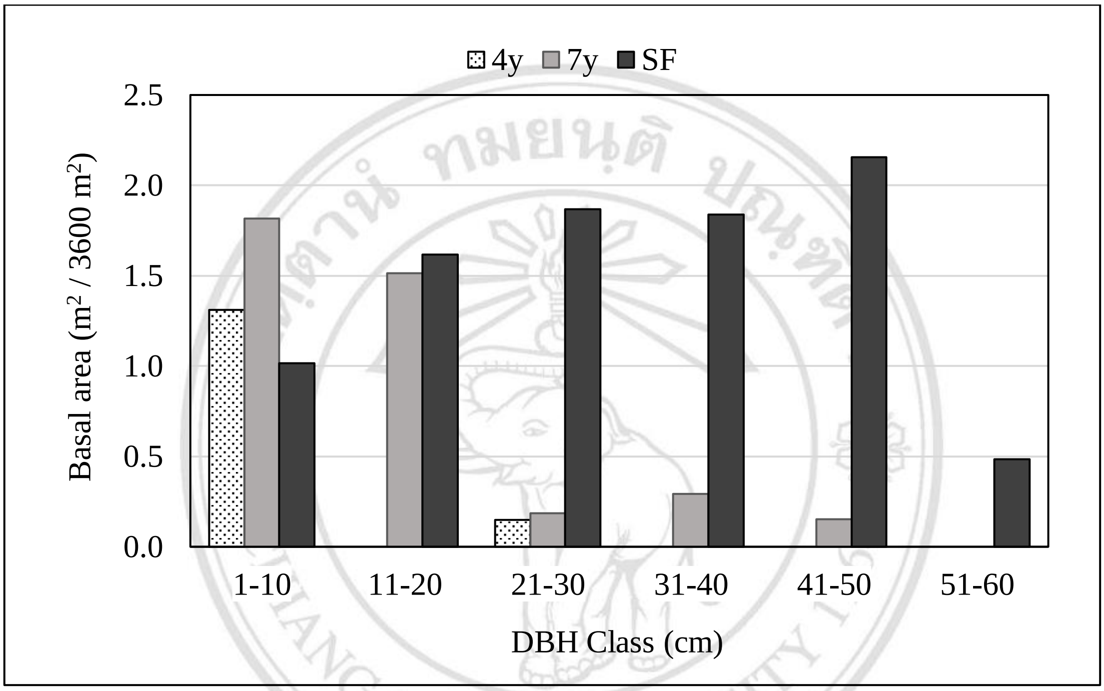


Figure 4.3 The distribution between DBH class size (cm) and basal area ($m^2/3600m^2$) in the 4-year-fallow (4Y), the 7-year-fallow (7Y), and the Secondary forest (SF).

4.2 Above-ground biomass

4.2.1 Harvested tree species

Harvested trees were selected from three different groups according to the plant diversity analysis; i) the IVI group – dominant species, that comprised cumulatively 50% of IVI (Table 4.2), ii) the S group – species present in all three study sites (Table 4.4), and iii) the F group – confirmed framework species, which are the list of species FORRU restoration method involves planting mixtures of 20 - 30 indigenous forest tree species that include both pioneer and climax species by following characteristics: i) high survival rate, ii) rapid growth, iii) dense, spreading crowns and iv) attractiveness to seed-dispersing wildlife. When these tree species planted on deforested land, help to re-establish the natural mechanisms of forest regeneration and accelerate biodiversity recovery (FORRU, 2005). Some framework species found in this study showed in Table 4.5.

Table 4.4 Tree species present all sites (S group).

S	Species name	Thai name	Family
1	*Aporosa villosa*	เหมือดโลด	Phyllanthaceae
2	*Canarium subulatum*	มะกอกเกลื้อน	Burseraceae
3	*Castanopsis acuminatissima*	ก่อเดือย	Fagaceae
4	*Eugenia fruticosa*	หว้าขี้กวาง	Myrtaceae
5	*Lithocarpus polystachyus*	ก่อนก	Fagaceae
6	*Phoebe lanceolata*	ตองหอม	Lauraceae
7	*Phyllanthus emblica*	มะขามป้อม	Phyllanthaceae
8	*Schima wallichii*	ทะโล้	Theaceae
9	*Styrax benzoides*	กำยาน	Styracaceae
10	*Wendlandia tinctoria*	แข้งกวาง	Rubiaceae

Table 4.5 Confirmed framework tree species (F group) (FORRU, 2005).

F	**Species name**	**Thai name**	**Family**
1	*Archidendron clypearia*	มะขามแป	Leguminosae
2	*Castanopsis acuminatissima*	มะกอกเกลื้อน	Burseraceae
3	*Castanopsis tribuloides*	ก่อใบเลื่อม	Fagaceae
4	*Erythrina subumbrans*	ทองหลางป่า	Leguminosae
5	*Eugenia fruticosa*	หว้าขี้กวาง	Myrtaceae
6	*Ficus fistulosa*	ชิ้งขาว	Moraceae
7	*Ficus hispida*	มะเดื่อปล้อง	Moraceae
8	*Heynea trijuga*	จางจืด	Meliaceae
9	*Quercus semiserrata*	ก่อกระดุม	Fagaceae
10	*Sapindus rarak*	มะซัก	Sapindaceae
11	*Sarcosperma arboreum*	มะยาง	Sapotaceae

For the IVI species, trees to harvest were determined based on DBH class. In the 7Y and the SF sites, three trees of each IVI species were collected in the DBH 4.5-10 cm class. This class was chosen because it contained a high number of individuals to facilitate replication, while making the harvesting process relatively uncomplicated. Three trees of each species in the DBH class were cut where density was highest. Finally, one tree per species in each of the bigger classes were harvested. However, the 4Y site contained only trees in the two smallest DBH classes. Also, the large amount of small coppicing trees made it difficult to select trees to harvest by considering the DBH classes, as in the 7Y and the SF sites. Therefore, the trees in the 4Y site were selected only from the two first DBH classes, with coppices included in both these 2 classes. Subsequently, 3 trees of each IVI species were collected, including every coppice of the selected trees. Furthermore, one tree of each species in the S and F groups were harvested at each study site.

After identifying which tree species to harvest, individual trees were randomly selected using the number assigned to each tree in the plant inventory data and a random number generator (at www.random.org). In some cases, a randomly selected tree could not be harvested (because it had died, fallen, been damaged by fire or been felled since the inventory, or it was simply too big to handle with the available infrastructure). In these cases, the next number on the list was selected, or when this was not possible, the best available alternative of that species was chosen. Harvested tree species, numbers of trees, and coppice samples from the different study sites are shown in Table 4.6-4.8.

Table 4.6 Number of destructively sampled trees (N) and total number of destructive trees including coppicing (numbers in parentheses) in 4-year-fallow

Group	Family	Species name	Thai name	N
1/S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	3 (16)
2/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	3 (14)
3/S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	3 (17)
4	Aquifoliaceae	*Ilex umbellulata*	เน่าใน	3 (7)
S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	1
S	Lauraceae	*Phoebe lanceolata*	ตองหอม	1
S	Theaceae	*Schima wallichii*	ทะโล้	1 (4)
S	Styracaceae	*Styrax benzoides*	กำยาน	1
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	1 (2)
S/F	Fagaceae	*Castanopsis acuminatissima*	ก่อเดือย	1 (2)
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	1 (4)
F	Moraceae	*Ficus fistulosa*	ชิ้งขาว	1 (3)
F	Moraceae	*Ficus semicordata*	มะเดื่อปล้องขาว	1 (2)
Total	10 Families	13 species		21(74)

Trees were harvested from three groups. The number (1, 2 and 3) signifies the rank in the IVI group, S consists of species present at every site, while F indicated framework tree species (FORRU, 2005).

Table 4.7 Number of destructively sampled trees (N) and total number of destructive trees including coppicing (numbers in parentheses) in 7-year-fallow.

Group	**Family**	**Species name**	**Thai name**	**N**
1	Fagaceae	*Quercus kingiana*	ก่อแดง	7 (8)
2/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	4 (5)
3	Leguminosae	*Dalbergia cultrata*	กระพี้เขาควาย	4 (4)
S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	1
S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	1
S/F	Fagaceae	*Castanopsis acuminatissima*	ก่อเดือย	1 (2)
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	1
S	Lauraceae	*Phoebe lanceolate*	ตองหอม	1
S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	1
S	Theaceae	*Schima wallichii*	ทะโล้	1 (2)
S	Styracaceae	*Styrax benzoides*	กำยาน	1 (2)
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	1
F	Fagaceae	*Quercus semiserrata*	ก่อกระดุม	1
Total	9 Families	13 species		25(30)

Trees were harvested from three groups. The number (1, 2 and 3) signifies the rank in the IVI group, S consists of species present at every site, while F indicated framework tree species (FORRU, 2005).

Table 4.8 Number of destructively sampled trees (N) in Secondary forest.

Group	**Family**	**Species name**	**Thai name**	**N**
1/F	Fagaceae	*Castanopsis tribuloides*	ก่อใบเลื่อม	4
2/S	Theaceae	*Schima wallichii*	ทะโล้	2
3	Fagaceae	*Castanopsis diversifolia*	ก่อแป้น	4
4/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	4
5/S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	4
6	Leguminosae	*Albizia chinensis*	กางหลวง	1
7	Proteaceae	*Helicia nilagirica*	ชิ้งขาว	4
S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	1
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	1
S/F	Lauraceae	*Phoebe lanceolata*	ตองหอม	1
S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	1
S	Styracaceae	*Styrax benzoides*	กำยาน	1
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	1
F	Leguminosae	*Archidendron clypearia*	มะขามแป	1
F	Sapindaceae	*Sapindus rarak*	มะซัก	1
F	Sapotaceae	*Sarcosperma arboreum*	มะยาง	1
Total	12 Families	16 species		32

Trees were harvested from three groups. The number (1, 2 and 3) signifies the rank in the IVI group, S consists of species present at every site, while F indicated framework tree species (FORRU, 2005).

In total, 78 trees (136 stems) representing 23 species, 19 genera, and 14 families were harvested and measured for aboveground biomass estimation in the three study sites. Tree diameter ranged from 1-32.9 cm and height from 2.1-19.3 cm. (Table 4.9). The most harvested species was *Lithocarpus polystachyus* (23 samples), followed by *Phyllanthus emblica* (19 samples) and *Aporosa villosa* (18 samples). In contrast, only one tree was harvested of *Albizia chinensis*, *Archidendron clypearia*, *Quercus semiserrata*, *Sapindus rarak*, *Sarcosperma arboretum* (Figure 4.4). The destructive samples, classified by DBH classes and H classes, is shown in Figure 4.5- 4.6.

Table 4.9 All destructive tree species from three study sites, number of trees (T), number of coppices (C), total stem samples (trees and coppices), DBH range in cm, and height (H) in cm

Species	Family	Tree (T)	Coppice (C)	Total (T+C)	DBH range (cm)	H range (cm)
Albizia chinensis	Leguminosae	1		1	21.6	19.3
Aporosa villosa	Phyllanthaceae	5	13	18	1.4-15.2	2.1-11.3
Archidendron clypearia	Leguminosae	1		1	5.9	5.9
Canarium subulatum	Burseraceae	6		6	2.7-30.9	3.8-15.1
Castanopsis acuminatissima	Fagaceae	2	2	4	5.1-11.1	4.1-7.3
Castanopsis diversifolia	Fagaceae	4		4	5.1-11.5	5.9-14.6
Castanopsis tribuloides	Fagaceae	4		4	4.8-15.3	6.5-16.5
Dalbergia cultrata	Leguminosae	4		4	5.2-10.8	5.0-8.9
Eugenia fruticosa	Myrtaceae	3	3	6	10.8-15.1	2.2-8.7
Ficus fistulosa	Moraceae	1	2	3	1.3-1.9	3.1-3.3
Ficus semicordata	Moraceae	1	1	2	2.1-3.3	3.9-4.0
Helicia nilagirica	Proteaceae	4		4	5.1-19.1	5.9-13.4
Ilex umbellulata	Aquifoliaceae	3	4	7	1-4.1	2.3-4.8
Lithocarpus polystachyus	Fagaceae	11	12	23	1-18.1	2.3-16.8
Phoebe lanceolata	Lauraceae	3		3	3.6-12.6	3.8-15.5
Phyllanthus emblica	Phyllanthaceae	5	14	19	1.8-13.1	3.3-10.7
Quercus kingiana	Fagaceae	7	1	8	6.9-32.9	4.9-13.6
Quercus semiserrata	Fagaceae	1		1	10.8	8.7
Sapindus rarak	Sapindaceae	1		1	16.2	15.5
Sarcosperma arboreum	Sapotaceae	1		1	6.1	7.2
Schima wallichii	Theaceae	4	4	8	2.2-17.8	3.9-17.0
Styrax benzoides	Styracaceae	3	1	4	4.1-10.5	5.3-8.2
Wendlandia tinctoria	Rubiaceae	3	1	4	1.4-8.5	2.8-11.7
23	**14**	**78**	**58**	**136**	**1-32.9**	**2.1-19.3**

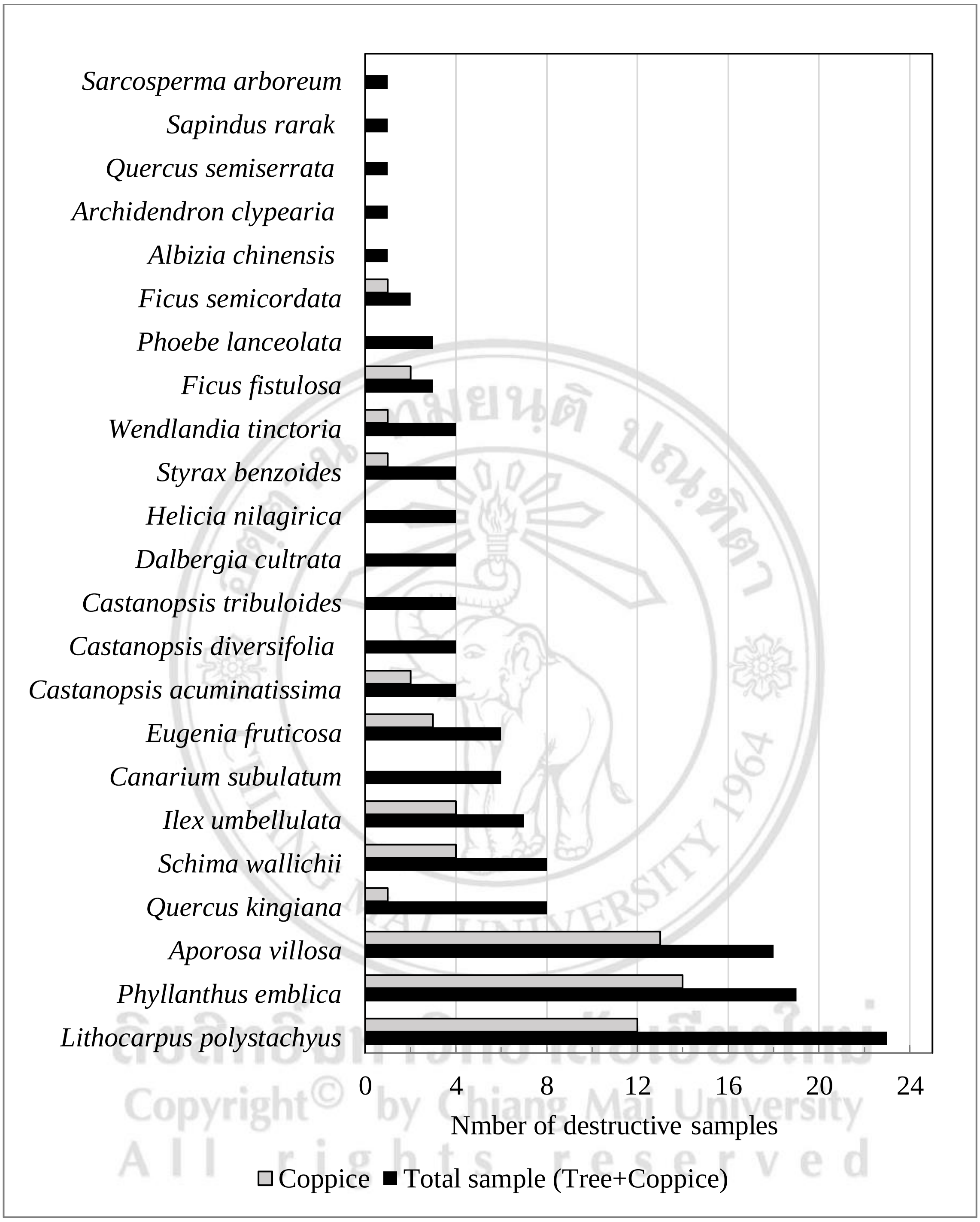


Figure 4.4 Total number of destructive samples for the different tree species

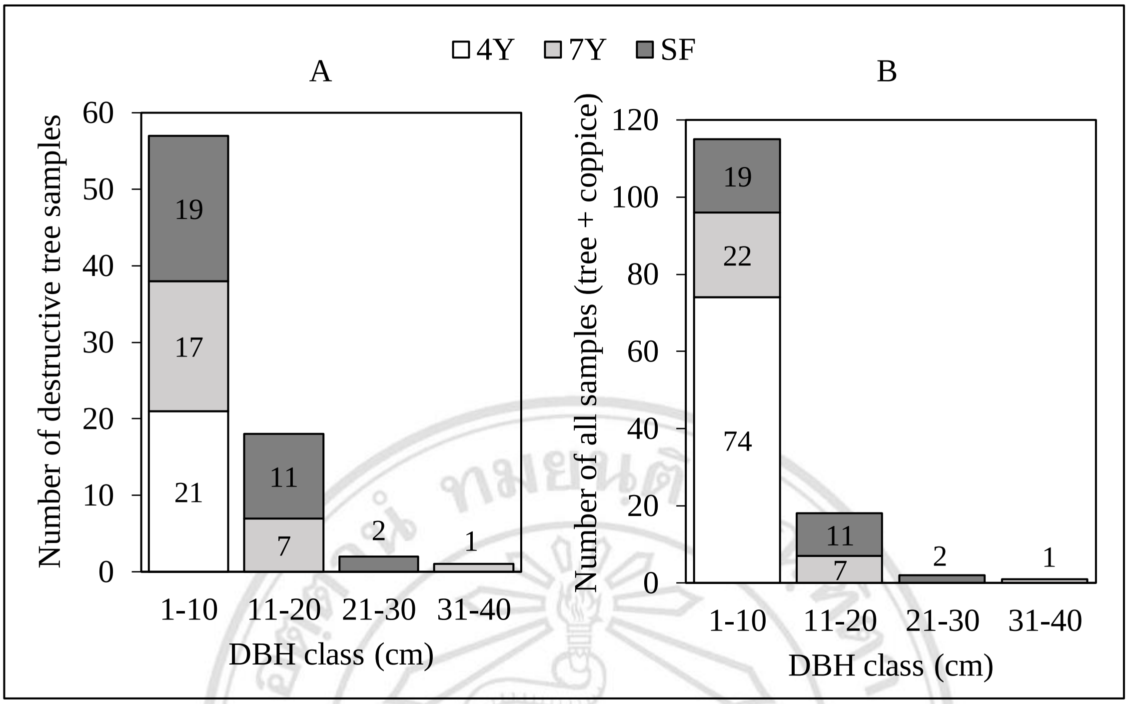


Figure 4.5 A) Distribution of destructive tree samples by DBH class (n = 78), and B) All individual stems including coppice tree (n = 136).

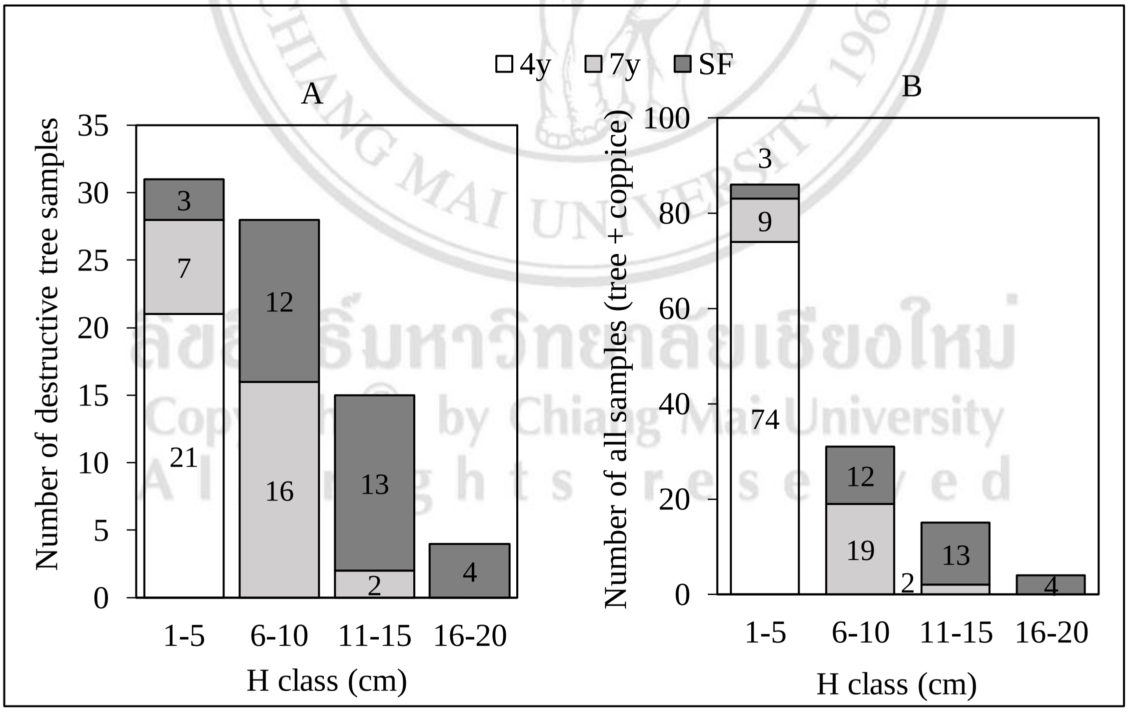


Figure 4.6 A) Distribution of destructive tree samples by height (H) class (n = 78), and B) All individual stems including coppice trees (n = 136).

4.2.2 Biomass allocation among tree parts averaging across species and plots

The highest proportion of biomass was found in stems (Ws), containing more than 40% of the total biomass in every DBH class (ranging from 45-78%). This was followed by branches (Wb), while the lowest biomass proportion was found in leaves (Wl). The highest percentage of the biomass was observed in stems with diameters 11-30 cm. Branch biomass had a similar proportion in the three DBH classes (I-III), after which it increased until reaching about 53% in the largest class. Meanwhile, leaves showed the opposite pattern, with the highest proportion found in the smallest DBH class and decreased from 12% to 2% with larger diameters (Figure 4.7). In addition, average biomass of different tree parts for the all species in each DBH class are shown in Appendix B.

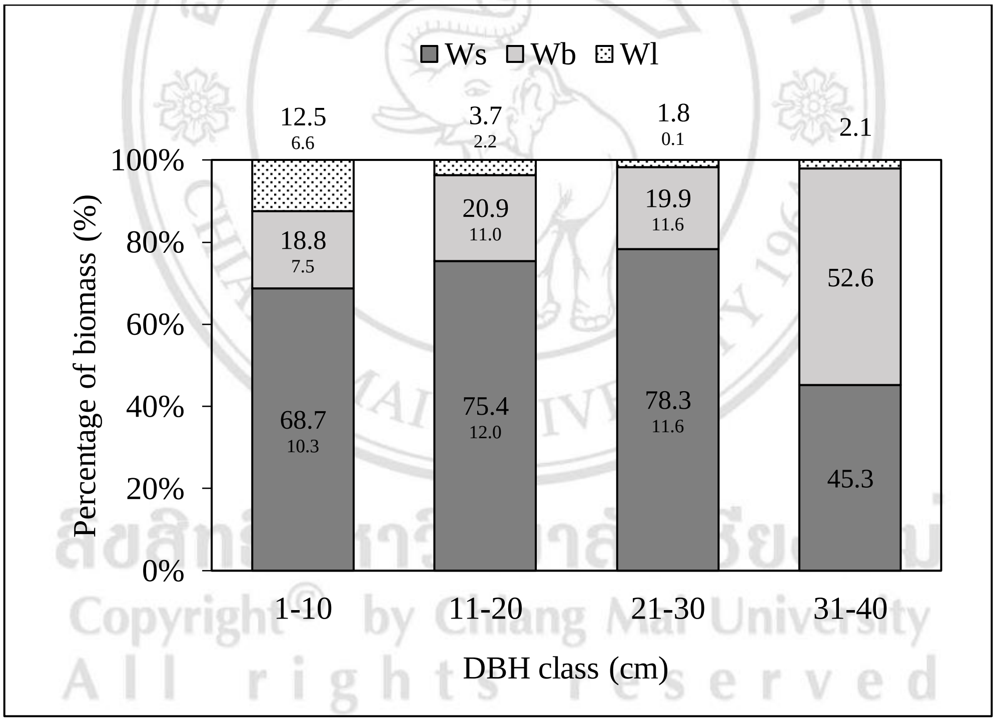


Figure 4.7 Above-ground biomass proportion of tree components across diameter classes. The larger numbers show mean values of all tree species, the smaller numbers below show standard deviations.

4.3 Wood density

Initially, 81 tree species were set to be collected, but 2 species in the inventory, *Dalbergia ovata* and *Lepisanthes tetraphylla*, died before the collection. Then, in total, 883 wood density samples (244 core and 639 discs) were collected from 79 species. Of these 79 species, 44 were included in the Global Wood Density Database (GWD) (Zanne et al., 2009), while 35 species (44%) were missing from the GWD. For 32 of these missing species, the genera were represented in the GWD. However, the genera of two species; was not found in the GWD, *Craibiodendron crepidioides*, and *Schoepfia fragrans* were not found either in the GWD and Tree Functional Attributes and Ecological Database.

Overall, the average wood density of all species in this study was 0.51±0.11g/cm^3. The species had the highest average wood density in this study was *Quercus kerrii* (0.68 g/cm^3) while *Bombax anceps* (0.19 g/cm^3) had the lowest. WD could not be collected for some species at the 7Y and SF sites with a DBH < 4.5 cm, since no disc samples were collected from trees in that DBH class and species at the 4Y site, which were not harvested (Appendix C-1). Differences in wood density, between increment borer and disc samples, was not significantly different within species for most species, except for: *Aporosa villosa, Dalbergia cultrata, Eugenia fruticosa, Lithocarpus polystachyus,* and *Phyllanthus emblica* (Independent Samples t-Test, $p < 0.05$) (Table 4.10). Furthermore, Duncan's Multiple Range tests showed significant differences in mean WD between some species (when $n \geq 3$) ($p < 0.05$). The lowest value of mean WD was found in *Ficus* spp. and the highest was found in *Flacourtia indica* (Figure 4.8, Appendix C-2).

Average wood density values of all species from destructive samples was 0.52±0.09 g/cm^3, ranging from 0.23 to 0.75 g/cm^3 and derived from direct measurement of 136 stems, were included for model development (Appendix D). Subsequently, biomass was estimated for all vegetation in the study (in total 117 species) by applying average wood density data of the 79 tree-specific species from this study and 23 species from GWD. Genus-level data was used for the 15 species missing from the GWD (Appendix C-1).

Table 4.10 Comparison of wood density (WD) (mean±SD) using in, different methods between increment borer and disc samples methods. Means sharing the same superscript are not significantly different from each other ($p < 0.05$), n is number of borer (one sample per trees), and N is number of discs (multiple samples per tree).

No.	Species name	Increment borer		Disc	
		WD (g/cm^3)	n	WD (g/cm^3)	N
1	*Albizia chinensis*	0.34±0.08 ^{a}	3	0.42±0.05 ^{a}	6
2	*Aporosa villosa*	0.60±0.06 ^{a}	10	0.50±0.08 ^{b}	60
3	*Archidendron clypearia*	0.38±0.05 ^{a}	3	0.43±0.03 ^{a}	5
4	*Canarium subulatum*	0.44±0.03 ^{a}	6	0.40±0.09 ^{a}	32
5	*Castanopsis acuminatissima*	0.60±0.11 ^{a}	6	0.58±0.12 ^{a}	20
6	*Castanopsis diversifolia*	0.63±0.09 ^{a}	6	0.56±0.09 ^{a}	29
7	*Castanopsis tribuloides*	0.61±0.06 ^{a}	6	0.60±0.07 ^{a}	24
8	*Dalbergia cultrata*	0.57±0.04 ^{a}	7	0.52±0.05 ^{b}	25
9	*Eugenia fruticosa*	0.59±0.03 ^{a}	7	0.47±0.08 ^{b}	24
10	*Helicia nilagirica*	0.54±0.03 ^{a}	6	0.53±0.07 ^{a}	30
11	*Lithocarpus polystachyus*	0.72±0.06 ^{a}	12	0.64±0.11 ^{b}	107
12	*Phoebe lanceolata*	0.51±0.06 ^{a}	7	0.52±0.10 ^{a}	17
13	*Phyllanthus emblica*	0.61±0.09 ^{a}	3	0.50±0.07 ^{b}	69
14	*Quercus kingiana*	0.64±0.08 ^{a}	7	0.57±0.09 ^{a}	43
15	*Sarcosperma arboreum*	0.57±0.06 ^{a}	4	0.53±0.03 ^{a}	7
16	*Schima wallichii*	0.54±0.01 ^{a}	4	0.53±0.06 ^{a}	43
17	*Styrax benzoides*	0.59±0.02 ^{a}	7	0.58±0.08 ^{a}	26
18	*Wendlandia tinctoria*	0.57±0.07 ^{a}	12	0.53±0.10 ^{a}	15

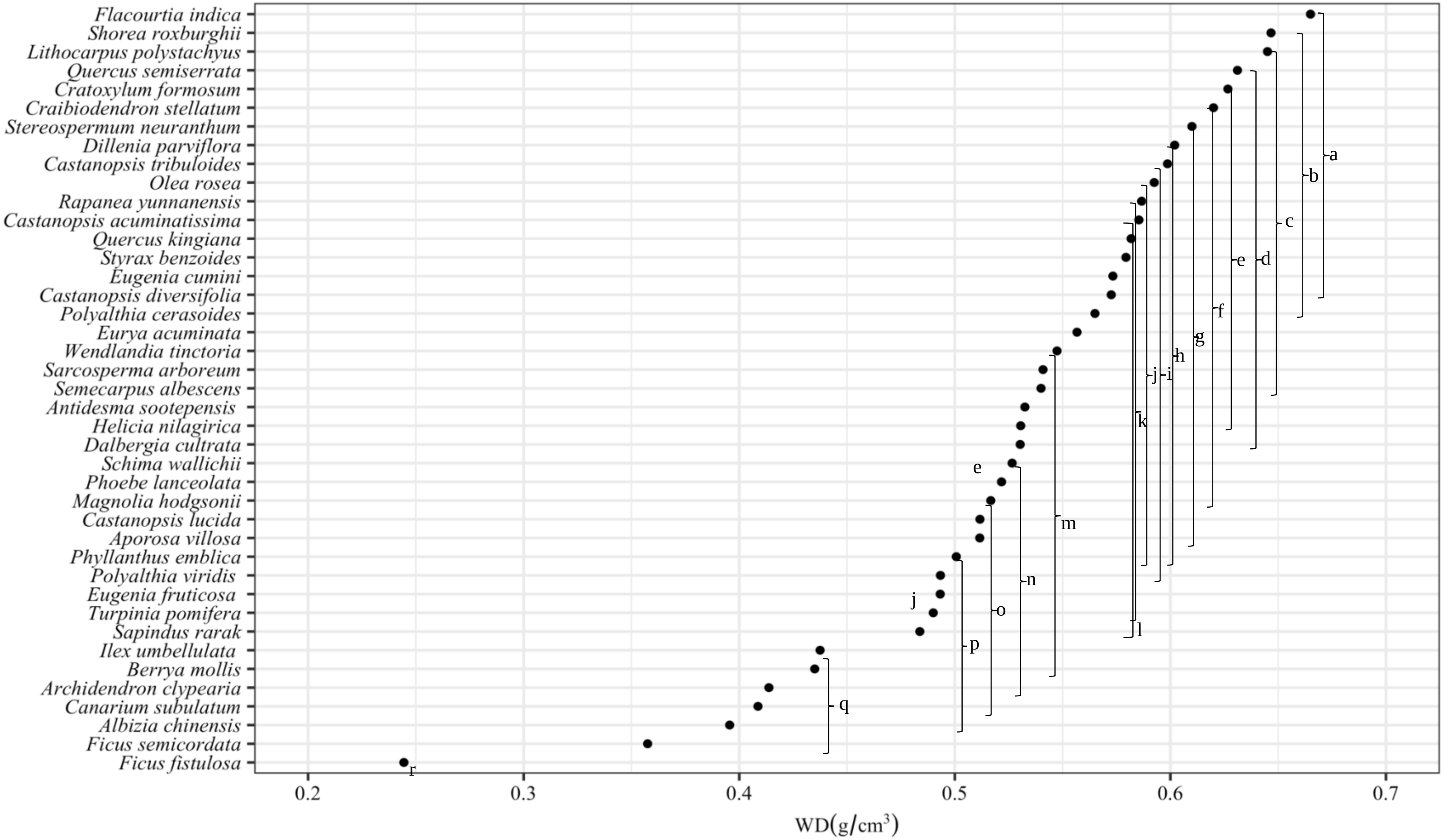


Figure 4.8 Average of wood density (g/cm3) between tree species of all WD samples of each species (n≥3).

4.4 Data analysis

4.4.1 Relationship between parameters

The scatterplot matrix showing the histograms, kernel density overlays, create a smooth curve given a set of data, absolute correlations and significance asterisks (p<0.05*, p<0.01**, p<0.001***) for the relationship between parameters of above-ground biomass (AGB), stem diameter at breast height (DBH), tree height (H), wood density (WD) for all the 136 destructive samples are shown in Figure 4.9 The three parameters of AGB, DBH, and H had strong significant correlations, and the correlation between WD with the other parameter are quite low.

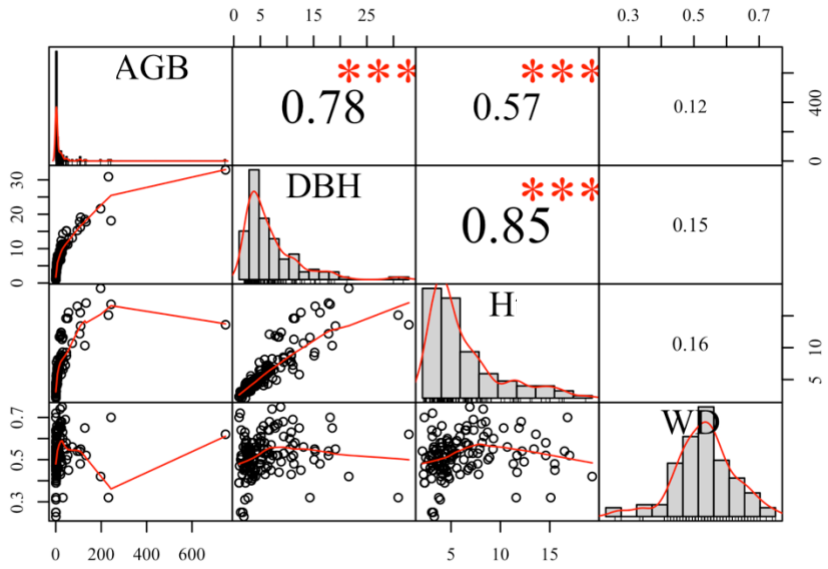


Figure 4.9 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for 136 trees against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

Moreover, the relationship between parameters of the tree species which contained the destructive samples more than 10 individual trees; *Lithocarpus polystachyus*, *Phyllanthus emblica*, *Aporosa villosa*, *Quercus kingiana*, *Schima wallichii*, *Ilex umbellulata*, *Canarium subulatum*, and *Eugenia fruticosa* are shown in Figures 4.10- 4.17 The relationships between AGB and DBH, AGB and H, DBH and H are highly significant in every species. Although, the correlations of WD and the other parameters showed the opposite results, excepted for *Lithocarpus polystachyus* that had the higher correlations between DBH and WD, H and WD, and for *Quercus kingiana* it was also shown to be significant between H and WD.

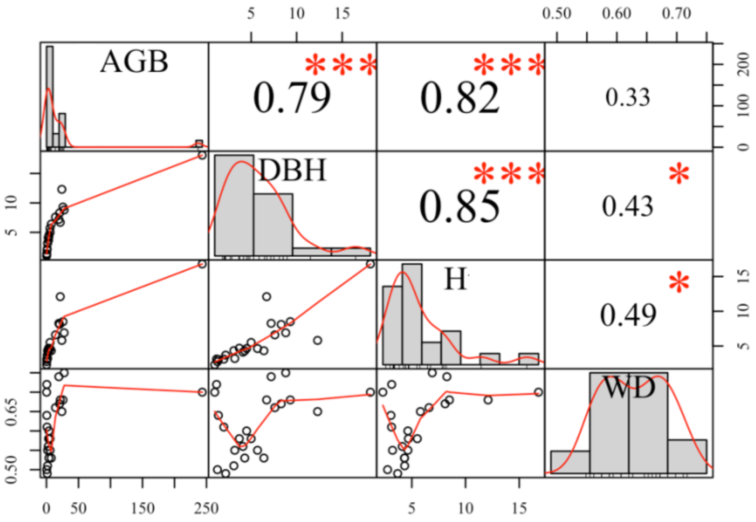


Figure 4.10 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks ($p<0.001$***, $p<0.01$**, $p<0.05$*) for the relationship of above-ground biomass (AGB) for *Lithocarpus polystachyus* (n=23, DBH = 1.0-18.1 cm), against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

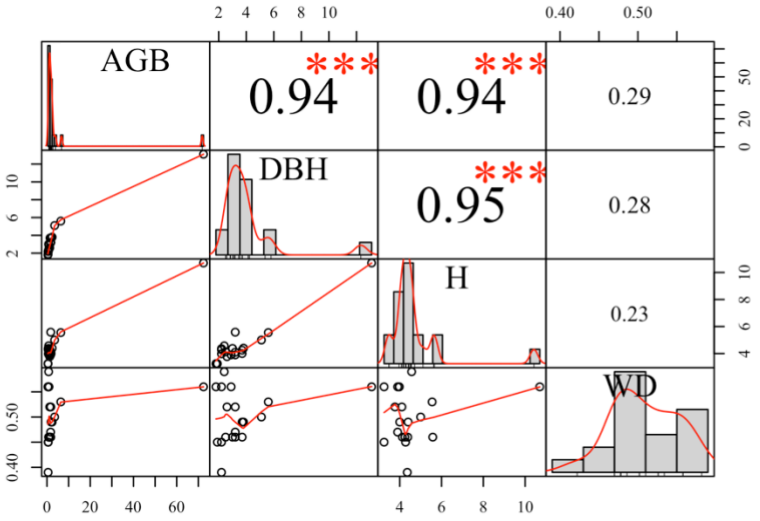


Figure 4.11 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Phyllanthus emblica* (n=19, DBH = 1.8-13.1 cm), against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

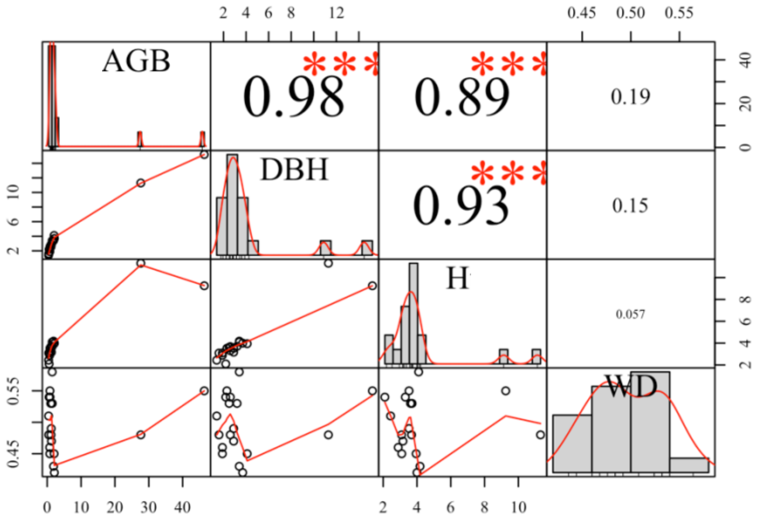


Figure 4.12 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Aporosa villosa* (n=18, DBH = 1.4 -15.2 cm), against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

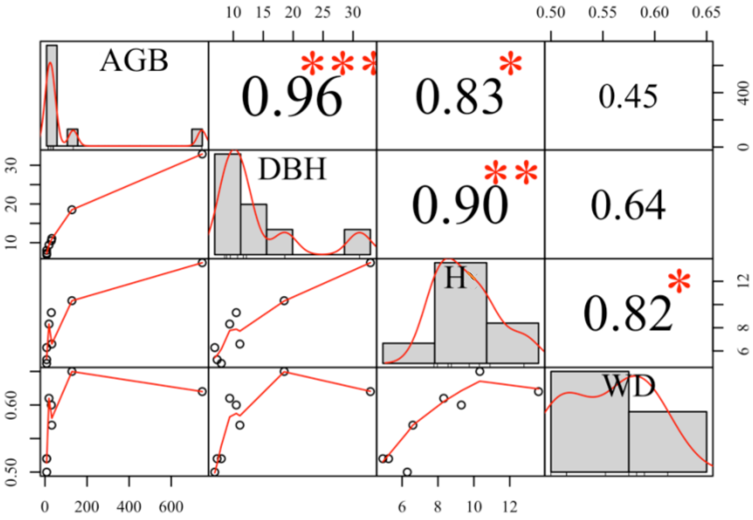


Figure 4.13 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Quercus kingiana* (n=8, DBH = 6.9-32.9 cm), against the variables of DBH, H, and WD. Correlations are significant at p < 0.05.

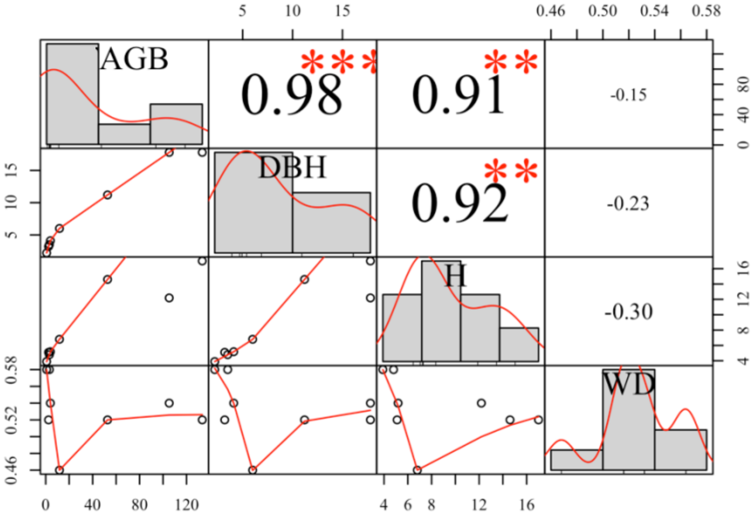


Figure 4.14 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Schima wallichii* (n=8, DBH = 2.2-17.8 cm), against the variables of DBH, H, and WD. Correlations are significant at p < 0.05.

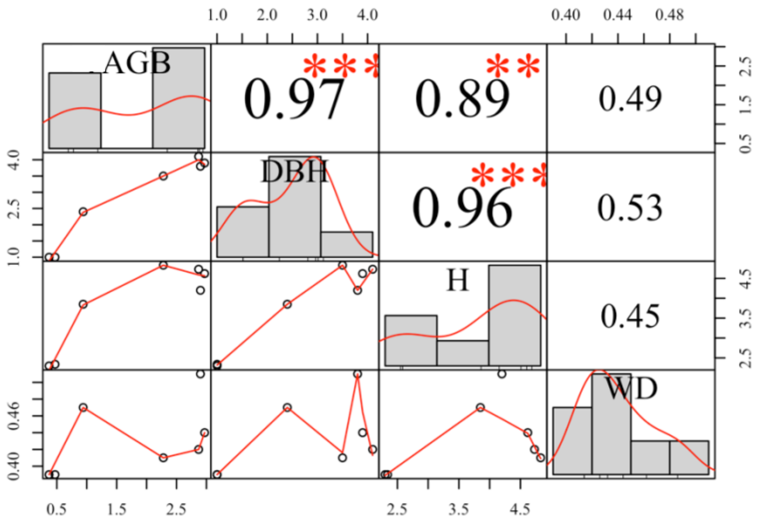


Figure 4.15 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Ilex umbellulata* (n=7, DBH = 1.0-4.1 cm), against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

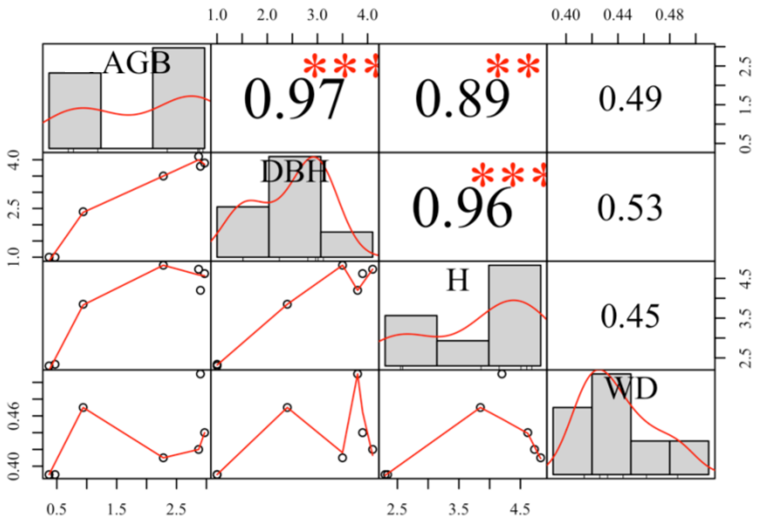


Figure 4.16 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Canarium subulatum* (n=6, DBH = 2.7-30.9 cm), against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

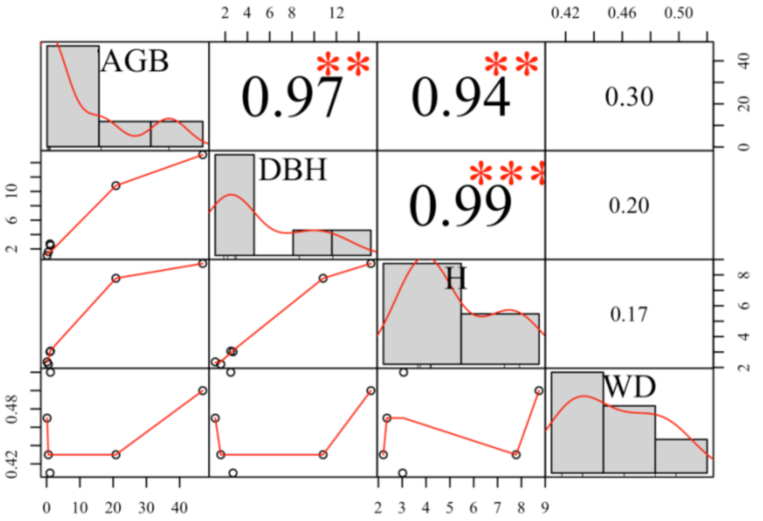


Figure 4.17 Scatterplot matrix showing histograms, kernel density overlays, absolute correlations and significance asterisks (p<0.001***, p<0.01**, p<0.05*) for the relationship of above-ground biomass (AGB) for *Eugenia fruticosa* (n=6, DBH= 1.1-15.1 cm), against the variables of DBH, H, and WD. Correlations are significant at $p < 0.05$.

4.4.2 Model validation and comparison

All destructive data from 136 trees were randomly split 200 times into training data and validating data. Eighty percent of the observed data (109 trees) were used for model development, while 20% (27 trees) were used for model validation. The same sets were used for validating and comparing all 8 common models. Cross-validation statistics were also computed for each realization of randomly selected data. The averaged validation statistic over the 200 realizations and %Bias, %RMSE and %MAPE are presented in Table 4.11. The Bias of all models ranged from -4.85% to -6.66%, RMSE ranged from 29.62% to 38.30%, and MAPE ranged from 22.02% to 29.33%. Model VI-VIII shared the same variables (DBH, H, and WD), and model VII showed the lowest values of Bias, RMSE, and MAPE, with fewer parameters requiring estimation.

Table 4.11 Model validation and comparison between eight common models. Cross-validation statistics were computed for each realization of randomly selected validation data, and averaged over the 200 realizations; N=109.

No.	**Model**	**Bias (%)**	**RMSE (%)**	**MAPE (%)**
I	$\ln(AGB) = a + b\ln(DBH)$	-6.66	37.22	29.33
II	$\ln(AGB) = a + b\ln(DBH) + c(\ln(DBH))^2$	-6.19	38.30	28.27
III	$\ln(AGB) = a + b\ln(DBH) + c\ln(H)$	-6.27	35.29	26.24
IV	$\ln(AGB) = a + b\ln(DBH) + c\ln(WD)$	-5.46	33.26	25.72
V	$\ln(AGB) = a + b\ln(DBH^2H)$	-6.35	35.56	26.17
VI	$\ln(AGB) = a + b\ln(DBH^2H) + c\ln(WD)$	-4.91	29.88	22.16
VII	$\ln(AGB) = a + b\ln(DBH^2H \cdot WD)$	-4.85	29.62	22.02
VIII	$\ln(AGB) = a + b\ln(DBH) + c\ln(H) + d\ln(WD)$	-4.89	29.83	22.30

AGB: above-ground biomass, DBH: stem diameter at breast height, H: tree height, WD: wood density

4.4.3 Model development and selection

Eight common allometric models were fitted with data from 136 harvested individual trees to establish relationships between measured AGB and DBH, H, and WD as predictor variables. Adjusted R^2 exceeded 0.9 in all models. The lowest adjusted R^2 value was 0.959 in the model I (DBH only). Adding H or WD into the equations increased R^2 slightly, while RSE, AIC, and %S decreased. In contrast, the highest R^2, 0.972, was found in model VI-VII, which provided a better fit by adding WD together with DBH and H. The best fit model was model VII, which had the highest adjusted R^2, a low average deviation (S%) of 21.64 and the lowest RSE and AIC values of 0.298 and 61.3, respectively. The relationship between AGB and the parameter of independent variables of all models and all regression coefficients used were statistically significant ($p < 0.001$) (Table 4.12).

Table 4.12 Comparison of different allometric equations for estimating aboveground biomass (AGB) with different input variables (entire dataset, 136 trees).

Model No.		Parameter estimated				Adj. R^2	RSE	AIC	S%
		a	*b*	*c*	*d*				
I	ln(AGB) = *a* + *b* ln(DBH)	-2.032	2.275			0.959	0.365	115.5	29.19
II	ln(AGB) = *a* + *b* ln(DBH) + *c* (ln(DBH))^2	-1.618	1.603	0.209		0.966	0.333	92.1	27.11
III	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(H)	-2.571	1.832	0.721		0.966	0.334	92.7	25.69
IV	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(WD)	-1.473	2.227	0.723		0.965	0.337	95.3	25.52
V	ln(AGB) = *a* + *b* ln(DBH^{2}H)	-2.675	0.869			0.966	0.334	91.8	25.78
VI	ln(AGB) = *a* + *b* ln(DBH^{2}H) + *c* ln(WD)	-2.069	0.850	0.768		0.972	0.299	63.0	21.61
VII	ln(AGB) = *a* + *b* ln(DBH^{2}H·WD)	-2.003	0.847			0.972	0.298	61.3	21.64
VIII	ln(AGB) = *a* + *b* ln(DBH)+ *c* ln(H) + *d* ln(WD)	-2.008	1.761	0.756	0.761	0.972	0.300	64.4	21.71

DBH indicate stem diameter at breast height, H: tree height, WD: wood density, Parameter estimated; a, b, c and d are the coefficients estimated of regression model, Adj R^2 is the coefficient of determination, RSE: residual standard error of the estimate, AIC: Akaike Information Criterion, and S%: average deviation. All regression coefficients used were statistically significant in all models ($p < 0.001$

The allometric relationship between AGB and DBH^{2}HWD based on model VII is shown in Figure 4.18. The best fit equation for AGB estimation in this study was:

$$ln(AGB) = -2.003 + 0.847 ln(DBH^2HWD)$$

$$\text{or } AGB = \exp(-2.003 + 0.847 ln(DBH^2HWD))$$

$$\text{or } AGB = 0.134\ (DBH^2HWD)^{\ 0.847}$$

However, the destructive trees with highest residual error was found in a *Canarium subulatum* tree (DBH = 30.9 cm, H=15.1 m) in the SF site, and two coppices were *Ilex umbellulata* with DBHs of 1 cm and H were 2.30 cm, and 2.34 cm, respectively.

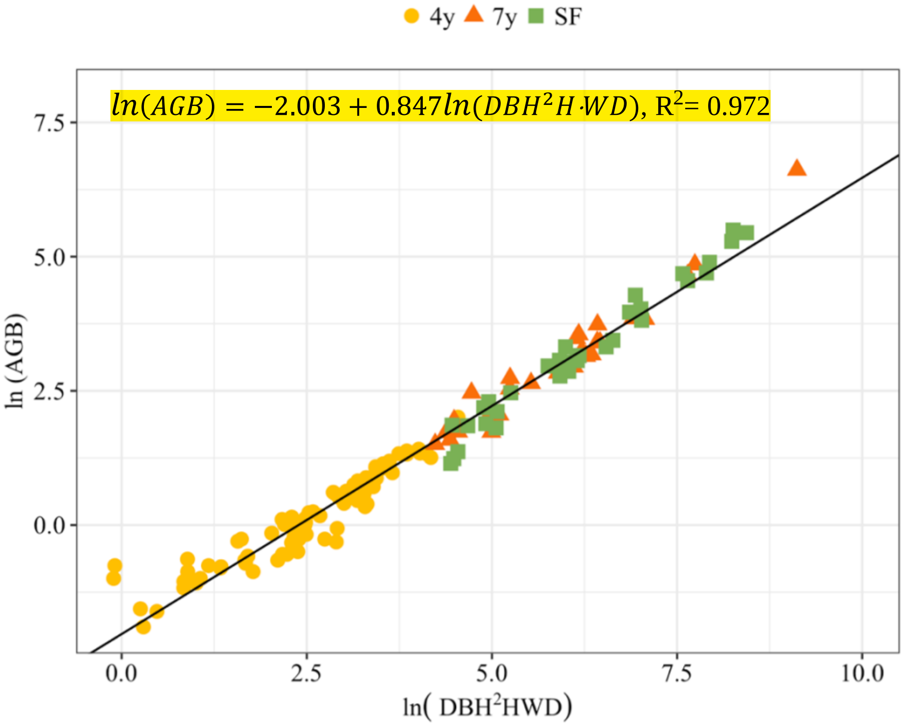


Figure 4.18 Relationship between the natural log transformation of above-ground biomass values observed in this study (AGB) and the best-fit explanatory variable $DBH^2H{\cdot}WD$ (N=136)

Moreover, allometric equation for species-specific of *Lithocarpus polystachyus*, *Phyllanthus emblica*, and *Aporosa villosa*, which were harvested from more than 10 samples were tested by following the eight general models. The AGB estimation equation of *Lithocarpus polystachyus* from 23 harvested individual trees showed the best fit on Model VII with DBH^2HWD as a parameter with ($R^2 = 0.99$) is shown in Table 4.13 and Figure 4.19 The best fit equation for species-specific AGB estimation of *Lithocarpus polystachyus* was:

$$ln(AGB) = -1.912 + 0.846ln(DBH^2H{\cdot}WD)$$

$$\text{or } AGB = \exp(-1.912 + 0.846ln(DBH^2H{\cdot}WD))$$

$$\text{or } AGB = 0.147\ (DBH^2H{\cdot}WD)^{0.846}$$

Table 4.13 Comparison of different allometric equations for estimating aboveground biomass (AGB) with different input variables of *Lithocarpus polystachyus* (23 individual trees).

Model No.		Parameter estimated				Adj. R^2	RSE	AIC	S%
		a	*b*	*c*	*d*				
I	$\ln(AGB) = a + b\ln(DBH)$	-1.682	2.186			0.957	0.360	22.3	26.84
II	$\ln(AGB) = a + b\ln(DBH) + c(\ln(DBH))^2$	-1.345	1.430	0.282*		0.967	0.316	17.0	22.78
III	$\ln(AGB) = a + b\ln(DBH) + c\ln(H)$	-2.756	1.468	1.311		0.990	0.168	-11.9	11.87
IV	$\ln(AGB) = a + b\ln(DBH) + c\ln(WD)$	-0.736	2.102	1.677		0.971	0.296	14.0	19.35
V	$\ln(AGB) = a + b\ln(DBH^2H)$	-2.414	0.864			0.987	0.198	-5.4	14.08
VI	$\ln(AGB) = a + b\ln(DBH^2H) + c\ln(WD)$	-1.865	0.843	0.922**		0.991	0.163	-13.2	12.10
VII	$\ln(AGB) = a + b\ln(DBH^2H{\cdot}WD)$	-1.912	0.846			0.992	0.160	-15.1	12.02
VIII	$\ln(AGB) = a + b\ln(DBH) + c\ln(H) + d\ln(WD)$	-2.241	1.524	1.148	0.674*	0.992	0.152	-15.6	11.95

DBH indicate stem diameter at breast height, H: tree height, WD: wood density, Parameter estimated; a, b, c and d are the coefficients estimated of regression model, Adj R^2 is the coefficient of determination, RSE: residual standard error of the estimate, AIC: Akaike Information Criterion, and S%: average deviation. Significance of the parameter estimate is indicated with ‘*’ for $P < 0.05$; ‘**’ for $P < 0.01$, for ‘ ’ for $P < 0.001$.

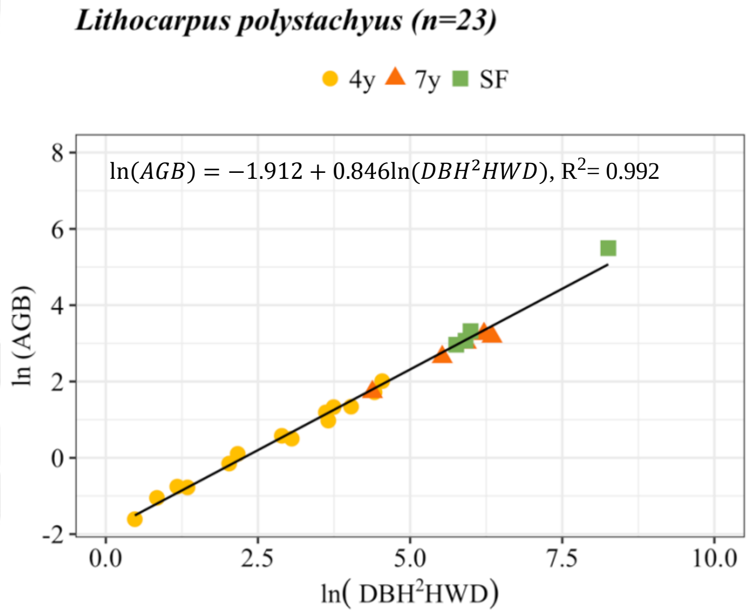


Figure 4.19 Species-specific relationship between the natural log transformation of above-ground biomass values observed in this study (AGB) and the best-fit explanatory variable DBH^2HWD of *Lithocarpus polystachyus*

However, the species specific models of *Phyllanthus emblica* (n=19) (Table 4.14, Figure 4.20), and *Aporosa villosa* (n=18) (Table 4.15, Figure 4.21) showed the best fit on model II, which contained only DBH as a parameter, had the highest adjusted R^2, the lowest RSE and AIC. The best fit equation for species-specific AGB estimation of *Phyllanthus emblica* was:

$$ln(AGB) = -1.743 + 1.327ln(DBH) + 0.393(ln(DBH))^2),\ R^2 = \ 0.962$$

$$\text{or } AGB = \exp(-1.743 + 1.327ln(DBH) + 0.393(ln(DBH))^2)$$

and equation for species-specific of *Apososa villosa* was:

$$ln(AGB) = -1.277 + 1.056ln(DBH) + 0.318(ln(DBH))^2),\ R^2 = \ 0.985$$

$$\text{or } AGB = \exp(-1.743 + 1.327ln(DBH) + 0.393(ln(DBH))^2)$$

Table 4.14 Comparison of different allometric equations for estimating aboveground biomass (AGB) with different input variables of *Phyllanthus emblica* (19 individual trees).

Model No.		Parameter estimated				Adj. R^2	RSE	AIC	S%
		a	*b*	*c*	*d*				
I	ln(AGB) = *a* + *b* ln(DBH)	-2.505	2.510			0.952	0.257	6.2	34.00
II	ln(AGB) = *a* + *b* ln(DBH) +*c*(ln(DBH))^2	-1.743	1.327*	0.393*		0.962	0.229	2.8	30.19
III	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(H)	-2.963	2.269	0.494^{ns}		0.952	0.257	7.1	30.80
IV	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(WD)	-2.010	2.474	0.648^{ns}		0.953	0.255	7.1	29.62
V	ln(AGB) = *a* + *b* ln(DBH^{2}H)	-3.418	1.003			0.952	0.258	6.3	30.60
VI	ln(AGB) = *a* + *b* ln(DBH^{2}H) + *c* ln(WD)	-2.840	0.987	0.738		0.954	0.254	6.5	24.11
VII	ln(AGB) = *a* + *b* ln(DBH^{2}HWD)	-2.644	0.980			0.956	0.247	4.7	23.37
VIII	ln(AGB) = *a* + *b* ln(DBH)+ *c* ln(H) + *d* ln(WD)	-2.470	2.213	0.530^{ns}	0.688^{ns}	0.953	0.2543	6.9	25.32

DBH indicate stem diameter at breast height, H: tree height, WD: wood density, Parameter estimated; a, b, c and d are the coefficients estimated of regression model, Adj R^2 is the coefficient of determination, RSE: residual standard error of the estimate, AIC: Akaike Information Criterion, and S%: average deviation. Significance of the parameter estimate is indicated with 'ns' for p > 0.05 (on-significant), '*' for P < 0.05; '**' for P < 0.01, for ' ' for P < 0.001.

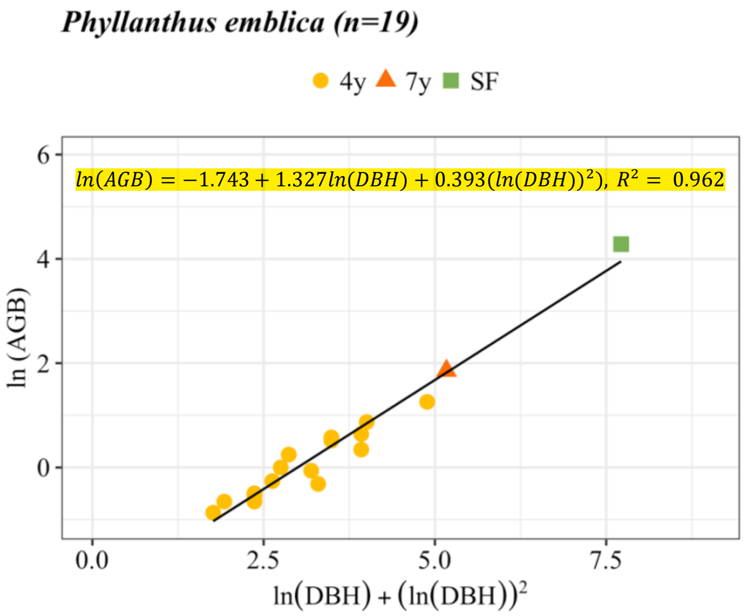


Figure 4.20 Species-specific relationship between the natural log transformation of above-ground biomass values observed in this study (AGB) and the best-fit explanatory variable DBH, DBH^2 of *Phyllanthus emblica*

Table 4.15 Comparison of different allometric equations for estimating aboveground biomass (AGB) with different input variables of *Apososa villosa* (18 individual trees).

Model No.		Parameter estimated				Adj. R^2	RSE	AIC	S%
		a	*b*	*c*	*d*				
I	ln(AGB) = *a* + *b* ln(DBH)	-1.871	2.041			0.972	0.209	-1.3	29.92
II	ln(AGB) = *a* + *b* ln(DBH) + *c*(ln(DBH))^2	-1.277	1.056**	0.318**		0.985	0.152	-11.9	32.97
III	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(H)	-2.428	1.493	0.878**		0.982	0.167	-8.6	26.83
IV	ln(AGB) = *a* + *b* ln(DBH) + *c* ln(WD)	-2.299	2.048	-0.596^{ns}		0.972	0.208	-0.7	36.16
V	ln(AGB) = *a* + *b* ln(DBH^{2}H)	-2.368	0.779			0.983	0.162	-10.4	27.13
VI	ln(AGB) = *a* + *b* ln(DBH^{2}H) + *c* ln(WD)	-2.677	0.780	-0.431^{ns}		0.983	0.162	-9.6	32.69
VII	ln(AGB) = *a* + *b* ln(DBH^{2}HWD)	-1.799	0.771			0.976	0.195	-3.8	17.79
VIII	ln(AGB) = *a* + *b* ln(DBH)+ *c* ln(H) + *d* ln(WD)	-2.704	1.520	0.842**	-0.417^{ns}	0.982	0.168	-7.7	32.37

DBH indicate stem diameter at breast height, H: tree height, WD: wood density, Parameter estimated; a, b, c and d are the coefficients estimated of regression model, Adj R^2 is the coefficient of determination, RSE: residual standard error of the estimate, AIC: Akaike Information Criterion, and S%: average deviation. Significance of the parameter estimate is indicated with ‘ns’ for p > 0.05 (on-significant), ‘*’ for P < 0.05; ‘**’ for P < 0.01, for ‘ ’ for P < 0.001.

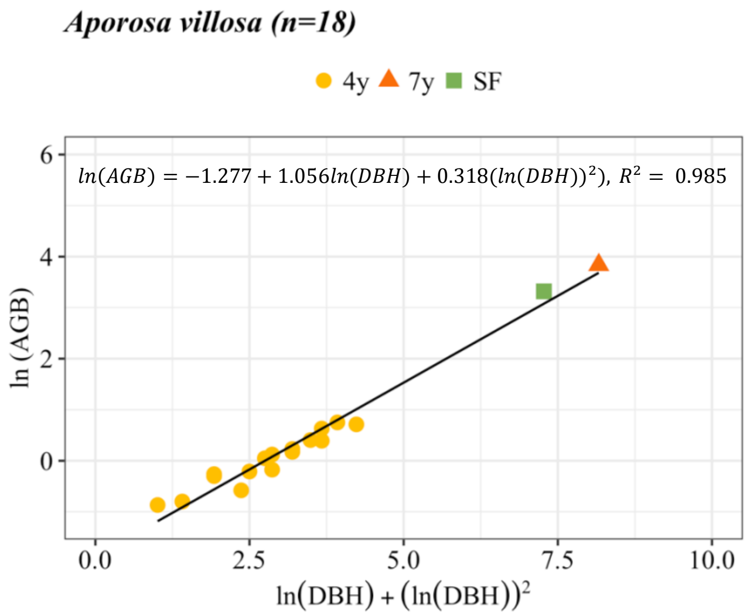


Figure 4.21 Species-specific relationship between the natural log transformation of above-ground biomass values observed in this study (AGB) and the best-fit explanatory variable DBH, DBH^2 of *Apososa villosa*

4.4.4 Carbon content

Carbon concentration in dry wood mass was analysed in 899 samples from 23 destructive tree species. The highest average carbon (%) was found in *Archidendron clypearia*, 46.67% (±1.89), while the lowest value was seen in *Ficus fistulosa*, 39.43% (±3.87). Overall, the average carbon content was 44.84 % (±1.63) (Appendix E). Moreover, significant differences between the species-specific average carbon content was observed by applying Duncan's Multiple Range test, $p < 0.05$ (Figure 4.22)

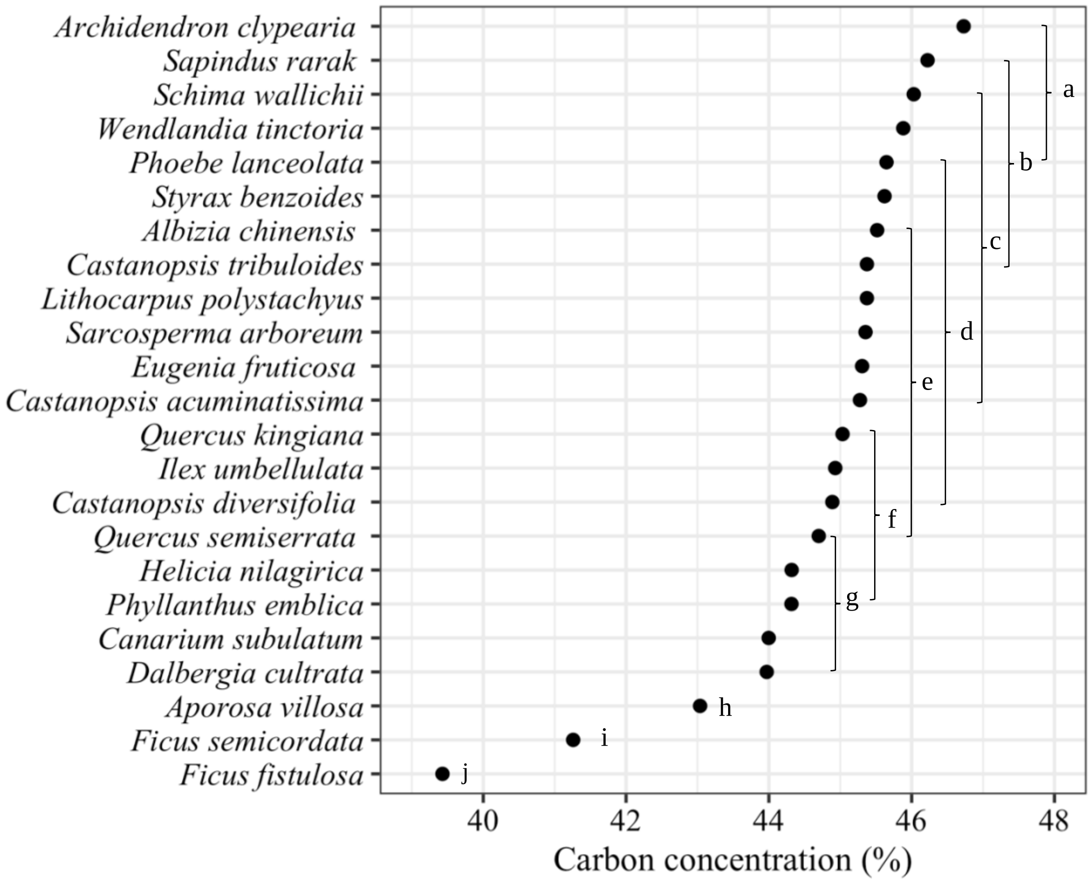


Figure 4.22 Average carbon concentration (%) differences among destructive tree species. Bars not sharing the same superscript are significantly different ($p < 0.05$).

4.4.5 Applying the allometric model and carbon content for above-ground biomass (AGB) estimation and above-ground carbon (AGC) sequestration

Aboveground biomass accumulation was estimated by applying the vegetation data, recorded in the beginning of this study, to the best-fit allometric equation (Model VII) as a function of DBH^2HW. Even though a bamboo species (*Gigantochloa albociliata*) found only in the 7-year-follow site, a bamboo-specific allometric equation was used to calculate biomass based on a mixed bamboo species model, which included *Gigantochloa* sp. (Yuen et al., 2017); $AGB = 0.269D^{2.017}$, where AGB in kg and D is culm DBH in cm. This equation is based on 65 bamboo samples collected in Chiang Mai Province, Thailand, with a culm DBH ranging from 2 to 7.5 cm.

Species specifics carbon concentration analysis results were used for the 23 species found in the inventory data. For the remaining species, the average carbon content across species was used. Only bamboo species using carbon factor of 50% (following Smith et al., 2010, cited in Yuen et al., 2017). Above-ground carbon (AGC) values were then evaluated by multiplying above-ground biomass (AGB) by the carbon factor.

Biomass increased 10 fold from 4Y to mature SF. In 3600 m^2, the 4Y had accumulated 3.7 Mg above-ground biomass, corresponding to 6.7% of total above-ground biomass. This increased to 13.8 Mg in the 7Y, or 24.9% of total above-ground biomass, including bamboo biomass of 0.9 Mg. Unsurprisingly, the highest amount was found in the secondary forest site, 37.9 Mg or 68.4% of total above-ground biomass. Moreover, the SF site sequestered the highest amount of carbon (17.2 Mg C/ha), followed by the 7Y site at 6.3 Mg C/ha, and 4Y site at 1.7 Mg C/ha.

Per hectare, the highest AGB and AGC values were recorded in the SF site (105.3 Mg/ha and 47.7 Mg C/ha), followed by the 7Y site (38.3 Mg/ha and 17.4 Mg C/ha). Being the youngest study site, the 4Y site had accumulated AGB at 10.3 Mg/ha and AGC at 4.6 Mg/ha. In average, the three sites in this study are estimated to accumulate 51.3 Mg/ha of biomass and 23.2 Mg C/ha carbon (Table 4.16, Figure 4.23).

Table 4.16 Above-ground biomass (AGB) and above-ground carbon (AGC) accumulation among study site per ha.

Type		AGB (Mg/ha)				AGC (Mg C/ha)			
		4Y	7Y	SF		4Y	7Y	SF	
Tree	DBH ≥1-4.5 cm	5.6	2.5	1.1		2.5	1.2	0.5	
	DBH ≥ 4.5 cm	4.7	33.3	104.2		2.1	15.0	47.1	
Bamboo	*G. albociliata*	-	2.50	-		-	1.3	-	
	Total	10.3	38.3	105.3		4.6	17.4	47.7	
	Average				51.3				23.2

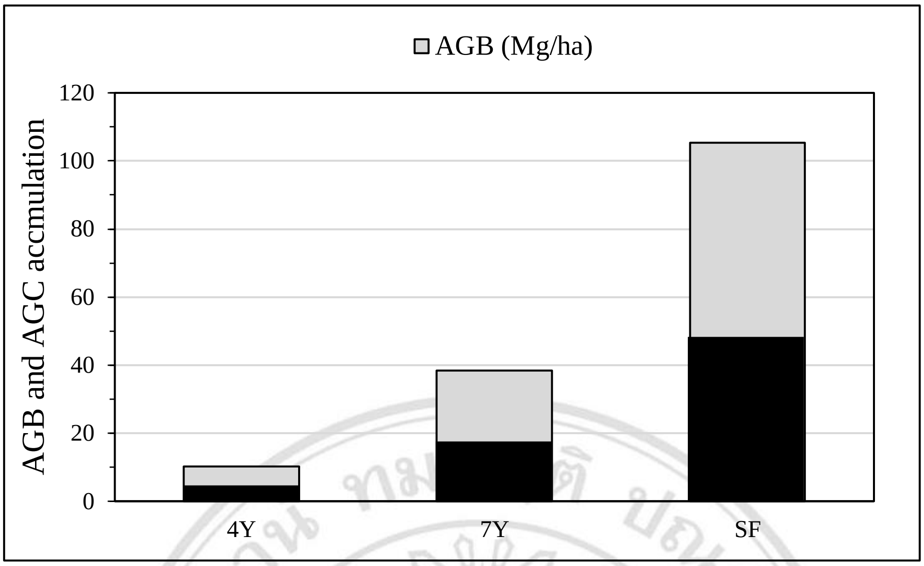


Figure 4.23 Accumulation of above-ground biomass (AGB) and above-ground carbon (AGC) per ha (including bamboo).

4.4.6 Above-ground biomass (AGB) accumulation in the selected destructive tree species

Using the newly developed equation, the selected tree species in the 4Y site was estimated to contain up to 75% of all biomass in the site. *Lithocarpus polystachyus* had the largest biomass (2.72 Mg/ha), largest BA (0.91 m^2/ha), and second highest stem density (747 stems/ha), followed by *Schima wallichii* (1.52 Mg/ha) with lower BA and stem density values. *Aporosa villosa* had the third largest biomass in the 4Y site, although it had a higher BA than *S. Wallichii* and the highest stem density of all species. Moreover, the FORRU framework tree species *Castanopsis acuminatissima*, *Eugenia fruticose, Ficus semicordata* and *Ficus fistulosa* stored about 4.2% of all biomass in this site (Table 4.17).

Table 4.17 Above-ground biomass (AGB), basal area (BA) and stem density of the destructive species in the 4-year-fallow (4Y).

Group	Family	Species name	Thai name	AGB (Mg/ha)	AGB (%)	BA (m^2/ha)	Stems/ha
IVI/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	2.72	26.511	0.91	747
S	Theaceae	*Schima wallichii*	ทะโล้	1.52	14.782	0.44	106
IVI/S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	1.44	14.038	0.75	1297
IVI/S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	0.65	6.328	0.31	533
S	Styracaceae	*Styrax benzoides*	กำยาน	0.47	4.598	0.16	147
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	0.35	3.393	0.17	89
IVI	Aquifoliaceae	*Ilex umbellulata*	เน่าใน	0.33	3.221	0.19	328
S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	0.11	1.073	0.05	83
S/F	Fagaceae	*Castanopsis acuminatissima*	ก่อเดือย	0.07	0.692	0.02	19
S	Lauraceae	*Phoebe lanceolata*	ตองหอม	0.04	0.407	0.02	25
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	0.02	0.205	0.01	31
F	Moraceae	*Ficus semicordata*	มะเดื่อปล้องขาว	0.01	0.094	0.01	11
F	Moraceae	*Ficus fistulosa*	ชิ้งขาว	0.00	0.015	0.00	8
	Sum of all species			7.74	75.359	3.03	3425
	Total data in 4Y			10.27	100	4.05	4975

In the 7-year-fallow, *Quercus kingiana* contained by far the highest amount of AGB of the selected species, 57% of the total biomass in the site, followed by *Lithocarpus polystachyus* (8.7%). Together, the selected species accounted for 85% of the total biomass accumulation in 7Y site, with the FORRU species (*Castanopsis acuminatissima, Eugenia fruticose, Quercus semiserrata, Erythrina subumbrans*) accounting for 4.7% (Table 4.18).

In the secondary forest, the highest AGB accumulation of the selected destructive species was 21.1 Mg/ha, recorded in *Schima wallichii,* which also had the highest BA but not the highest stem density. It was followed by *Castanopsis diversifolia* and *C.tribuloides* with 19.6 Mg/ha and 15.1 Mg/ha, respectively. The selected species were estimated to store 83% of all biomass in the SF site. Many FORRU trees species were found in SF site, and one of them are also part of the most dominant species. Consequently, 22.4% of the total biomass in SF site was stored in FORRU species (Table 4.19).

Table 4.18 Above-ground biomass (AGB), basal area (BA) and stem density of the destructive species in the 7-year-fallow (7Y).

Group	Family	Species name	Thai name	AGB (Mg/ha)	AGB (%)	BA (m^2/ha)	Stems/ha
IVI	Fagaceae	*Quercus kingiana*	ก่อแดง	20.5	57.0	5.8	511
IVI/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	3.1	8.7	1.0	144
S	Styracaceae	*Styrax benzoides*	กำยาน	1.5	4.3	0.4	456
IVI	Leguminosae	*Dalbergia cultrata*	กระพี้เขาควาย	1.3	3.5	0.4	175
S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	1.0	2.9	0.4	372
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	0.9	2.6	0.3	42
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	0.9	2.4	0.3	172
S/F	Fagaceae	*Castanopsis acuminatissima*	ก่อเดือย	0.4	1.1	0.1	14
S	Theaceae	*Schima wallichii*	ทะโล้	0.3	0.9	0.1	11
F	Leguminosae	*Erythrina subumbrans*	ทองหลางป่า	0.2	0.7	0.1	3
F	Fagaceae	*Quercus semiserrata*	ก่อกระดุม	0.1	0.4	0.0	6
S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	0.1	0.3	0.1	25
S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	0.1	0.3	0.0	72
S	Lauraceae	*Phoebe lanceolata*	ตองหอม	0.1	0.2	0.0	14
	Sum of all species			30.6	85.3	9.2	2016.7
	Total data in 7Y site (without bamboo)			35.9	100.0	11.0	2903

IVI species, S is species present at every site, while F is FORRU framework tree species.

Table 4.19 Above-ground biomass (AGB), basal area (BA) and stem density of the destructive species in the Secondary forest (SF).

Group	Family	Species name	Thai name	AGB (Mg/ha)	AGB (%)	BA (m^2/ha)	Stems/ha
IVI/S	Theaceae	*Schima wallichii*	ทะโล้	21.1	20.0	4.7	69
IVI	Fagaceae	*Castanopsis diversifolia*	ก่อแป้น	19.9	18.9	4.0	86
IVI/F	Fagaceae	*Castanopsis tribuloides*	ก่อใบเลื่อม	15.1	14.3	3.3	103
IVI/S	Fagaceae	*Lithocarpus polystachyus*	ก่อนก	7.0	6.6	1.5	139
IVI	Leguminosae	*Albizia chinensis*	กางหลวง	6.1	5.7	1.7	25
IVI/S	Burseraceae	*Canarium subulatum*	มะกอกเกลื้อน	5.0	4.7	1.5	42
S/F	Fagaceae	*Castanopsis acuminatissima*	ก่อเดือย	3.3	3.1	0.7	39
F	Meliaceae	*Heynea trijuga*	จางจืด	1.9	1.8	0.5	3
IVI	Proteaceae	*Helicia nilagirica*	ชิ้งขาว	1.9	1.8	0.8	36
S/F	Myrtaceae	*Eugenia fruticosa*	หว้าขี้กวาง	1.8	1.7	0.5	39
S	Rubiaceae	*Wendlandia tinctoria*	แข้งกวาง	1.4	1.3	0.4	56
S/F	Lauraceae	*Phoebe lanceolata*	ตองหอม	0.7	0.7	0.2	150
S	Styracaceae	*Styrax benzoides*	กำยาน	0.6	0.5	0.1	28
S	Phyllanthaceae	*Aporosa villosa*	เหมือดโลด	0.4	0.4	0.2	25
F	Sapotaceae	*Sarcosperma arboreum*	มะยาง	0.3	0.3	0.1	14
F	Sapindaceae	*Sapindus rarak*	มะซัก	0.3	0.3	0.1	3
F	Leguminosae	*Archidendron clypearia*	มะขามแป	0.3	0.3	0.1	61
S	Phyllanthaceae	*Phyllanthus emblica*	มะขามป้อม	0.1	0.1	0.0	6
	Sum of all species			87.0	82.5	20.6	922
	Total data in SF site			105.4	100	24.9	2156

CHAPTER 5

Discussion

5.1 Developing allometric models for tree biomass estimation

In this study, allomeric equations were developed based on previously established models, by starting with one simple independent parameter, namely dimeter at breast height (DBH), which is easy to measure and also the best parameter for biomass estimation (Brown, 1997; Hashimoto et al., 2004; Basuki et al., 2009; Kenzo et al., 2009). Subsequently, parameters like tree height (H) and other common combination parameters, such as D^2H (Ogawa et al., 1965; Tsutsumi et al., 1983, Chan et al., 2013) and D^2HWD (Chave et al., 2005, 2014) were added. As expected, introducing more independent parameters increased the R^2 and reduced the values of AIC, RSE, and S% of the AGB estimation (Table 4.13). Adding tree height in the models with two dimensions variables (D^2H) resulted in a higher correlation with AGB, which was also reported by Chan et al. (2013). The same combined variable (D^2H) also showed smaller AIC values than the model using separate variables, even though H or WD was added to the model. The inclusion of the three parameters (DBH, H, and WD) in the same model improved the goodness of fit, and Model VII, which combined the variables in term of DBH^2HWD, showed the best fit. Including wood density as a parameter improved accuracy, in line with a number of previous studies (Chave et al., 2005, 2014; Basuki et al., 2009; van Breugel et al., 2011; Nam et al., 2016; Huy et al., 2016b; Kralicek et al., 2017).

5.2 Allometric model validation and comparison

Cross-validation was processed for each type of model and compared separately to previous models from other studies, using the same number of independent variables. The AGB models with only DBH as predictor variable in this study (Model I, II) were compared with the allometric equations of Brown (1997) and IPCC (2003), which were created using DBH data from tropical forests, as well as the equation of Kenzo et al. (2009), created from trees in post-fire secondary forests in Malaysia. The model that used DBH and H (Model V) was compared with the Tsutsumi et al. (1983) model commonly used for biomass estimation in Thailand, and the model from Chan et al. (2013), developed as the best fit model in term of DHH^{2}H from swidden cultivation fallows in Myanmar. Moreover, McNicol et al. (2015) proposed DBH and H as the best fit model, based on data from swidden cultivation fallows in Laos. After this, all the three variables together in the term of DBH^{2}HWD (Model VII) were compared to the most well-known published equations from Chave et al. (2005, 2014), which were developed from a large secondary dataset from tropical forests on several continents.

The statistical validation means through the 200 iterations are shown in Table 5.1. The RMSE and MAPE values for Model I, based only on DBH, were comparable to Kenzo et al. (2009). Most of the models resulted in a negative %Bias, the only exception being the Kenzo et al. (2009)'s model, which tended to underestimate the AGB. Nevertheless, the RMSE and MAPE values for Model II were higher than for Model I. However, one DBH-based variable developed in this study showed considerably lower values compared to the models of Brown (1997) and IPCC (2003).

For the two-parameter Model V (D^{2}H), the Bias, RMSE and MAPE values were similar to those of Chan et al. (2013) and McNicol et al. (2015), but much lower than Tsutsumi et al (1983), which were established from the data collected in Thailand. The fact that the values from Chan et al (2013) and McNicol et al (2015) were close to Model V can be explained by them using similar DBH sizes to establish the biomass model. In contrast, the Tsutsumi et al. (1983) model was based on trees with larger diameters.

Model VII, that used the three parameters together in the term DBH^{2}HWD, showed lower Bias, RMSE, and MAPE values, compared to all three equations from Chave et al. (2005, 2014) with the same variable parameters.

The WD dataset comprises the average wood density data of species analysed in this study, whilst WD data from Global Wood Density data base (GWD) from Zanne et al. (2009) were used for species where WD was missing. However, For 15 species, where WD data were not available from either source, the average WD of the genus from GWD (WDg) was used instead. Such allocation to a higher taxonomical level has previously been suggested by Baker et al. (2004) and Fayolle et al. (2013).

Consequently, average wood density of each species (WDa) were applied to the model validation instead of using direct WD data from direct measurement of each individual tree. As expected, the Bias, RMSE and MAPE percentages increased slightly in all models when applying D^2HWDa. Moreover, using the average wood density of genera (WDg) in the model resulted in higher Bias, RMSE and MAPE values in the validation analysis, compared to using wood density from WD and WDa (Table 5.1).

Furthermore, one of the 200 validation datasets was chosen from the lowest values of %Bias, %RMSE, %MAPE and applied to selected models from this study (Model I, II,V, and VII) and other models for above-ground biomass estimation. Considering the allometric equations from previous studies, Brown (1997)'s equation was developed for dry zones with rainfall > 900-1500 mm/year, whereas moist equation was developed for moist forests with rainfall >1500 mm/year, as were the equation from IPCC (2003). The remaining three equations were established from young secondary forests in Malaysia (Kenzo et al., 2009), swidden fallows in Myanmar (Chan et al., 2013), and swidden fallows in Laos (McNicol et al., 2015). Pantropical equations were established from a big dataset from both dry and moist tropical forests (Chave et al., 2005, 2014), while the Tsutsumi et al. (1983) equation was developed from dry evergreen forest in Thailand. Above-ground biomass was evaluated with all the models named as AGB(predicted) and compared with AGB(observed), which was the destructive AGB data collected in this study.

The AGB(predicted) from the models based on only DBH, Model I and II in this study, were broadly similar to the model from Brown (1997) for dry forest and Kenzo et al. (2009). Model I had the best fit DHB base equation, with a result close to that of the model developed by Kenzo et al. (2009). This may be explained by the fact that these two models were developed from trees within approximately the same range of DBH: 0.11-28.7 in Kenzo et al. (2009) compared to 1-32.9 in this study. In contrast, both the Brown (1997) model and the IPCC (2003) model for moist tropical forests overestimated the AGB(predicted) and showed a higher % relative error (Figure 5.1-5.2). The Kenzo et al. (2009) model, on the other hand, underestimated the % relative error (Figure.5.2) and showed a positive %Bias (Table 5.1).

The models using DBH^2H as explanatory parameters overestimated the AGB in Tsutsumi et al. (1983) and McNicol et al. (2015). When applying the data to Chan et al. (2013), it exhibited an under-predictive trend for biomass even though that model was built on a similar tree size, from 1.2 to 25.4 cm. Chan's model also underestimated the AGB when using the D^2H equation by applying explanatory data from their study and comparing with Tsutsumi et al. (1983)'s equation (Figure 5.3-5.4).

Lastly, the model that included WD in term of DBH^2HWD showed the best goodness of fit compared to the other models in this study. The results clearly showed that all equations from pantropical forests over-predicted the AGB compared to Model VII. This overestimation has also been reported in McNicol et al. (2015) and van Breugel et al. (2011) when using Chave et al. (2005)'s moist forests equation for biomass estimation in secondary forests. As seen in Figure 5.5, the trend line from Chave et al. (2005)'s equation for dry forest showed a higher over-prediction than the other models in the graph. However, the new equation from Chave et al. (2014) presented better values of % relative error (Figure 5.5.-5.6).

Table 5.1 Validation of selected models and comparison to previous models (N = 27 trees by splitting randomly 200 times). Cross-validation statistics were computed and averaged over the 200 iterations.

Input variables	Site	Forest type	Reference equation		DBH (cm)	N	Bias (%)	RMSE (%)	MAPE (%)
DBH	India	DF	Brown (1997) (Dry)	$AGB = exp(-1.996 + 2.32 ln(DBH))$	5-40	28	-18.30	44.05	33.70
	WMT		Brown (1997) (Moist)	$AGB = exp(-2.134 + 2.530\, ln(DBH))$	5-130	269	-44.72	70.60	53.11
	Malaysia.	ESF	Kenzo et al. (2009)	$AGB = 0.0829(DBH)^{2.43}$	0.11-28.7	107	14.02	33.60	28.28
	This study	**HEF,F**	**Model I**	$\boldsymbol{AGB = exp(-2.03185 + 2.27503 ln(DBH))}$	**1-32.9**	**136**	**-6.41**	**36.62**	**28.84**
	WMT		IPCC (2003)	$AGB = exp(-2.289 + 2.649\, ln(DBH - 0.021(ln(DBH))^2)$	5-148	170	-41.18	69.39	51.48
	This study	**HEF,F**	**Model II**	$\boldsymbol{AGB = \exp(-1.61844 + 1.60341 ln(DBH) + 0.20919\, (ln(DBH))^2)}$	**1-32.9**	**136**	**-7.40**	**42.48**	**30.04**
DBH,H	Chaiyapoom, Thailand	DEF	Tsutsumi et al. (1983)	$AGB = Ws + Wb + Wl$	~ 60(DBHmax)	60	-32.40	53.98	40.37
			Stem	$Ws = 0.0509\, (DBH^2H)^{0.919}$	-	-	-42.90	58.75	45.37
			Branch	$Wb = 0.00893(DBH^2H)^{0.977}$	-	-	-63.49	143.06	89.25
			Leaves	$Wl = 0.0140(DBH^2H)^{0.669}$	-	-	-14.76	89.75	60.23
	Myanmar	MDF,F	Chan et al. (2013)	$AGB = 0.063(DBH^2H)^{0.862}$	1.2-25.4	160	6.13	31.37	24.67
	Laos	MF,F	McNicol et al., (2015)	$AGB = 0.19 + 0.027(DBH^2H)$	1.7-36.2	150	6.27	31.18	26.29
	This study	**HEF,F**	**Model V**	$\boldsymbol{AGB = exp(-2.67506 + 0.86882 ln(DBH^2H))}$	**1-32.9**	**136**	**-6.02**	**34.93**	**25.66**
DBH,H,WD	Pan tropical forest		Chave et al. (2005) (Dry)	$AGB = \exp(-2.187 + 0.916 \ln(DBH^2HWD))$ $\equiv 0.112(DBH^2HWD)^{0.916}$	5-156	2410	-16.04	36.98	28.39
			Chave et al. (2005) (Moist)	$AGB = exp(-2.977 + ln(DBH^2HWD))$ $\equiv 0.0509(DBH^2HWD)$	5-156	2410	22.95	36.23	30.56
	Pan tropical forest		Chave et al. (2014)	$AGB = 0.0673(DBH^2HWD)^{0.976}$	5-212	4004	8.88	32.00	26.72
	This study	**HEF,F**	**Model VII**	$\boldsymbol{AGB = exp(-2.00325 + 0.84730\, ln(DBH^2HWD))}$	**1-32.9**	**136**	**-4.66**	**29.14**	**21.60**

WMT = world moist tropical, DF= dry forest, ESF=early succession secondary forest, HEF= hill evergreen forest, F=fallow after shifting or swidden cultivation, DEF= dry evergreen forest, MDF=mixed deciduous forest, MF=moist forest

Table 5.1 Continued

Input variables	Site	Forest type		Reference equation	DBH (cm)	N	Bias (%)	RMSE (%)	MAPE (%)
DBH,H,WDa	Pan tropical forest		Chave et al. (2005) (Dry)	$AGB = exp(-2.187 + 0.916\, ln(DBH^2HWDa))$ $\equiv 0.112(DBH^2HWDa)^{0.916}$	5-156	2410	-18.80	39.15	30.33
			Chave et al. (2005) (Moist)	$AGB = \exp(-2.977 + \ln(DBH^2HWDa))$ $\equiv 0.0509(DBH^2HWDa)$	5-156	2410	21.23	35.93	30.51
	Pan tropical forest		Chave et al. (2014)	$AGB = 0.0673(DBH^2HWDa)^{0.976}$	5-212	4004	6.87	32.43	27.11
	HEF,F	**This study**	**Model VII**	$\boldsymbol{AGB = exp(-2.00325 + 0.84730 ln(DBH^2HWDa))}$	**1-32.9**	**136**	**-6.77**	**30.23**	**22.21**
DBH,H,WDg	**HEF,F**	**This study**	**Model VII**	$\boldsymbol{AGB = exp(-2.00325 + 0.84730 ln(DBH^2HWDg))}$	**1-32.9**	**136**	**-21.16**	**44.06**	**33.05**

WMT = world moist tropical, DF= dry forest, ESF=early succession secondary forest, HEF= hill evergreen forest, F=fallow after shifting or swidden cultivation, DEF= dry evergreen forest, MDF=mixed deciduous forest, MF=moist forest

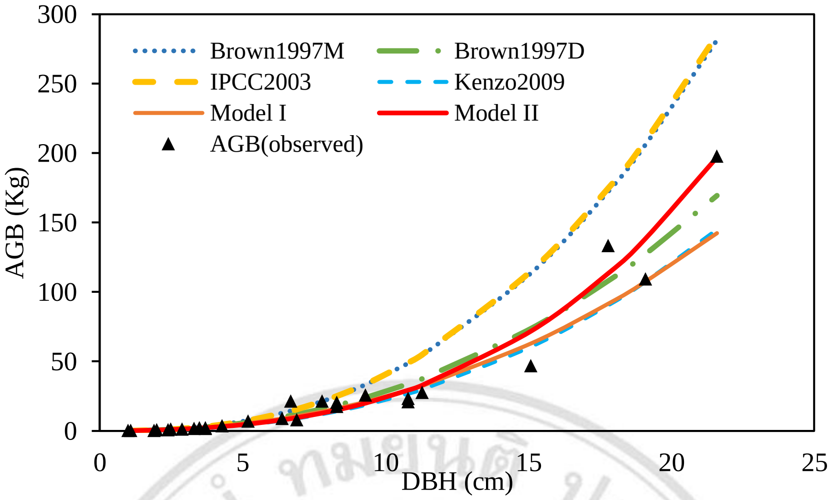


Figure 5.1 The above-ground biomass (AGB observed) from validation data and predicted values using four existing DBH-based models: Brown1997D and Brown 1997M developed for dry and moist forests, respectively, IPCC (2003), and Kenzo et al. (2009). Model I and II are models from this study.

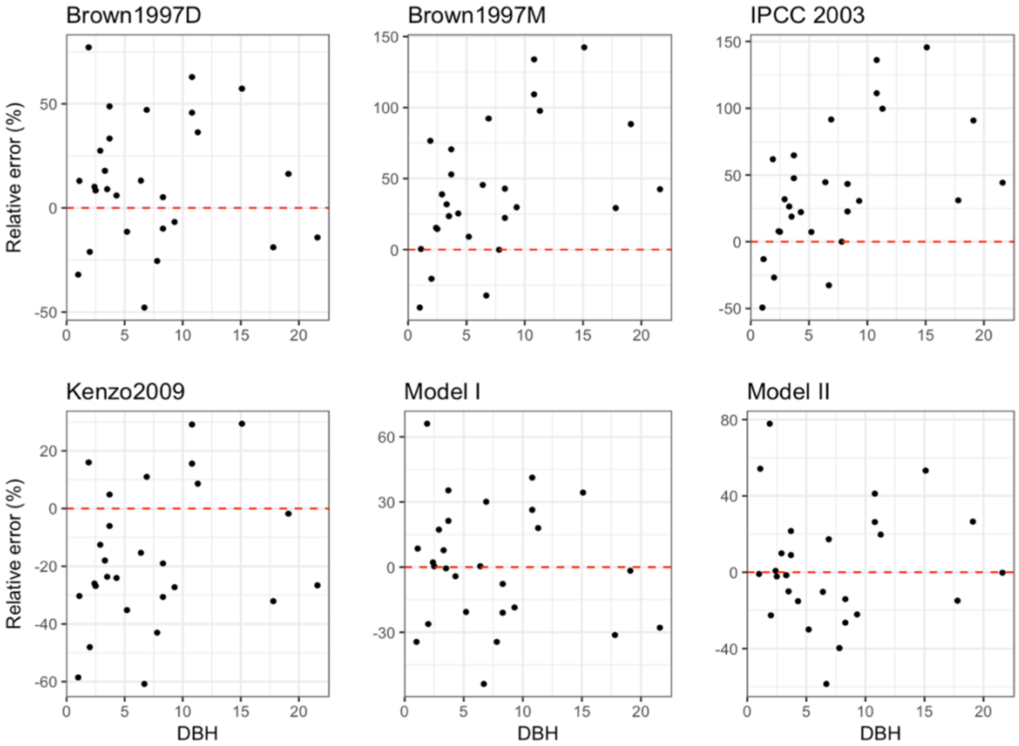


Figure 5.2 Relationships between the relative error percentage of AGB estimation and the model using DBH as a predictor parameter from previous research and two models from this study (Model I, II).

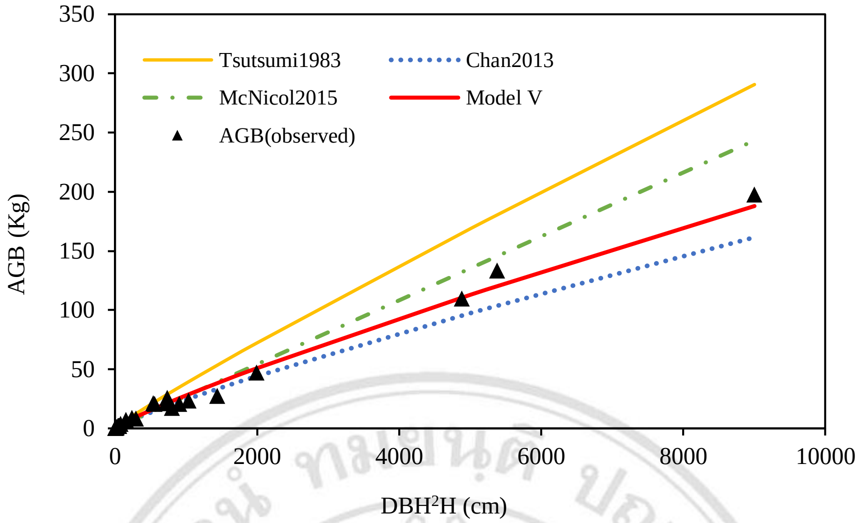


Figure 5.3 Above-ground biomass (AGB observed) from validation data and predicted values using three previous models including DBH^{2}H as a parameter: Tsutsumi et al. (1983), Chan et al. (2013), McNicol et al. (2015), and Model V from this study.

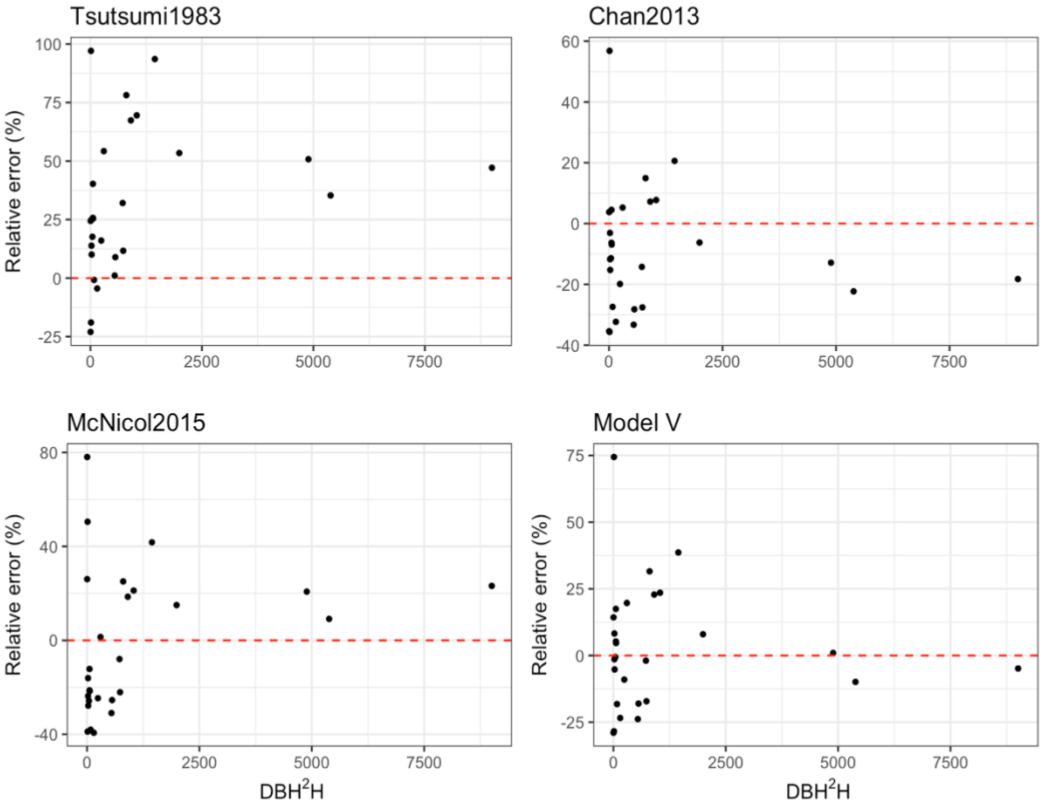


Figure 5.4 Relationships between the relative error percentage of AGB estimation and the model using DBH^{2}H as predictor parameter from previous research and Model V from this study.

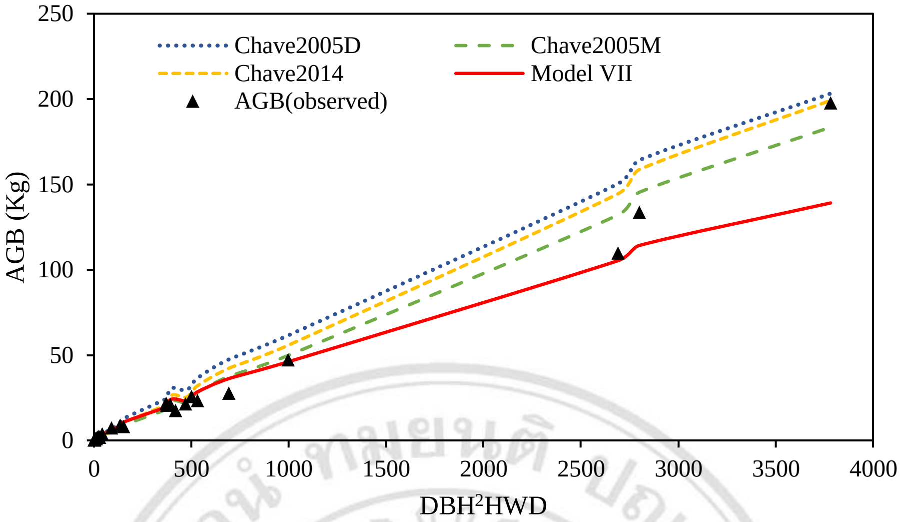


Figure 5.5 The above-ground biomass (AGB observed) from validation data and predicted values using three previous models including DBH^{2}HWD as a predictor parameter: Chave2005D (Chave et al. 2005) developed for dry forests, Chave2005M (Chave et al. 2005) for moist forests, Chave et al. (2014), and Model VII from this study.

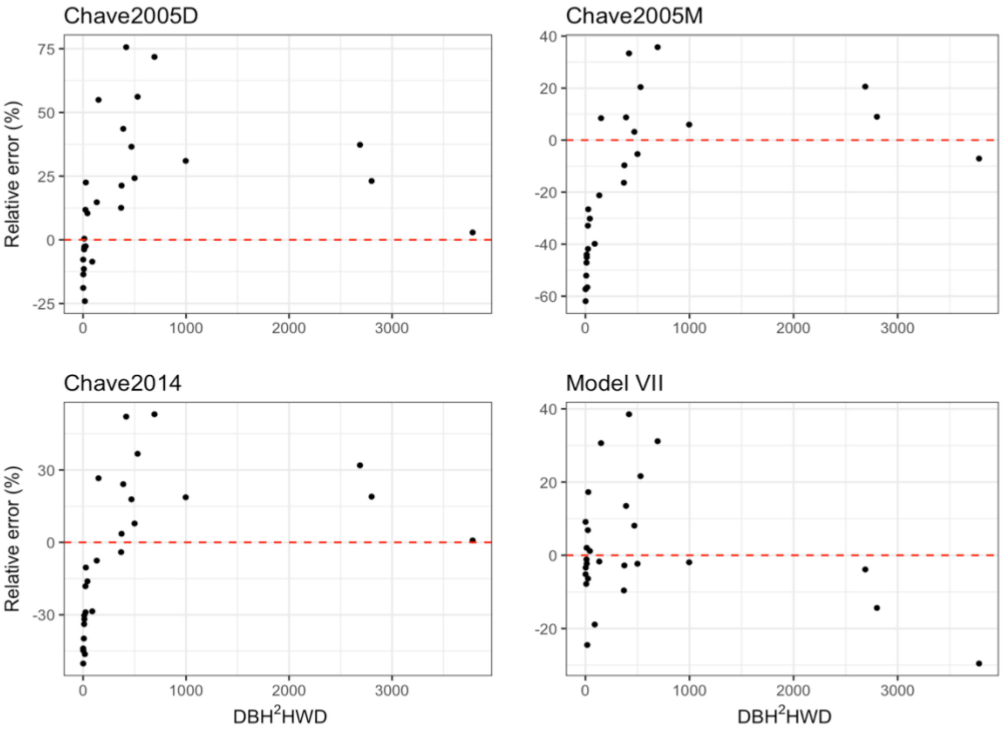


Figure 5.6 Relationships between the relative error percentage of AGB estimation and the model using DBH^{2}HWD as an independent parameter from previous research and Model VII from this study.

5.3 Comparison of above-ground biomass estimation with previous models

The model with DBH^2HWD as predictor parameter from Model VII was found to be the best selected model in this study. Subsequently, DBH, H, and WD data from 136 destructive samples were applied to the best selected equation as well as to other equations as mentioned above to estimate above-ground biomass (AGB(predicted)), and finally, compare all the results with AGB(observed), which was the destructive AGB data from this study (Table 5.2, Appendix F).

However, applying the data from this study to both moist tropical forest equations (Brown, 1997; IPCC, 2003) resulted in high values of Bias, RMSE, and MAPE, and also gave large overestimations of AGB; 47% for Brown (1997) moist model and 48% for IPCC (2003). This is in line with findings by Kenzo et al. (2009), where using the moist forest equation from Brown (1997) on secondary forest data resulted in an overestimation of approximately 100%. However, when using the dry equation from Brown (1997), AGB(predicted) did not deviate significantly from the AGB(observed). This may be explained by the fact that their equations were developed from moist forests using a DBH from 5 cm to 148 cm. In this study, the allometric models were developed with a DBH from 1 cm to 32.9 cm, while Brown’s equation for dry forest was developed with a DBH from 5 to 40 cm, a more similar range to the present study. Certain parameters, such as DBH and precipitation, may affect the growth rate for different species and also result in a higher biomass estimation in moist tropical forests. The precipitation and DBH factors were also mentioned in Chan et al. (2013) and Yuen et al. (2016). Moreover, Breugel et al. (2011) suggested that models that focus on larger trees (Brown et al.,1997; Chave et al., 2005) may overestimate the biomass of smaller trees.

The models of swidden cultivation fallow in mixed deciduous forest from Chan et al. (2013) and lowland mixed dipterocarp forest from Kenzo et al. (2009) provided lower AGB(predicted) compared to the other equations. Although the model of swidden fallows was classified as moist forest in Laos, it showed less estimation error for total accumulation (McNicol et al., 2015). Furthermore, Tsutsumi et al. (1983)’s equation (which is one of the most commonly used equations in Thailand) overestimated AGB(predicted) with approximately 17% (Table 5.2). However, AGB(predicted) of

Chave et al. (2014)’s equation was very similar to the AGB(observed), and better than Chave et al. (2005). This may be explained by the latter equation including more dry forests datasets and more moist forests, including data from other disturbed areas, and secondary forests. In contrast, the earlier study of Chave et al. (2005) used data from totally 27 sites, only three of them being dry forests. The new equations, however, were developed based on a big dataset of 4004 trees, with the added data resulting in a better accuracy of above-ground biomass estimations (Chave et al., 2014). Consequently, more data for establishing equations provide more accuracy to estimate above-ground biomass in various specific sites (van Breugel et al. 2011, McNicol et al., 2015).

In the youngest fallow site (4Y), the model developed in this study and Chan et al. (2013) had the best prediction, with the former showing a smaller error of estimation of overall biomass than the other models. This result suggests that the model from this study provide more precise AGB estimation results for smaller sized trees (1-7 cm) in 4Y. A likely explanation is that small trees (DBH 1-10 cm) accounted for 80% of all samples used to create the model. Although McNicol et al. (2015) showed less % error of estimation, this model' s lack of a WD parameter may introduce more error when applied on a larger scale. However, when applying the model to bigger data with various tree sizes, heights or wood densities, Chave et al. (2014) seems to be a better choice, with more accurate biomass prediction close to AGB(observed) as well as also showing a goodness of fit in model validation and comparison with DBH, H, and WD data available.

Choosing a suitable model for above-ground biomass estimation is of great concern for specific forest types and other land-use changes. When doing so, it is important to also consider tree size, height, and wood density. The results from this study were compared to a number of models from previous studies, only a few of them based on the same disturbed system. The comparisons show that an unsuitable choice of model could easily result in a large over-estimation of above-ground biomass. This has also been suggested by McNicol et al. (2015).

Table 5.2 Error percentage (% error) of above-ground biomass estimation for the study sites and total error for the each model

Variable	Model	4Y (% error)	7Y (% error)	SF (% error)	Total (% error)	Ref
DBH	Brown1997Dry	23	-12	-3	-6	Brown (1997)
	Brown1997Moist	41	40	54	47	Brown (1997)
	IPCC2003	36	41	55	48	IPCC (2003)
DBH^{2}H	Kenzo2009	-13	-27	-19	-22	Kenzo et al. (2009)
	Tsutsumi1983	23	-9	40	17	Tsutsumi et al. (1983)
	Chan2013	-9	-45	-18	-30	Chan et al. (2013)
	McNicol2015	-20	-29	11	-9	McNicol et al. (2015)
DBH^{2}HWD	Chave2005Dry	14	-11	21	6	Chave et al. (2005)
	Chave2005Moist	-31	-25	3	-11	Chave et al. (2005)
	Chave2014	-16	-17	14	-1	Chave et al. (2014)
	Ho M.VII	9	-35	-13	-23	This study

5.4 Including wood density in allometric equations

Adding wood density as an explanatory variable resulted in a significantly better fit model of mixed-species. Earlier studies also preferred to add WD in local and global models, including models for tropical forests (Chave et al., 2005; van Breugel et al., 2011, Fayolle et al., 2013; Chave et al., 2014). Considering wood density results in this study, significant differences were found among the different species. However, it is important to note that the average WD varies not only between species, but also between trees of the same species, and even within the same tree, depending on many factors such as age, succession stage, environment, and geographical location (Chave, et al., 2006; Henry, et al., 2010; Yeboah et al., 2014). Also, since average WD can vary significantly between different tropical regions, locally developed models may be less useful if WD is not included (Baker et al., 2004; Chave et al., 2009; van Breugel et al., 2011). This may explain why the Kenzo (2009) model, which is based on trees with an average WD of 0.35 g/cm^3 (0.29–0.53 g/cm^3), and average WD was 0.38 g/cm^3 (0.1-0.86 g/cm^3) from Chan et al. (2013) underestimated above-ground biomass in this study, where the average WD was 0.52 g/cm^3 (0.23-0.75 g/cm^3) (Figure 5.3).

Pioneer species tended to have lower wood density, while later succession species had higher values, as suggested by other studies (Bruun et al., 2009; Henry et al., 2010; Yeboah et al., 2014). An exception was *Flacourtia indica*, a fast growing species found in the youngest fallow, which had the third high wood density (0.67±0.03 g/cm^3) of all species in this study. The Global Wood Density database lists *F. indica* with a wood density of (0.74±0.07 g/cm^3).

Furthermore, using species-specific data is preferable for a more accurate biomass estimation, but average wood density at a higher taxonomical level of genus, family or order can be used when species-specific information was not available (Baker et al., 2004; Fayolle et al., 2013). However, when calculating the average total above-ground biomass applying either direct WD, the average wood density of each species (WDa), and wood density at genus level (WDg), no significant difference was found (ANOVA, $p > 0.05$).

Three species in this study, *Craibiodendron crepidioides* and *Schoepfia fragrans*, lack references in the Global Wood Density database, and for some other species data, only a few samples were collected. This suggests that gathering missing wood density data for more species, genera, and families in the local and international tropical area, which contain a substantial number of tree species, is needed for more accurate biomass estimation. It may be argued that adding WD in the model will make it more complicated to apply, but a large dataset of species-specific wood density is available to use for AGB estimation such as Zanne et al., (2009) or ICRAF's Tree Functional and Ecological Databases.

5.5 Carbon content

According to the carbon analysis, the average carbon percentage ranged from 39.4-46.7% in this study, with carbon concentration varying significantly among species. This variation is in line with previous studies in China (Thomas and Malczewski, 2007; Zhang et al., 2009). A study of Panamanian rainforest tree species also reported that carbon content varied widely across tropical species, ranging from 41.9 to 51.6% (Martin and Thomas, 2011).

The average carbon content across all tree species in this study was 44.84% ±1.63. This value is lower than the average most commonly used to convert biomass to carbon stock in regional and global carbon stock assessments, which is 50% (Brown, 1997). This number has also been used for several studies in Thailand (Terakunpisut et al., 2003; Jampanin 2004; Pibumrung, 2007; Pothong, 2012). Moreover, the recorded carbon content in this study is also slightly lower than the 47% the IPCC (2006) recommend for tropical forest, and the 48.97% average carbon of all tree parts (DBH ≥ 4.5 cm) found in the study of dry evergreen forest in Thailand (Tsutsumi et al., 1983). However, the average carbon content in this study closely matches the 44.67% ±0.54 reported in a study of restoration plots and evergreen trees in the same region in Thailand (Jantawong et al., 2017). Another previously reported carbon concentration value in Thailand is 48.77% ±1.08 in a study of dry dipterocarp forest (Hanpattanakit et al., 2016).

Using a carbon factor of 50% on the data from this study results in an overestimation of approximately 11.5%. This overestimation decreases to 4.8% when a carbon factor of 0.47 is applied. Similarly, the overestimation reported in the study of a Panamanian forest using a 50% as carbon factor was 5.3% (Martin and Thomas, 2011), and about 6% in a study of tropical lowland Dipterocarp rainforest in Malaysian Borneo (Saner et al., 2012).

This indicates that carbon content not only varies among species, but also among different forest types. As seen, using a generic 50% carbon factor often results in an overestimation of carbon sequestration. Applying species-specific carbon content, or at least forest type specific values, would be highly useful for more precise carbon stock assessments. Additionally, more studies of species- and site-specific carbon content would also be beneficial.

5.6 Above-ground biomass in fallow areas and secondary forests in this study and other studies

Biomass was estimated by applying the best-fit model as a function of DBH^2HWD to all vegetation data in this study. The above-ground tree biomass accumulated 10.3 Mg C/ha in 4-year-fallow. This value includes big trees, which contained 12.2% of the total biomass in the 4Y site. Total biomass found in the 4Y site was similar to the 10.4 Mg/ha reported in 6-year-fallow in Nam Yao sub-watershed, Nan province, Thailand (Pibumrung, 2007), as well as the 13.1 Mg/ha stored in 5-year-fallow in Myanmar (Chan et al., 2013). In contrast, a 5-year-old restoration plot in Ban Mae Sa Mai in Chiang Mai ,was found to store 29.9 Mg/ha (Jantawong et al., 2017), thus absorbing considerably more biomass than fallow areas after shifting cultivation. Consequently, active restoration –tree planting is recommended to accelerate carbon storage, rather than passive regeneration in fallows.

In the 7-year-fallow site, the few older trees left standing increased biomass to 38.8 Mg/ha. This area stored more biomass than a 9-year-old reforestation site (21.54 kg/ha) reported in Pibumrung, (2007), and more than 25-year-old fallows in Myanmar, which stored between 17.3 to 31.3 Mg/ha in 10-25-years-old fallows (Chan et al., 2013).

The secondary forest site (approximately 50 years old) stored 105.3 Mg/ha in an area left after shifting cultivation, but still with some signs of human disturbance from the villagers. The biomass accumulation in the secondary forest was similar to that of a 10-year-old of restoration plot in the same region (Jantawong et al., 2017), greater than the 74.3 Mg/ha found in dry evergreen forest in Kaeng Krachan National Park (Jampanin, 2004), and the 92.4 Mg/ha stored in secondary hill evergreen forest at Doi Mae Salong stored (Pothong, 2012), However, a considerably higher biomass accumulation has been recorded in primary hill evergreen forests in many areas of Thailand, with a site in Nam Yao sub-watershed, Nan province absorbing 289.6 Mg/ha or 175% more than the SF site in this site (Pibumrung, 2007), followed by hill evergreen forest in Kaeng Krachan National Park with 258.0 Mg/ha (Jampanin, 2004), and the same forest type in Doi Suthep Pui National Park with 209.5 Mg/ha (Khamyong, 2009). Other studies have also recorded higher biomass in other forest types, e.g. 140.6 Mg/ha in dry evergreen forest in Thong Pha Phume, National Forest (Terakunpisut et al., 2003), and 152.3 Mg/ha in secondary dry dipterocarp forest in Ratchaburi province (Hanpattanakit et al., 2016), and the highest biomass accumulation was found in degraded primary forest with 412.5 Mg/ha (Jantawong et al., 2017). Additionally, higher biomass has been recorded for the same land use type, from 126.2 Mg/ha 20-29 years after shifting rice cultivation up to 227.6 Mg/ha 30-49 years after shifting cultivation (Fukushima et al., 2008). A 14-year-old reforestation plot also showed a higher amount of biomass of 240.5 Mg/ha, which means that already at a quite young age it can store as much biomass as primary hill evergreen forests (Jantawong et al., 2017). This suggests that well managed restoration accumulates biomass faster than natural regeneration.

Although there are many studies of older forests to compare with, few have been reported of young secondary forests or fallow areas left over after cultivation in Thailand or other countries. While accurate tree biomass estimation is still necessary for carbon assessment, many factors may lead to differences in biomass and carbon accumulation, such as tree species, forest type, forest structure, stand ages, geographical factors (slope, aspect, and altitude), soil fertility, prevailing climate, land use history and land management (Slik et al. 2008; Chan et al., 2013; Yeboah et al., 2014). Also, using equations that are not suitable for the specific site may affect biomass estimation (Chan et al., 2013).

Previous studies have reported carbon accumulation calculated by applying a certain carbon factor to the biomass values. However, some studies did not report which value was used. Therefore, it is reasonable to use biomass content for comparisons in this study. Nevertheless, above-ground carbon (AGC) in each study is listed in Table 5.3. As expected, above-ground biomass and carbon increased from the youngest fallow to the oldest secondary forest in this study, in agreement with previous studies in the same region (Fukushima et al., 2008; Chan et al., 2013; Mukul et al., 2016). Secondary forests and young secondary forests after shifting cultivation are important carbon sinks in Thailand and in many places in the tropical region.

5.7 Above-ground biomass and carbon in the small trees (DBH < 4.5 cm)

The proportion of all stems in the smaller tree with DBH less than 4.5 cm contained more than 50% in the 7Y and SF. Whereas the 4Y site showed the high proportion of small trees up to 89% (Figure 5.8A). In addition, the proportion of basal area in 4Y site also showed high proportion, 59% for small tree (DBH < 4.5 cm). While, the older age of fallows contained small proportion only 8% in 7Y and 2% in SF site (Figure 5.8B). Accordingly, the small tree also contained percentage of above-ground biomass (AGB) and above-ground carbon (AGC) more than 50% in the youngest 4-year-fallow site. Again, in the 7Y and SF sites had very low percentage of AGB in 7Y

(7%) and SF (1%), which were found to be the same trend as the proportion of AGC (Figure 5.8C and 5.8D). The older fallow and forest contained enormous proportion of biomass in the tree with DBH > 4.5 cm. However, about 90% of plant diversity data will be missed to evaluated and more than 50% of AGB and AGC in the 4Y site if the small stems (DBH 1-4.5 cm) were not recorded in this time. Even though the young fallow can store less amount of biomass and carbon compare to the older area, but it is very crucial to focus on biomass and carbon estimation in young secondary forest where contain substantial amount of smaller trees.

5.8 Biomass accumulation in dominant species

The dominant species stored a high amount of biomass in each area of this study. The high biomass accumulation can mostly be explained by the basal area. Nevertheless, a considerable part of the biomass was found in the large trees left standing in the fallows; *Schima wallichii* (2 trees) and *Eugenia fruticosa* (1 tree), DBH between 23-26 cm stored 12% of all biomass in the 4Y site. The biomass of these three trees almost corresponds to the biomass of all 519 trees of *Aporosa villosa* (14%) found in the 4Y site. Similarly, the 4 large trees with a DBH>30 cm in the 7Y site stored 12% of the total biomass of that site, a higher proportion than all the 52 trees of *Lithocarpus polystachyus*, which accounted for only 8% of the biomass in the same site.

However, when considering biomass accumulation of the dominant tree species, not only biomass and basal area, but also stem density of a species is worth considering. Fukushima et al. (2008) also suggested that biomass accounting in dominant species should be considered along with the frequency of species.

In this study, *A. villosa, L. polystachyus* and *S. wallichii* contained the highest amount of biomass in the young fallow (4Y). In the older fallows, most biomass was stored in *Castanopsis* spp., *Quercus* spp. and *S. wallichii*. The same dominant species (*Castanopsis* spp. and *S. wallichii*) were also found to contain a high percentage of the biomass in 20–29-year-old, and 30–49-year-old fallows after upland rice cultivation (Fukushima et al., 2008). All of these species have been recorded as dominant species in Wangpakapattanawong et al. (2010) and Junsongduang et al. (2014) in Mae Chaem watershed, the same area as this study, as well as in Doi Inthanon National Park

(Fukushima et al., 2008). In addition, several earlier studies showed that the Fagaceae family, such as *Castanopsis* spp. and *Lithocarpus* spp., is common in fallow forests in Northern Thailand (Kanjunt and Oberhauser, 1994, Schmidt-Vogt, 1999). Moreover, *Castanopsis* spp., *Lithocarpus* spp., *Quercus* spp and *S. wallichii* occurred in primary hill evergreen forest in Kaeng Krachan National Park, Kanchanaburi (Jampanin, 2004), Doi Suthep Pui National Park (Khamyong, 2009) and Doi Mae Salong, Chiang Rai (Pothong, 2012), while *S. wallichii*, *Dalbergia cultrata*, and *Canarium subulatum* were reported with high IVI index in secondary hill evergreen forest (Pothong, 2012). Finally, *A. villosa* and *Quercus* spp. were recorded in shifting cultivation fallows in Northern Laos (McNicol et al., 2015), while *Castanopsis* spp. and *Quercus* sp. were recorded in restoration plots, Chiang Mai, Thailand (FORRU, 2005).

It is evident that the same tree species and genera that were used to develop the allometric model in this study are found in many areas in the region. Therefore, it should be possible to apply the best fit equation from this study in many areas where the same species or genera were found. However, the model includes not only dominant species, but also species such as *Archidendron clypearia*. *Dalbergia cultrata*, *Phyllanthus emblica*, *Styrax benzoides*, *Wendlandia tinctoria*. These species are also commonly found in primary forest, secondary forest, and fallow areas (Wangpakapattanawong et al. 2010, Pothong, 2012. Junsongduang et al., 2014).

Table 5.3 Above-ground biomass (AGB), above-ground carbon (AGC) in different forest types and other land use in Thailand and other countries.

Thailand

Reference	Study site	Rainfall (mm/year)	ALT (m asl)	Forest type	Age (year)	Model	AGB (Mg/ha)	AGC (Mg C/ha)	CF
This study	Ban Ho, Mae Chaem, Chiang Mai	980	1,000 - 1,300	Secondary forest or fallow after rice cultivation in hill evergreen forest	4	This study	10.3	4.6	0.45
					7		38.3	17.4	
					app. 50		105.3	47.7	
Jantawong et al. (2017)	Ban Mae Sa Mai, Chiang Mai	704	1,200 - 1,400	Restoration	5	Jantawong et al. (2017)	*29.9	13.2	0.44
				Restoration	10		*100.8	44.3	
				Restoration	14		*240.5	105.8	
				Degraded primary forest	-		*412.5	181.5	
Hanpattanakit et al. (2016)	Ratchaburi	890	-	Dry Dipterocarp Forest	Secondary forest	Hanpattanakit et al. (2016)	152.3	74.6	0.49
Pothong (2012)	Doi Mae Salong, Chiang Rai	-	1,100-1,200	Hill evergreen	Secondary forest	Tsutsumi et al. (1983)	92.4	46.2	0.5
Khamyong (2009)	Doi suthep pui national park, Chiang Mai	-	1,000 - 1,600	Hill evergreen	Primary forest	Tsutsumi et al. (1983)	209.5	104.7	0.5

Table 5.3 (Continued)

Thailand

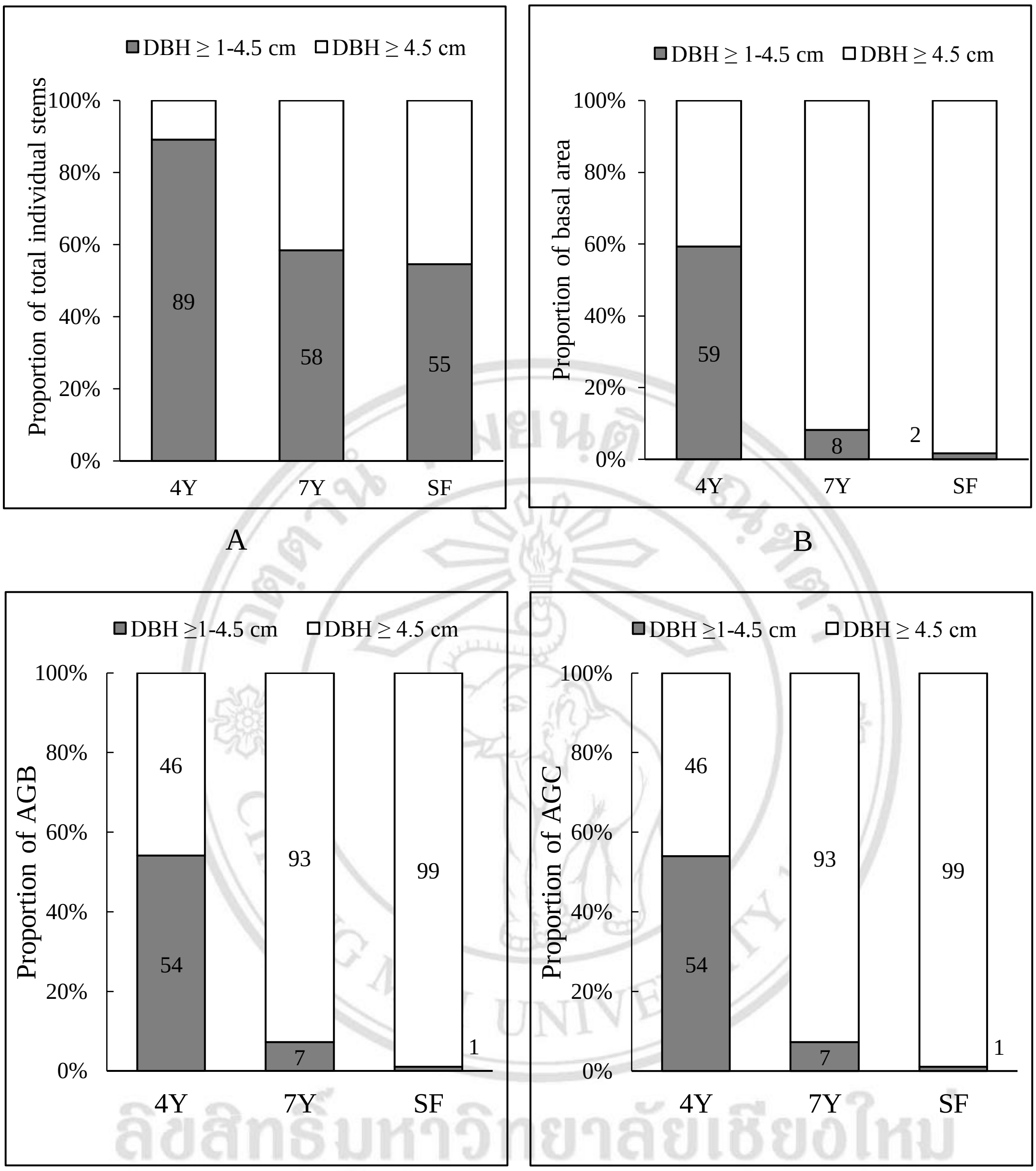
Reference	Study site	Rainfall (mm/year)	ALT (m asl)	Forest type	Age (year)	Model	AGB (Mg/ha)	AGC (Mg C/ha)	CF
Fukushima et al. (2008)	Doi Inthanon National Park, Chiang Mai	1,908	1,300	Secondary forest or fallow after rice cultivation in evergreen forest (montane forest)	20-29	Ogawa and Saito (1965)	126.2	-	-
					30-49		227.6	-	-
Pibumrung (2007)	Nam Yao sub-watershed, Nan	1,405	-	Hill evergreen forest	Primary forest	Tsutsumi et al. (1983)	289.6	144.8	0.5
				Reforestation	26		71.8	35.9	
				Reforestation	9		21.5	10.8	
				Fallow	6		10.4	5.2	
Jampanin (2004)	Kaeng Krachan National Park, Kanchanaburi	968	1200	Dry evergreen	Primary forest	Tsutsumi et al. (1983)	74.3	37.1	0.5
				Hill evergreen	Primary forest		258.0	129.0	
Terakunpisut et al. (2003)	Thong Pha Phume Natural Forest	1,650	-	Primary forest	Dry evergreen	Tsutsumi et al. (1983)	140.6	70.3	0.5

Table 5.3 (Continued)

Myanmar

Reference	Study site	Rainfall (mm/year)	ALT (m asl)	Forest type	Age (year)	Model	AGB (Mg/ha)	AGC (Mg C/ha)	CF
Chan et al. (2013)	Bago, Myanmar	1900	250-450	Secondary forest or fallows after swidden cultivation in mixed deciduous forest	1	Chan et al. (2013)	3.6	-	-
					5		13.1	-	-
					10		17.3	-	-
					15		36.6	-	-
					20		33.8	-	-
					25		31.3	-	-
					30		51.9	-	-

*AGB (Mg/ha) was calculated by dividing AGC (Mg C/ha) with the carbon factor.
ALT = altitude, CF = carbon factor,



A B

C D

Figure 5.7 Proportion of stems structure (A), basal area (B), above-ground biomass (C), and above-ground carbon (D) in 4-year-fallow (4Y), 7-year-fallow (7Y), and Secondary forest (SF).

CHAPTER 6

Conclusions

Developing allometric equations for secondary tropical forests is a major challenge due to the vast number of tree species and large variations in tree architecture, wood density, and carbon content among species. Consequently, it is all, but impossible to create a single, optimal model that can estimate biomass across different tropical forests. However, increasing the number of variables from one to three decreased the uncertainty of biomass estimation in this study. A mixed-species allometric equation with three explanatory variables, DBH, H, and WD, was found to be the best fit. Wood density was confirmed to be an important predictor in the model, a conclusion which is supported by the significant variation found in wood density between tree species. Consequently, the combination of three variables as DBH^2HWD was the best predictor variable of the allometric equation for above-ground biomass estimation in young fallow areas and secondary forests in this study. At the same time, it can be argued that adding wood density and using more variables make the equation more difficult to use than a simple model without WD. However, for tropical secondary forests with a high number of tree species and structural traits, the mixed-species allometric model with more input variables is recommended in order to improve the accuracy of above-ground biomass estimation. The present study also reports two new species not found either in the Global Wood Density database and Tree Functional Attributes and Ecological Database: *Craibiodendron crepidioides* and *Schoepfia fragrans*. A more complete wood density database would be useful for tropical forests in Thailand and Southeast Asia region.

The allometric model from this study showed the smallest error of biomass estimation for small tree sizes with a DBH from 1-7 cm in the 4-year fallow. This model could provide better biomass estimation in young secondary forests or fallow areas, which are widespread as the fallow rotation cycle now commonly is only 3 to 5 years in northern Thailand. However, when applying allometric equations to a region or larger area with a higher variation of tree structures, the pan-tropical model based on a big and varied dataset seems to be the best and preferred choice for a more accurate biomass estimation. In contrast, Tsutsumi et al. (1983), the most widely used equation in Thailand, was found to consistently overestimate biomass in this study. The number of destructive trees used for model development has a strong effect on biomass estimation accuracy, with large datasets generally performing better in larger scale evaluations.

Model comparisons between recent and previous studies in various types of tropical forests not only provide a clear understanding of the accuracy of different models, but also imply that great care should be taken when choosing a model for a specific area. To identify the most suitable model, it is not enough to focus on only one condition, it is important to also understand the limitations of the model, such as forest type, floristic composition, geographical and climatic conditions, and land use history, which can all affect tree growth and biomass.

Furthermore, this study also found that the carbon concentration differed significantly across the harvested tree species. The average carbon content was 44.8%, lower than the 50% that is commonly used as a carbon factor, and lower than in dry evergreen forest and dry dipterocarp forest in Thailand. This result could provide a better understanding of the carbon accumulation in forests. Choosing an unsuitable model and inaccurate carbon factor would have a major impact on biomass estimation and, accordingly, also affects the reliability of carbon assessment for carbon trading scheme.

This study confirms that biomass and carbon sequestering capacity increase with fallow age, and is higher in older secondary forest after shifting cultivation. Secondary forests and fallow areas not only act as important pools for biomass and carbon, but also contribute to improve ecological services for human livelihoods, including soil fertility, watershed protection, and providing food or traditional medicine for local communities. In addition, forest restoration has a potential to store substantial amount of biomass and carbon. Better tree planting design can help mitigating greenhouse gas emissions and promoting both live biomass and carbon accumulation. Carbon content data may be used in forest restoration and forest management working with multi-purpose tree species to improve biodiversity as well as carbon sequestration. Clearly, forests of all kinds play a part in mitigating carbon dioxide emissions, and will do so more efficiently if preserved or protected from anthropogenic disturbance. However, this is a challenge in the shifting cultivation fallows, which are very sensitive areas used for subsistence farming for indigenous people in remote areas. It is important to develop national forest management policies or strategies to conserve and increase forest cover while respecting indigenous hill tribe people's right to stay in their ancestral land, perhaps by giving them a role in taking care of the forests that provide ecological services and act as carbon pools. Accurate carbon evaluation of these forests is a first step to being able to offer incentives to conserve and enhance the carbon storage capacity and opens up a possibility for international funding by maintaining and increasing these carbon sinks.

Furthermore, This study discusses an alternative way to choose more proper tools to increase the accuracy of biomass and carbon evaluation in Thailand. A better understanding of allometric equations would be useful to improve the accuracy of future above-ground biomass and carbon assessments and, eventually, generate carbon credits by participating in REDD+ and other carbon market projects. Currently, the price of carbon credits on the voluntary market ranges from 3 to 10 USD per ton CO_2 for forest carbon projects (Concawe, 2017). Applying these values to the tree carbon sequestration of the present study sites, converted into tCO_2/ha, shows that carbon offsetting could generate a yearly income per hectare of 50-169 USD from the 4Y site, 191-638 USD from the 7Y site and 525-1,749 USD from the approximately 50-year-old SF site. For hill tribe people, this would be a sizeable and secure source of income that would also increase every year. Additionally, it would provide a powerful incentive to observe longer rotation periods, protect secondary forests after shifting cultivation, and adopt proper forest management practices. Moreover, further studies of below-ground carbon assessment in forests, including roots and soils, which are also important carbon pools, are still needed in Thailand.

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APPENDIX A

List of tree species from DBH ≥1 cm in 4-year-fallow, 7-year-fallow and Secondary Forest. No. is number of tree species. N is number of tree. BA is basal area (cm^2/ha). RD is relative density. RF is relative frequency. RDo is relative dominance. IVI is Importance Value Index

4-year-fallow (DBH ≥ 1 cm)

No.	**Species name**	**N**	**BA**	**Frequency**	**Density**	**RD**	**RF**	**RDo**	**IVI**	**%IVI**
1	*Aporosa villosa* (Lindl.) Baill.	110	7451.9	0.78	0.03	23.40	11.86	18.40	53.66	17.89
2	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	82	9147.8	0.81	2.28	17.45	12.29	22.58	52.32	17.44
3	*Phyllanthus emblica* L.	40	3075.9	0.69	1.11	8.51	10.59	7.59	26.70	8.90
4	*Ilex umbellulata* (Wall.) Loes.	35	1867.0	0.42	0.97	7.45	6.36	4.61	18.41	6.14
5	*Glochidion sphaerogynum* (Müll.Arg.) Kurz	24	1614.4	0.58	0.67	5.11	8.90	3.99	17.99	6.00
6	*Schima wallichii* Choisy	13	4422.8	0.19	0.36	2.77	2.97	10.92	16.65	5.55
7	*Flacourtia indica* (Burm.f.) Merr.	23	1913.6	0.33	0.64	4.89	5.08	4.72	14.70	4.90
8	*Callicarpa arborea* Roxb.	9	1913.9	0.25	0.25	1.91	3.81	4.72	10.45	3.48
9	*Styrax benzoides* W. G. Craib	13	1569.1	0.25	0.36	2.77	3.81	3.87	10.45	3.48
10	*Eugenia fruticosa* (Roxb. ex DC.) Roxb.	10	1716.2	0.19	0.28	2.13	2.97	4.24	9.33	3.11
11	*Canarium subulatum* Guillaumin	16	494.6	0.14	0.44	3.40	2.12	1.22	6.74	2.25
12	*Dalbergia cultrata* Benth.	9	336.8	0.19	0.25	1.91	2.97	0.83	5.71	1.90
13	*Quercus kingiana* Craib	6	776.7	0.11	0.17	1.28	1.69	1.92	4.89	1.63
14	*Anneslea fragrans* Wall.	6	165.3	0.11	0.17	1.28	1.69	0.41	3.38	1.13
15	*Albizia lebbeck* (L.) Benth.	4	315.0	0.11	0.11	0.85	1.69	0.78	3.32	1.11
16	*Antidesma sootepense* Craib	8	130.1	0.08	0.22	1.70	1.27	0.32	3.29	1.10
17	*Anogeissus acuminata* (Roxb. ex DC.) Wall. ex Guillem. & Perr.	4	423.2	0.08	0.11	0.85	1.27	1.04	3.17	1.06
18	*Phoebe lanceolata* (Nees) Nees	5	161.4	0.08	0.14	1.06	1.27	0.40	2.73	0.91
19	*Eriolaena candollei* Wall.	3	160.5	0.08	0.08	0.64	1.27	0.40	2.31	0.77
20	*Eugenia albiflora* Duthie ex Kurz	2	400.3	0.06	0.06	0.43	0.85	0.99	2.26	0.75
21	*Rapanea yunnanensis* Mez	5	276.4	0.03	0.14	1.06	0.42	0.68	2.17	0.72
22	*Protium serratum* (Wall. ex Colebr.) Engl.	3	62.4	0.08	0.08	0.64	1.27	0.15	2.06	0.69
23	*Mallotus philippensis* (Lam.) Müll.Arg.	4	102.4	0.06	0.11	0.85	0.85	0.25	1.95	0.65
24	*Wendlandia tinctoria* (Roxb.) DC.	4	101.4	0.06	0.11	0.85	0.85	0.25	1.95	0.65
25	*Mangifera indica* L.	1	429.4	0.03	0.03	0.21	0.42	1.06	1.70	0.57

4-year-fallow (DBH ≥ 1 cm) (Continued)

No.	Species name	N	BA	Frequency	Density	RD	RF	RDo	IVI	%IVI
26	*Castanopsis acuminatissima* (Blume) A.DC.	3	246.7	0.03	0.08	0.64	0.42	0.61	1.67	0.56
27	*Lagerstroemia tomentosa* C. Presl	2	140.7	0.06	0.06	0.43	0.85	0.35	1.62	0.54
28	*Stereospermum tetragonum* DC.	2	108.0	0.06	0.06	0.43	0.85	0.27	1.54	0.51
29	*Dillenia parviflora* Griff.	2	86.5	0.06	0.06	0.43	0.85	0.21	1.49	0.50
30	*Ficus semicordata* Buch.-Ham. ex Sm.	2	64.7	0.06	0.06	0.43	0.85	0.16	1.43	0.48
31	*Antidesma acidum* Retz.	2	64.1	0.06	0.06	0.43	0.85	0.16	1.43	0.48
32	*Turpinia pomifera* (Roxb.) DC.	2	56.7	0.06	0.06	0.43	0.85	0.14	1.41	0.47
33	*Colona winitii* (Craib) Craib	2	48.4	0.06	0.06	0.43	0.85	0.12	1.39	0.46
34	*Dimocarpus longan* Lour. subsp. longan var. longan	2	37.1	0.06	0.06	0.43	0.85	0.09	1.36	0.45
35	*Cratoxylum formosum* (Jacq.) Benth. & Hook.f. ex Dyer	2	31.2	0.06	0.06	0.43	0.85	0.08	1.35	0.45
36	*Castanopsis tribuloides* (Sm.) A.DC.	2	171.4	0.03	0.06	0.43	0.42	0.42	1.27	0.42
37	*Markhamia stipulata* (Wall.) Seem.	2	101.1	0.03	0.06	0.43	0.42	0.25	1.10	0.37
38	*Muntingia calabura* L.	1	100.3	0.03	0.03	0.21	0.42	0.25	0.88	0.29
39	*Aporosa octandra* (Buch.-Ham. ex D.Don) Vickery	1	67.7	0.03	0.03	0.21	0.42	0.17	0.80	0.27
40	*Spondias lakonensis* Pierre	1	63.9	0.03	0.03	0.21	0.42	0.16	0.79	0.26
41	*Engelhardtia spicata* Lechen ex Blume var. spicata	1	49.9	0.03	0.03	0.21	0.42	0.12	0.76	0.25
42	*Adenanthera microsperma* Teijsm. & Binn.	1	23.8	0.03	0.03	0.21	0.42	0.06	0.70	0.23
43	*Ficus fistulosa* Reinw ex Blume	1	18.0	0.03	0.03	0.21	0.42	0.04	0.68	0.23

7-year-fallow (DBH ≥ 1 cm)

No.	Species name	N	BA	Frequency	Density	RD	RF	RDo	IVI	%IVI
1	*Quercus kingiana* Craib	119	57928.3	0.861	3.31	17.55	9.39	52.70	79.64	26.55
2	*Aporosa villosa* (Lindl.) Baill.	91	4214.9	0.833	2.53	13.42	9.09	3.83	26.35	8.78
3	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	31	10143.0	0.444	0.86	4.57	4.85	9.23	18.65	6.22
4	*Dalbergia cultrata* Benth.	46	4213.3	0.722	1.28	6.78	7.88	3.83	18.50	6.17
5	*Styrax benzoides* W. G. Craib	52	4132.1	0.556	1.44	7.67	6.06	3.76	17.49	5.83
6	*Rhus chinensis* Mill.	60	943.8	0.556	1.67	8.85	6.06	0.86	15.77	5.26
7	*Wendlandia tinctoria* (Roxb.) DC.	44	3129.3	0.556	1.22	6.49	6.06	2.85	15.40	5.13
8	*Berrya mollis* Wall. ex Kurz	29	3483.4	0.556	0.81	4.28	6.06	3.17	13.51	4.50
9	*Phyllanthus emblica* L.	20	472.4	0.389	0.56	2.95	4.24	0.43	7.62	2.54
10	*Cratoxylum cochinchinense* (Lour.) Blume	21	150.5	0.306	0.58	3.10	3.33	0.14	6.57	2.19
11	*Eugenia fruticosa* (Roxb. ex DC.) Roxb.	6	3044.5	0.167	0.17	0.88	1.82	2.77	5.47	1.82

7-year-fallow (DBH ≥ 1 cm) (Continued)

No.	Species name	N	BA	Frequency	Density	RD	RF	RDo	IVI	%IVI
12	*Craibiodendron stellatum* (Pierre) W.W.Sm.	13	1505.1	0.194	0.36	1.92	2.12	1.37	5.41	1.80
13	*Gluta usitata* (Wall.) Ding Hou	7	2489.9	0.139	0.19	1.03	1.52	2.27	4.81	1.60
14	*Sterculia balanghas* L.	13	85.8	0.194	0.36	1.92	2.12	0.08	4.12	1.37
15	*Stereospermum neuranthum* Kurz	5	1876.2	0.139	0.14	0.74	1.52	1.71	3.96	1.32
16	*Oroxylum indicum* (L.) Kurz	5	1144.0	0.139	0.14	0.74	1.52	1.04	3.29	1.10
17	*Castanopsis acuminatissima* (Blume) A.DC.	5	1359.0	0.111	0.14	0.74	1.21	1.24	3.19	1.06
18	*Fernandoa adenophylla* (Wall. ex G.Don) Steenis	6	461.4	0.167	0.17	0.88	1.82	0.42	3.12	1.04
19	*Flacourtia indica* (Burm.f.) Merr.	7	939.1	0.111	0.19	1.03	1.21	0.85	3.10	1.03
20	*Antidesma sootepense* Craib	10	114.7	0.139	0.28	1.47	1.52	0.10	3.09	1.03
21	*Glochidion sphaerogynum* (Müll.Arg.) Kurz	7	123.3	0.167	0.19	1.03	1.82	0.11	2.96	0.99
22	*Canarium subulatum* Guillaumin	7	557.3	0.111	0.19	1.03	1.21	0.51	2.75	0.92
23	*Schima wallichii* Choisy	3	1085.8	0.083	0.08	0.44	0.91	0.99	2.34	0.78
24	*Magnolia baillonii* Pierre	5	80.3	0.139	0.14	0.74	1.52	0.07	2.33	0.78
25	*Ixora cibdela* Craib	8	88.9	0.083	0.22	1.18	0.91	0.08	2.17	0.72
26	*Anneslea fragrans* Wall.	3	871.4	0.083	0.08	0.44	0.91	0.79	2.14	0.71
27	*Cratoxylum formosum* (Jacq.) Benth. & Hook.f. ex Dyer	6	644.9	0.056	0.17	0.88	0.61	0.59	2.08	0.69
28	*Albizia lebbeck* (L.) Benth.	5	49.5	0.111	0.14	0.74	1.21	0.05	1.99	0.66
29	*Callicarpa arborea* Roxb.	3	638.1	0.083	0.08	0.44	0.91	0.58	1.93	0.64
30	*Olea rosea* Craib	4	33.4	0.111	0.11	0.59	1.21	0.03	1.83	0.61
31	*Bombax anceps* Pierre var. anceps	2	982.0	0.056	0.06	0.29	0.61	0.89	1.79	0.60
32	*Colona winitii* (Craib) Craib	5	114.9	0.083	0.14	0.74	0.91	0.10	1.75	0.58
33	*Erythrina subumbrans* (Hassk.) Merr.	1	1344.9	0.028	0.03	0.15	0.30	1.22	1.67	0.56
34	*Litsea glutinosa* (Lour.) C.B.Rob.	4	143.3	0.083	0.11	0.59	0.91	0.13	1.63	0.54
35	*Gardenia sootepensis* Hutch.	4	100.1	0.083	0.11	0.59	0.91	0.09	1.59	0.53
36	*Phoebe lanceolata* (Nees) Nees	3	258.0	0.083	0.08	0.44	0.91	0.23	1.59	0.53
37	*Antidesma acidum* Retz.	4	27.8	0.083	0.11	0.59	0.91	0.03	1.52	0.51
38	*Anogeissus acuminata* (Roxb. ex DC.) Wall. ex Guillem. & Perr.	3	57.5	0.083	0.08	0.44	0.91	0.05	1.40	0.47
39	*Turpinia pomifera* (Roxb.) DC.	3	56.4	0.083	0.08	0.44	0.91	0.05	1.40	0.47
40	*Diospyros glandulosa* Lace	2	220.4	0.056	0.06	0.29	0.61	0.20	1.10	0.37
41	*Dodonaea viscosa* (L.) Jacq.	2	34.2	0.056	0.06	0.29	0.61	0.03	0.93	0.31
42	*Quercus semiserrata* Roxb.	1	352.6	0.028	0.03	0.15	0.30	0.32	0.77	0.26
43	*Spondias lakonensis* Pierre	1	205.6	0.028	0.03	0.15	0.30	0.19	0.64	0.21
44	*Vitex limonifolia* Wall. ex C.B.Clarke	2	25.2	0.028	0.06	0.29	0.30	0.02	0.62	0.21

Secondary Forest (DBH ≥ 1 cm)

No.	Species name	N	BA	Frequency	Density	RD	RF	RDo	IVI	%IVI
1	*Schima wallichii* Choisy	22	46941.7	0.44	0.61	3.18	3.49	18.82	25.49	8.50
2	*Castanopsis diversifolia* (Kurz) King ex Hook.f.	28	40396.1	0.53	0.78	4.05	4.15	16.20	24.39	8.13
3	*Castanopsis tribuloides* (Sm.) A.DC.	36	33109.2	0.56	1.00	5.20	4.37	13.28	22.84	7.61
4	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	47	15343.0	0.69	1.31	6.79	5.46	6.15	18.40	6.13
5	*Phoebe lanceolata* (Nees) Nees	48	2483.8	0.64	1.33	6.94	5.02	1.00	12.95	4.32
6	*Macaranga kurzii* (Kuntze) Pax & K.Hoffm.	59	388.2	0.36	1.64	8.53	2.84	0.16	11.52	3.84
7	*Canarium subulatum* Guillaumin	14	15391.2	0.39	0.39	2.02	3.06	6.17	11.25	3.75
8	*Polyalthia cerasoides* (Roxb.) Bedd.	36	1808.7	0.56	1.00	5.20	4.37	0.73	10.29	3.43
9	*Albizia chinensis* (Osbeck) Merr.	9	16729.5	0.19	0.25	1.30	1.53	6.71	9.54	3.18
10	*Lindera meisneri* King ex Hook. f.	31	303.5	0.50	0.86	4.48	3.93	0.12	8.53	2.84
11	*Eurya acuminata* DC.	22	2892.9	0.44	0.61	3.18	3.49	1.16	7.83	2.61
12	*Helicia nilagirica* Bedd.	13	8303.6	0.28	0.36	1.88	2.18	3.33	7.39	2.46
13	*Wendlandia tinctoria* (Roxb.) DC.	17	3882.1	0.39	0.47	2.46	3.06	1.56	7.07	2.36
14	*Castanopsis acuminatissima* (Blume) A.DC.	11	7352.8	0.25	0.31	1.59	1.97	2.95	6.50	2.17
15	*Archidendron clypearia* (Jack) I.C.Nielsen	18	1181.3	0.42	0.50	2.60	3.28	0.47	6.35	2.12
16	*Eugenia fruticosa* (Roxb. ex DC.) Roxb.	14	5115.6	0.25	0.39	2.02	1.97	2.05	6.04	2.01
17	*Castanopsis lucida* (Nees) Soepadmo	14	2573.2	0.22	0.39	2.02	1.75	1.03	4.80	1.60
18	*Alstonia rostrata* C.E.C.Fisch.	17	382.7	0.28	0.47	2.46	2.18	0.15	4.79	1.60
19	*Canthium glabrum* Blume	15	445.6	0.31	0.42	2.17	2.40	0.18	4.75	1.58
20	*Cinnamomum camphora* (L.) J.Presl	19	307.5	0.19	0.53	2.75	1.53	0.12	4.40	1.47
21	*Styrax benzoides* W. G. Craib	9	1417.9	0.25	0.25	1.30	1.97	0.57	3.83	1.28
22	*Aporosa villosa* (Lindl.) Baill.	9	1793.5	0.22	0.25	1.30	1.75	0.72	3.77	1.26
23	*Glochidion sphaerogynum* (Müll.Arg.) Kurz	9	809.2	0.22	0.25	1.30	1.75	0.32	3.37	1.12
24	*Magnolia baillonii* Pierre	8	385.1	0.22	0.22	1.16	1.75	0.15	3.06	1.02
25	*Shorea roxburghii* G.Don	5	2939.6	0.14	0.14	0.72	1.09	1.18	2.99	1.00
26	*Turpinia pomifera* (Roxb.) DC.	8	1074.0	0.17	0.22	1.16	1.31	0.43	2.90	0.97
27	*Glochidion rubrum* Blume	10	105.7	0.17	0.28	1.45	1.31	0.04	2.80	0.93
28	*Macaranga denticulata* (Blume) Müll.Arg.	11	100.9	0.11	0.31	1.59	0.87	0.04	2.50	0.83
29	*Eugenia cumini* (L.) Druce var. cumini	5	2257.2	0.11	0.14	0.72	0.87	0.91	2.50	0.83
30	*Polyalthia viridis* W. G. Craib	4	2152.6	0.11	0.11	0.58	0.87	0.86	2.31	0.77
31	*Olea rosea* Craib	6	1355.1	0.11	0.17	0.87	0.87	0.54	2.28	0.76
32	*Antidesma sootepense* Craib	7	944.7	0.11	0.19	1.01	0.87	0.38	2.26	0.75
33	*Heynea trijuga* Roxb. ex Sims	1	4711.9	0.03	0.03	0.14	0.22	1.89	2.25	0.75

Secondary Forest (DBH ≥ 1 cm) (Continued)

No.	Species name	N	BA	Frequency	Density	RD	RF	RDo	IVI	%IVI
34	*Meliosma simplicifolia* (Roxb.) Walp.	6	113.4	0.17	0.17	0.87	1.31	0.05	2.22	0.74
35	*Semecarpus albescens* Kurz	5	985.0	0.14	0.14	0.72	1.09	0.39	2.21	0.74
36	*Buchanania cochinchinensis* (Lour.) M.R.Almeida	4	2148.6	0.08	0.11	0.58	0.66	0.86	2.09	0.70
37	*Rapanea yunnanensis* Mez	5	511.6	0.14	0.14	0.72	1.09	0.21	2.02	0.67
38	*Sarcosperma arboreum* Hook.f.	5	712.3	0.11	0.14	0.72	0.87	0.29	1.88	0.63
39	*Garcinia cowa* Roxb. ex Choisy	5	73.3	0.14	0.14	0.72	1.09	0.03	1.84	0.61
40	*Garcinia xanthochymus* Hook.f. ex T.Anderson	5	47.3	0.14	0.14	0.72	1.09	0.02	1.83	0.61
41	*Knema angustifolia* (Roxb.) Warb.	5	75.4	0.11	0.14	0.72	0.87	0.03	1.63	0.54
42	*Dillenia parviflora* Griff.	3	1211.8	0.08	0.08	0.43	0.66	0.49	1.57	0.52
43	*Markhamia stipulata* (Wall.) Seem.	4	176.6	0.11	0.11	0.58	0.87	0.07	1.52	0.51
44	*Dalbergia cana* Kurz	3	1601.2	0.06	0.08	0.43	0.44	0.64	1.51	0.50
45	*Stereospermum neuranthum* Kurz	4	73.8	0.11	0.11	0.58	0.87	0.03	1.48	0.49
46	*Magnolia hodgsonii* (Hook.f. & Thomson) H.Keng	3	889.2	0.08	0.08	0.43	0.66	0.36	1.45	0.48
47	*Spondias pinnata* (L.f.) Kurz	3	819.1	0.08	0.08	0.43	0.66	0.33	1.42	0.47
48	*Celtis tetrandra* Roxb.	2	1624.8	0.06	0.06	0.29	0.44	0.65	1.38	0.46
49	*Stereospermum colais* (B.-H. ex Dillw.) Mabb.	3	599.2	0.08	0.08	0.43	0.66	0.24	1.33	0.44
50	*Elaeocarpus stipularis* Blume	1	2277.3	0.03	0.03	0.14	0.22	0.91	1.28	0.43
51	*Dalbergia oliveri* Prain	3	848.0	0.06	0.08	0.43	0.44	0.34	1.21	0.40
52	*Castanopsis calathiformis* (Skan) Rehder & E.H.Wilson	2	1128.9	0.06	0.06	0.29	0.44	0.45	1.18	0.39
53	*Actinodaphne henryi* Gamble	3	45.8	0.08	0.08	0.43	0.66	0.02	1.11	0.37
54	*Engelhardtia serrata* Blume	3	45.2	0.08	0.08	0.43	0.66	0.02	1.11	0.37
55	*Grewia eriocarpa* Juss.	2	687.3	0.06	0.06	0.29	0.44	0.28	1.00	0.33
56	*Aporosa octandra* (Buch.-Ham. ex D.Don) Vickery	2	423.7	0.06	0.06	0.29	0.44	0.17	0.90	0.30
57	*Phyllanthus emblica* L.	2	386.0	0.06	0.06	0.29	0.44	0.15	0.88	0.29
58	*Lithocarpus garrettianus* (Craib) A.Camus	3	19.0	0.06	0.08	0.43	0.44	0.01	0.88	0.29
59	*Quercus kerrii* Craib	1	1243.4	0.03	0.03	0.14	0.22	0.50	0.86	0.29
60	*Xanthophyllum* virens Roxb.	1	1210.5	0.03	0.03	0.14	0.22	0.49	0.85	0.28
61	*Protium serratum* (Wall. ex Colebr.) Engl.	2	648.1	0.03	0.06	0.29	0.22	0.26	0.77	0.26
62	*Artocarpus lacucha* Buch.-Ham.	2	11.1	0.06	0.06	0.29	0.44	0.00	0.73	0.24
63	*Albizia odoratissima* (L.f.) Benth.	1	782.6	0.03	0.03	0.14	0.22	0.31	0.68	0.23
64	*Sapindus rarak* DC.	1	563.7	0.03	0.03	0.14	0.22	0.23	0.59	0.20
65	*Litsea lancifolia* (Roxb. ex Nees) Fern.-Vill.	1	467.7	0.03	0.03	0.14	0.22	0.19	0.55	0.18

Secondary Forest (DBH ≥ 1 cm) (Continued)

No.	Species name	N	BA	Frequency	Density	RD	RF	RDo	IVI	%IVI
66	*Symplocos macrophylla* Wall. ex DC. ssp. sulcata (Kurz) Noot. var. sulcata	1	270.8	0.03	0.03	0.14	0.22	0.11	0.47	0.16
67	*Schoepfia fragrans* Wall.	1	252.5	0.03	0.03	0.14	0.22	0.10	0.46	0.15
68	*Lepisanthes tetraphylla* Radlk.	1	248.1	0.03	0.03	0.14	0.22	0.10	0.46	0.15
69	*Litsea monopetala* (Roxb.) Pers.	1	198.9	0.03	0.03	0.14	0.22	0.08	0.44	0.15
70	*Dalbergia ovata* Benth.	1	185.9	0.03	0.03	0.14	0.22	0.07	0.44	0.15
71	*Memecylon scutellatum* (Lour.) Hook. & Arn.	1	132.7	0.03	0.03	0.14	0.22	0.05	0.42	0.14
72	*Toona ciliata* M. Roem.	1	71.6	0.03	0.03	0.14	0.22	0.03	0.39	0.13
73	*Diospyros glandulosa* Lace	1	67.7	0.03	0.03	0.14	0.22	0.03	0.39	0.13
74	*Calophyllum inophyllum* L.	1	63.9	0.03	0.03	0.14	0.22	0.03	0.39	0.13
75	*Cinnamomum verum* J.Presl	1	40.3	0.03	0.03	0.14	0.22	0.02	0.38	0.13
76	*Eriolaena candollei* Wall.	1	12.4	0.03	0.03	0.14	0.22	0.00	0.37	0.12
77	*Ficus hispida* L.f.	1	12.4	0.03	0.03	0.14	0.22	0.00	0.37	0.12
78	*Ficus hirta* Vahl	1	9.3	0.03	0.03	0.14	0.22	0.00	0.37	0.12
79	*Pterocarpus macrocarpus* Kurz	1	5.5	0.03	0.03	0.14	0.22	0.00	0.37	0.12
80	*Antidesma acidum* Retz.	1	3.2	0.03	0.03	0.14	0.22	0.00	0.36	0.12

7-year-fallow (DBH ≥ 4.5 cm)

No.	Species name	N	BA	Frequency	Density	RD	RF	RDo	IVI	%IVI
1	Quercus kingiana Craib	112	57787.6	0.86	3.11	40.29	20.53	57.29	118.11	39.37
2	Lithocarpus polystachyus (Wall. ex A.DC.) Rehder	24	9955.9	0.39	0.67	8.63	9.27	9.87	27.77	9.26
3	Dalbergia cultrata Benth.	19	3572.3	0.42	0.53	6.83	9.93	3.54	20.31	6.77
4	Wendlandia tinctoria (Roxb.) DC.	23	2637.8	0.39	0.64	8.27	9.27	2.61	20.16	6.72
5	Aporosa villosa (Lindl.) Baill.	14	2428.5	0.25	0.39	5.04	5.96	2.41	13.40	4.47
6	Craibiodendron stellatum (Pierre) W.W.Sm.	12	1454.7	0.17	0.33	4.32	3.97	1.44	9.73	3.24
7	Syzygium fruticosum DC.	6	3015.3	0.17	0.17	2.16	3.97	2.99	9.12	3.04
8	Berrya mollis Wall. ex Kurz	6	3165.1	0.14	0.17	2.16	3.31	3.14	8.61	2.87
9	Gluta usitata (Wall.) Ding Hou	7	2489.9	0.14	0.19	2.52	3.31	2.47	8.30	2.77
10	Styrax benzoides W. G. Craib	7	1496.2	0.14	0.19	2.52	3.31	1.48	7.31	2.44
11	Oroxylum indicum (L.) Kurz	5	1144.0	0.14	0.14	1.80	3.31	1.13	6.24	2.08
12	Stereospermum neuranthum Kurz	4	1815.4	0.11	0.11	1.44	2.65	1.80	5.89	1.96

7-year-fallow (DBH ≥ 4.5 cm) (Continued)

No.	Species name	N	BA	Frequency	Density	RD	RF	RDo	IVI	%IVI
13	Castanopsis acuminatissima (Blume) A.DC.	4	1348.5	0.08	0.11	1.44	1.99	1.34	4.76	1.59
14	Flacourtia indica (Burm.f.) Merr.	5	805.4	0.08	0.14	1.80	1.99	0.80	4.58	1.53
15	Anneslea fragrans Wall.	3	871.4	0.08	0.08	1.08	1.99	0.86	3.93	1.31
16	Canarium subulatum Guillaumin	4	508.2	0.08	0.11	1.44	1.99	0.50	3.93	1.31
17	Schima wallichii Choisy	2	1067.5	0.06	0.06	0.72	1.32	1.06	3.10	1.03
18	Bombax anceps Pierre var. anceps	2	982.0	0.06	0.06	0.72	1.32	0.97	3.02	1.01
19	Phyllanthus emblica L.	3	214.9	0.06	0.08	1.08	1.32	0.21	2.62	0.87
20	Callicarpa arborea Roxb.	2	559.9	0.06	0.06	0.72	1.32	0.56	2.60	0.87
21	Fernandoa adenophylla (Wall. ex G.Don) Steenis	2	364.5	0.06	0.06	0.72	1.32	0.36	2.41	0.80
22	Erythrina subumbrans (Hassk.) Merr.	1	1344.9	0.03	0.03	0.36	0.66	1.33	2.36	0.79
23	Cratoxylum formosum (Jacq.) Benth. & Hook.f. ex Dyer	3	614.3	0.03	0.08	1.08	0.66	0.61	2.35	0.78
24	Ocotea lancifolia (Schott) Mez	2	230.2	0.06	0.06	0.72	1.32	0.23	2.27	0.76
25	Quercus semiserrata Roxb.	1	352.6	0.03	0.03	0.36	0.66	0.35	1.37	0.46
26	Diospyros glandulosa Lace	1	217.7	0.03	0.03	0.36	0.66	0.22	1.24	0.41
27	Spondias lakonensis Pierre	1	205.6	0.03	0.03	0.36	0.66	0.20	1.23	0.41
28	Litsea glutinosa (Lour.) C.B.Rob.	1	97.5	0.03	0.03	0.36	0.66	0.10	1.12	0.37
29	Colona winitii (Craib) Craib	1	79.8	0.03	0.03	0.36	0.66	0.08	1.10	0.37
30	Gardenia sootepensis Hutch.	1	43.3	0.03	0.03	0.36	0.66	0.04	1.06	0.35

Secondary Forest (DBH ≥ 4.5 cm)

No.	Species name	N	BA	Frequency	Density	RD	RF	RDo	IVI	%IVI
1	Castanopsis tribuloides (Sm.) A.DC.	34	33044.5	0.53	0.94	10.40	7.51	13.48	31.39	10.46
2	Schima wallichii Choisy	18	46879.9	0.36	0.50	5.50	5.14	19.13	29.77	9.92
3	Castanopsis diversifolia (Kurz) King ex Hook.f.	20	40319.4	0.39	0.56	6.12	5.53	16.45	28.10	9.37
4	Lithocarpus polystachyus (Wall. ex A.DC.) Rehder	34	15106.0	0.58	0.94	10.40	8.30	6.16	24.86	8.29
5	Canarium subulatum Guillaumin	14	15391.2	0.39	0.39	4.28	5.53	6.28	16.09	5.36
6	Albizia chinensis (Osbeck) Merr.	7	16709.6	0.17	0.19	2.14	2.37	6.82	11.33	3.78
7	Helicia nilagirica Bedd.	12	8287.7	0.28	0.33	3.67	3.95	3.38	11.00	3.67
8	Wendlandia tinctoria (Roxb.) DC.	13	3836.0	0.31	0.36	3.98	4.35	1.57	9.89	3.30
9	Ocotea lancifolia (Schott) Mez	14	2112.2	0.31	0.39	4.28	4.35	0.86	9.49	3.16
10	Castanopsis acuminatissima (Blume) A.DC.	10	7299.4	0.22	0.28	3.06	3.16	2.98	9.20	3.07

Secondary Forest (DBH ≥ 4.5 cm) (Continued)

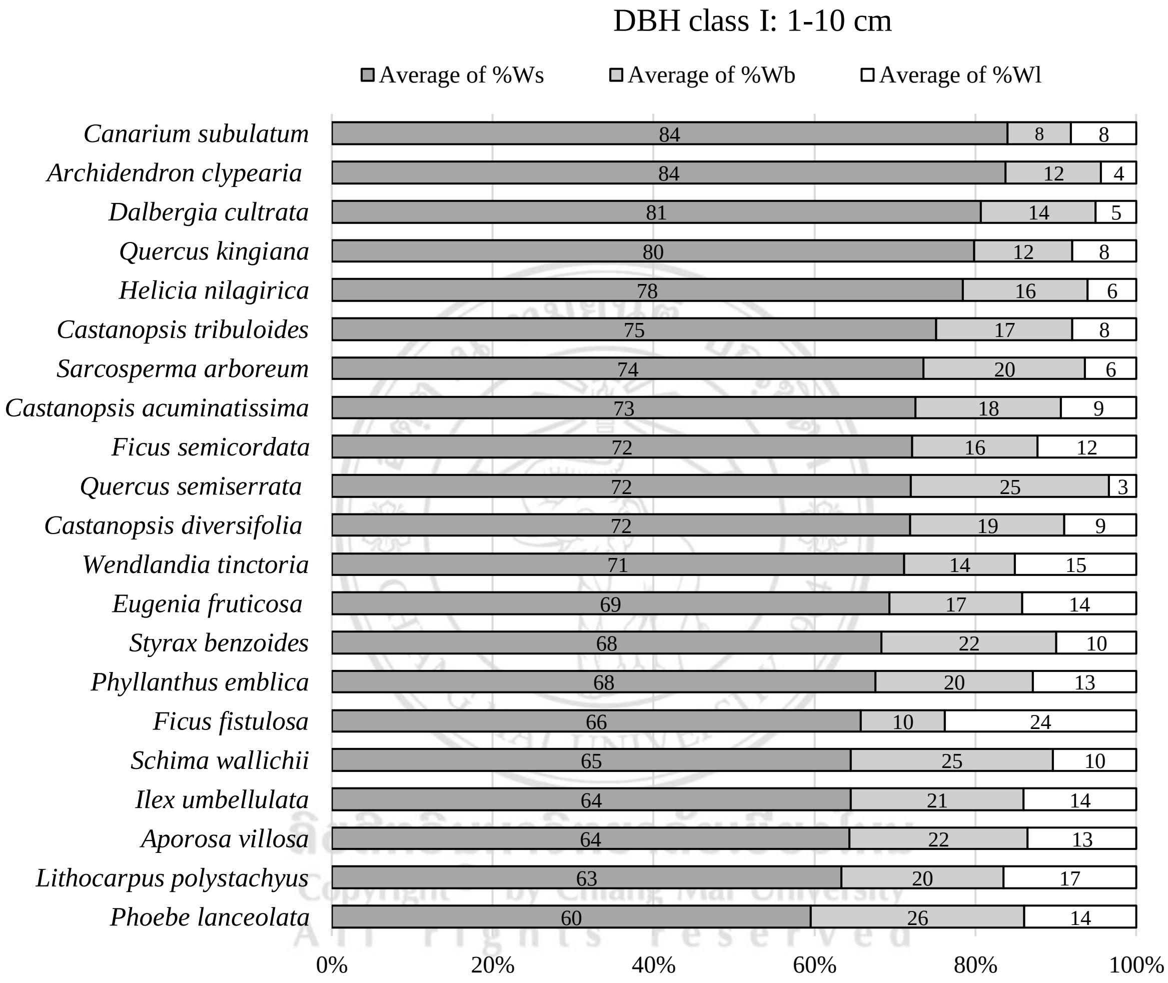
No.	Species name	N	BA	Frequency	Density	RD	RF	RDo	IVI	%IVI
11	Eurya acuminata DC.	13	2766.9	0.25	0.36	3.98	3.56	1.13	8.66	2.89
12	Castanopsis lucida (Nees) Soepadmo	14	2573.2	0.22	0.39	4.28	3.16	1.05	8.49	2.83
13	Syzygium fruticosum DC.	9	5078.5	0.17	0.25	2.75	2.37	2.07	7.20	2.40
14	Styrax benzoides W. G. Craib	6	1346.3	0.17	0.17	1.83	2.37	0.55	4.76	1.59
15	Archidendron clypearia (Jack) I.C.Nielsen	6	1039.4	0.17	0.17	1.83	2.37	0.42	4.63	1.54
16	Polyalthia cerasoides (Roxb.) Bedd.	6	1489.1	0.14	0.17	1.83	1.98	0.61	4.42	1.47
17	Antidesma sootepense Craib	7	944.7	0.11	0.19	2.14	1.58	0.39	4.11	1.37
18	Shorea roxburghii G.Don	4	2905.1	0.11	0.11	1.22	1.58	1.19	3.99	1.33
19	Polyalthia viridis W. G. Craib	4	2152.6	0.11	0.11	1.22	1.58	0.88	3.68	1.23
20	Turpinia pomifera (Roxb.) DC.	5	1035.2	0.11	0.14	1.53	1.58	0.42	3.53	1.18
21	Aporosa villosa (Lindl.) Baill.	4	1743.2	0.11	0.11	1.22	1.58	0.71	3.52	1.17
22	Sarcosperma arboreum Hook.f.	5	712.3	0.11	0.14	1.53	1.58	0.29	3.40	1.13
23	Myrsine seguinii H. Lév.	4	498.9	0.11	0.11	1.22	1.58	0.20	3.01	1.00
24	Buchanania cochinchinensis (Lour.) M.R.Almeida	3	2146.4	0.08	0.08	0.92	1.19	0.88	2.98	0.99
25	Heynea trijuga Roxb. ex Sims	1	4711.9	0.03	0.03	0.31	0.40	1.92	2.62	0.87
26	Syzygium cumini (L.) Skeels	3	2221.8	0.06	0.08	0.92	0.79	0.91	2.61	0.87
27	Olea rosea Craib	4	1338.2	0.06	0.11	1.22	0.79	0.55	2.56	0.85
28	Semecarpus albescens Kurz (Cassuvium albescens Kuntze)	3	945.5	0.08	0.08	0.92	1.19	0.39	2.49	0.83
29	Magnolia hodgsonii (Hook.f. & Thomson) H.Keng	3	889.2	0.08	0.08	0.92	1.19	0.36	2.47	0.82
30	Stereospermum tetragonum DC.	3	599.2	0.08	0.08	0.92	1.19	0.24	2.35	0.78
31	Celtis tetrandra Roxb.	2	1624.8	0.06	0.06	0.61	0.79	0.66	2.07	0.69
32	Dalbergia oliveri Prain	3	848.0	0.06	0.08	0.92	0.79	0.35	2.05	0.68
33	Dalbergia cana Kurz	2	1585.6	0.06	0.06	0.61	0.79	0.65	2.05	0.68
34	Dillenia parviflora Griff.	2	1200.0	0.06	0.06	0.61	0.79	0.49	1.89	0.63
35	Castanopsis calathiformis (Skan) Rehder & E.H.Wilson	2	1128.9	0.06	0.06	0.61	0.79	0.46	1.86	0.62
36	Glochidion sphaerogynum (Müll.Arg.) Kurz	2	721.5	0.06	0.06	0.61	0.79	0.29	1.70	0.57
37	Grewia eriocarpa Juss.	2	687.3	0.06	0.06	0.61	0.79	0.28	1.68	0.56
38	Elaeocarpus stipularis Blume	1	2277.3	0.03	0.03	0.31	0.40	0.93	1.63	0.54
39	Aporosa octandra (Buch.-Ham. ex D.Don) Vickery	2	423.7	0.06	0.06	0.61	0.79	0.17	1.58	0.53
40	Phyllanthus emblica L.	2	386.0	0.06	0.06	0.61	0.79	0.16	1.56	0.52
41	Magnolia baillonii Pierre	2	290.1	0.06	0.06	0.61	0.79	0.12	1.52	0.51
42	Markhamia stipulata (Wall.) Seem.	2	155.7	0.06	0.06	0.61	0.79	0.06	1.47	0.49
43	Protium serratum (Wall. ex Colebr.) Engl.	2	648.1	0.03	0.06	0.61	0.40	0.26	1.27	0.42

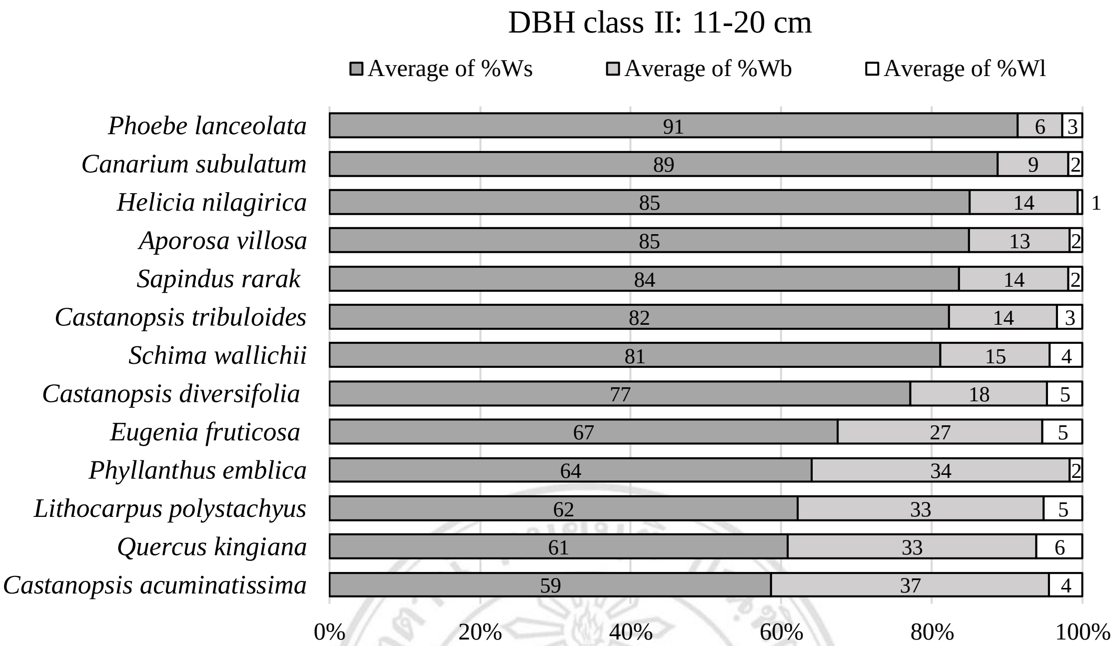
Secondary Forest (DBH ≥ 4.5 cm) (Continued)

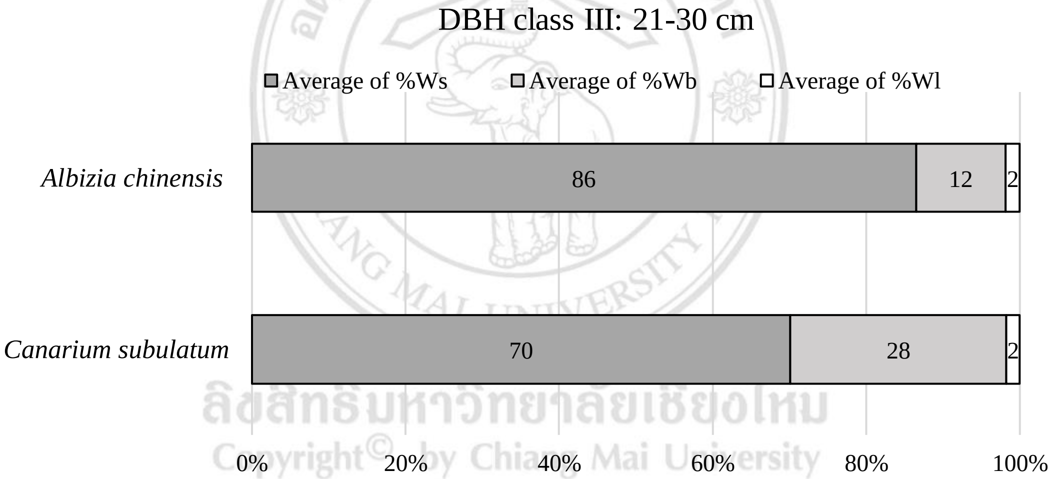
No.	**Species name**	**N**	**BA**	**Frequency**	**Density**	**RD**	**RF**	**RDo**	**IVI**	**%IVI**
44	Quercus kerrii Craib	1	1243.4	0.03	0.03	0.31	0.40	0.51	1.21	0.40
45	Xanthophyllum virens Roxb.	1	1210.5	0.03	0.03	0.31	0.40	0.49	1.19	0.40
46	Alstonia rostrata C.E.C.Fisch.	2	172.8	0.03	0.06	0.61	0.40	0.07	1.08	0.36
47	Spondias pinnata (L.f.) Kurz	1	809.1	0.03	0.03	0.31	0.40	0.33	1.03	0.34
48	Albizia odoratissima (L.f.) Benth.	1	782.6	0.03	0.03	0.31	0.40	0.32	1.02	0.34
49	Sapindus rarak DC.	1	563.7	0.03	0.03	0.31	0.40	0.23	0.93	0.31
50	Litsea lancifolia (Roxb. ex Nees) Fern.-Vill.	1	467.7	0.03	0.03	0.31	0.40	0.19	0.89	0.30
51	Symplocos sulcata Kurz	1	270.8	0.03	0.03	0.31	0.40	0.11	0.81	0.27
52	Schoepfia fragrans Wall.	1	252.5	0.03	0.03	0.31	0.40	0.10	0.80	0.27
53	Lepisanthes tetraphylla Radlk.	1	248.1	0.03	0.03	0.31	0.40	0.10	0.80	0.27
54	Canthium glabrum Blume	1	244.3	0.03	0.03	0.31	0.40	0.10	0.80	0.27
55	Litsea monopetala (Roxb.) Pers.	1	198.9	0.03	0.03	0.31	0.40	0.08	0.78	0.26
56	Dalbergia ovata Benth.	1	185.9	0.03	0.03	0.31	0.40	0.08	0.78	0.26
57	Memecylon scutellatum (Lour.) Hook. & Arn.	1	132.7	0.03	0.03	0.31	0.40	0.05	0.76	0.25
58	Toona ciliata M. Roem.	1	71.6	0.03	0.03	0.31	0.40	0.03	0.73	0.24
59	Diospyros glandulosa Lace	1	67.7	0.03	0.03	0.31	0.40	0.03	0.73	0.24
60	Calophyllum inophyllum L.	1	63.9	0.03	0.03	0.31	0.40	0.03	0.73	0.24

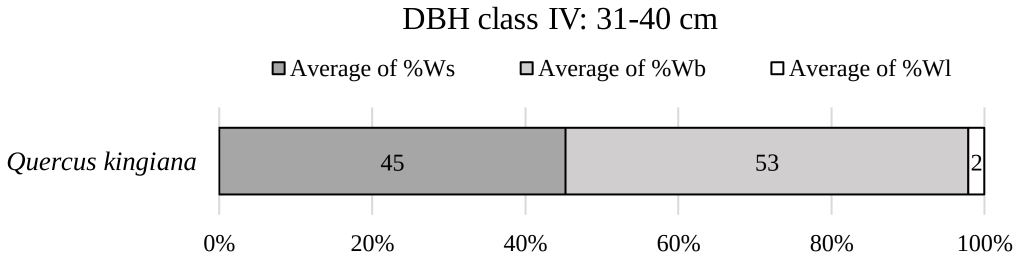
APPENDIX B

The proportion of average dry mass of stem (Ws), branches (Wb), and leaves (Wl) by species in different DBH Class:




DBH class II: 11-20 cm
Average of %Ws
Average of %Wb
Average of %Wl
Phoebe lanceolata 91 6 3
Canarium subulatum 89 9 2
Helicia nilagirica 85 14 1
Aporosa villosa 85 13 2
Sapindus rarak 84 14 2
Castanopsis tribuloides 82 14 3
Schima wallichii 81 15 4
Castanopsis diversifolia 77 18 5
Eugenia fruticosa 67 27 5
Phyllanthus emblica 64 34 2
Lithocarpus polystachyus 62 33 5
Quercus kingiana 61 33 6
Castanopsis acuminatissima 59 37 4
0%
20%
40%
60%
80%
100%


DBH class III: 21-30 cm
Average of %Ws
Average of %Wb
Average of %Wl
Albizia chinensis 86 12 2
Canarium subulatum 70 28 2
0%
20%
40%
60%
80%
100%


DBH class IV: 31-40 cm
Average of %Ws
Average of %Wb
Average of %Wl
Quercus kingiana 45 53 2
0%
20%
40%
60%
80%
100%

APPENDIX C

C-1 The average wood density (WD) among tree species from this study, global wood density (GWD) and Genus from Zanne et al. (2009)

N	Species name	This study WD (g/cm^3)			GWD (g/cm^3)			Genus (g/cm^3)		
		x̄±SD	n	min-max	x̄±SD	n	min-max	x̄±SD	n	min-max
1	*Actinodaphne henryi*							0.51±0.09	8	0.4-0.65
2	*Adenanthera microsperma*				0.64	1				
3	*Albizia chinensis*	0.4±0.07	9	0.26-0.49	0.30	1				
4	*Albizia lebbeck*				0.6±0.12	6	0.45-0.8			
5	*Albizia odoratissima*	0.63	1		0.64±0.06	6	0.57-0.71			
6	*Alstonia rostrata*	0.37±0	2	0.36-0.37						
7	*Anneslea fragrans*	0.58±0.07	2	0.53-0.63	0.68±0.05	3	0.63-0.72			
8	*Anogeissus acuminata*				0.88	1				
9	*Antidesma acidum*							0.65±0.08	13	0.51-0.8
10	*Antidesma sootepensis*	0.53±0.07	4	0.47-0.62						
11	*Aporosa octandra*	0.58±0.01	2	0.57-0.58						
12	*Aporosa villosa*	0.51±0.08	70	0.46-0.54						
13	*Archidendron clypearia*	0.41±0.04	8	0.34-0.47	0.32±0.06	3	0.26-0.37			
14	*Artocarpus lacucha*							0.48±0.1	63	0.27-0.73
15	*Berrya mollis*	0.44±0.03	4	0.39-0.46						
16	*Bombax anceps*	0.19±0.01	2	0.19-0.2	0.41	1				
17	*Buchanania lanzan*	0.47±0.07	3	0.42-0.56	0.39±0.09	2	0.33-0.45			
18	*Callicarpa arborea*	0.44	1							
19	*Calophyllum inophyllum*	0.34	1		0.58±0.04	5	0.53-0.64			
20	*Canarium subulatum*	0.41±0.08	38	0.2-0.52						
21	*Canthium glabrum*	0.54±0.05	11	0.47-0.63	0.41	1				
22	*Castanopsis acuminatissima*	0.59±0.11	26	0.42-0.76	0.58±0.01	2	0.58-0.59			
23	*Castanopsis calathiformis*	0.67±0.03	2	0.65-0.69						
24	*Castanopsis diversifolia*	0.57±0.09	35	0.35-0.78						
25	*Castanopsis lucida*	0.51±0.03	6	0.46-0.54	0.53	1				
26	*Castanopsis tribuloides*	0.6±0.07	30	0.48-0.77	0.59±0.12	2	0.51-0.68			
27	*Celtis tetrandra*	0.58±0.05	2	0.55-0.62	0.52	1				
28	*Cinnamomum camphora*				0.49±0.08	5	0.42-0.62			
29	*Cinnamomum verum*				0.50	1				
30	*Colona winitii*	0.44	1							
31	*Craibiodendron stellatum*	0.62±0.05	3	0.56-0.67						
32	*Cratoxylum cochinchinense*				0.67±0.1	2	0.6-0.74			
33	*Cratoxylum formosum*	0.62±0.02	3	0.6-0.64	0.72±0.06	4	0.64-0.76			
34	*Dalbergia cana*	0.62±0.08	2	0.57-0.68						
35	*Dalbergia cultrata*	0.53±0.05	32	0.43-0.67	0.77	1				
36	*Dalbergia oliveri*	0.46±0.03	2	0.44-0.48	0.88±0.04	2	0.85-0.91			
37	*Dalbergia ovata**				0.68	1				
38	*Dillenia parviflora*	0.6±0.06	5	0.53-0.68	0.56	1				
39	*Dimocarpus longan*				0.70	1				
40	*Diospyros glandulosa*	0.51±0.06	2	0.47-0.55						
41	*Dodonaea viscosa*				0.95±0.15	2	0.84-1.05			
42	*Elaeocarpus stipularis*	0.64	1		0.45±0.02	2	0.43-0.46			
43	*Engelhardtia serrata*				0.37	1				
44	*Engelhardtia spicata*				0.44±0.06	3	0.37-0.49			
45	*Eriolaena candollei*				0.70	1				
46	*Erythrina subumbrans*	0.32	1		0.23	1				
47	*Eugenia albiflora*							0.73±0.12	95	0.49-1.3
48	*Eugenia cumini*	0.57±0.05	3	0.52-0.61	0.56	1				
49	*Eugenia fruticosa*	0.49±0.09	31	0.34-0.71						
50	*Eurya acuminata*	0.56±0.06	6	0.47-0.62	0.50	1				
51	*Fernandoa adenophylla*	0.63±0.04	2	0.61-0.66	0.49	1				
52	*Ficus fistulosa*	0.24±0.05	9	0.14-0.31	0.38	1				
53	*Ficus hirta*							0.41±0.09	153	0.14-0.68
54	*Ficus hispida*				0.38±0.04	2	0.35-0.41			
55	*Ficus semicordata*	0.36±0.08	8	0.25-0.5						
56	*Flacourtia indica*	0.67±0.03	4	0.65-0.71	0.74±0.07	2	0.69-0.78			
57	*Garcinia cowa*				0.55	1				
58	*Garcinia xanthochymus*				0.79	1				
59	*Gardenia sootepensis*							0.67±0.07	14	0.56-0.77

C-1 (Continued)

N	Species name	This study WD (g/cm^3)			GWD (g/cm^3)			Genus (g/cm^3)		
		x̄±SD	n	min-max	x̄±SD	n	min-max	x̄±SD	n	min-max
60	*Glochidion rubrum*				0.64	1				
61	*Glochidion sphaerogynum*	0.46	1							
62	*Gluta usitata*	0.64	1		0.74	1				
63	*Grewia eriocarpa*	0.47±0.01	2	0.46-0.49	0.67	1				
64	*Helicia nilagirica*	0.53±0.07	36	0.42-0.76	0.64±0.02	3	0.62-0.66			
65	*Heynea trijuga*	0.53±0.07	2	0.48-0.57	0.45	2	0.45-0.55			
66	*Ilex umbellulata*	0.44±0.06	24	0.28-0.54						
67	*Ixora cibdela*							0.79±0.1	7	0.69-0.96
68	*Knema cinerea*							0.53±0.05	19	0.44-0.63
69	*Lagerstroemia tomentosa*				0.54	1				
70	*Lepisanthes tetraphylla**				0.81±0.21	2	0.66-0.96			
71	*Lindera meisneri*							0.52±0.1	8	0.36-0.64
72	*Lithocarpus garrettianus*							0.67±0.12	65	0.44-0.88
73	*Lithocarpus polystachyus*	0.65±0.11	119	0.41-1.03						
74	*Litsea glutinosa*	0.29	1		0.5±0.08	2	0.44-0.56			
75	*Litsea lancifolia*	0.43	1							
76	*Litsea monopetala*	0.44	1		0.42±0.03	6	0.38-0.45			
77	*Macaranga denticulata*				0.43±0.07	4	0.33-0.49			
78	*Macaranga kurzii*							0.38±0.12	57	0.23-0.7
79	*Magnolia baillonii*	0.42±0.04	2	0.39-0.45						
80	*Magnolia hodgsonii*	0.51±0.15	3	0.41-0.69	0.62	1				
81	*Mallotus philippensis*							0.5±0.12	29	0.32-0.7
82	*Mangifera indica*				0.55±0.07	6	0.48-0.68			
83	*Markhamia stipulata*	0.44±0.06	2	0.4-0.48	0.68±0.18	2	0.55-0.8			
84	*Meliosma simplicifolia*				0.45	1				
85	*Memecylon scutellatum*	0.41	1							
86	*Muntingia calabura*				0.30	1				
87	*Olea rosea Craib*	0.59±0.11	4	0.45-0.68						
88	*Oroxylum indicum*	0.32	1		0.41±0.07	3	0.34-0.48			
89	*Phoebe lanceolata*	0.52±0.09	24	0.4-0.78	0.69	1				
90	*Phyllanthus emblica*	0.5±0.07	72	0.35-0.72	0.64±0.06	3	0.57-0.68			
91	*Polyalthia cerasoides*	0.56±0.09	4	0.43-0.63	0.76±0.11	2	0.68-0.83			
92	*Polyalthia viridis*	0.49±0.03	3	0.45-0.52						
93	*Protium serratum*	0.43	1							
94	*Pterocarpus macrocarpus*				0.70	1				
95	*Quercus kerrii*	0.68	1							
96	*Quercus kingiana*	0.58±0.09	50	0.29-0.78						
97	*Quercus semiserrata*	0.63±0.05	9	0.55-0.73	0.71±0.05	3	0.66-0.76			
98	*Rapanea yunnanensis*	0.59±0.05	3	0.53-0.63						
99	*Rhus chinensis*							0.59±0.21	14	0.37-1.01
100	*Sapindus rarak*	0.48±0.04	8	0.43-0.55	0.51	1				
101	*Sarcosperma arboreum*	0.54±0.02	2	0.53-0.56	0.46	1				
102	*Schima wallichii*	0.53±0.06	47	0.39-0.72	0.56±0.04	8	0.5-0.62			
103	*Schoepfia fragrans*	0.57	1							
104	*Semecarpus albescens*	0.54±0.03	4	0.5-0.58	0.26	1				
105	*Shorea roxburghii*	0.64±0.05	3	0.61-0.71	0.70	1				
106	*Spondias lakonensis*	0.29	1							
107	*Spondias pinnata*	0.34	1		0.29±0.06	5	0.22-0.36			
108	*Sterculia balanghas*							0.43±0.13	79	0.2-0.7
109	*Stereospermum colais*	0.45±0.05	3	0.4-0.49						
110	*Stereospermum neuranthum*	0.61±0.06	3	0.54-0.66						
111	*Styrax benzoides*	0.58±0.07	33	0.35-0.8	0.00	1				
112	*Symplocos macrophylla*	0.53	1							
113	*Toona ciliata*	0.49	1		0.38±0.04	6	0.33-0.43			
114	*Turpinia pomifera*	0.49±0.04	5	0.45-0.56						
115	*Vitex limonifolia*							0.55±0.12	41	0.4-0.9
116	*Wendlandia tinctoria*	0.55±0.09	27	0.37-0.73						
117	*Xanthophyllum virens*	0.54	1							
	Average	**0.51±0.11**	**883**	**0.14-1.03**	0.56±0.15	142	0.22-0.88			

* Tree of this species died before sample collection

C-2 Average wood density (g/cm^3) differences among tree species (Duncan's Multiple Range test, $p \leq 0.05$).

Species	**WD**	**Duncan's test**	**Pioneer/Climax**
Flacourtia indica	0.67	a	Pioneer
Shorea roxburghii	0.65	ab	Climax
Lithocarpus polystachyus	0.65	abc	Climax
Quercus semiserrata	0.63	abcd	Climax
Cratoxylum formosum	0.63	abcde	Pioneer
Craibiodendron stellatum	0.62	abcdef	Climax
Stereospermum neuranthum	0.61	abcdefg	Climax
Dillenia parviflora	0.60	abcdefgh	Climax
Castanopsis tribuloides	0.60	abcdefghi	Climax
Olea rosea	0.59	abcdefghij	Climax
Rapanea yunnanensis	0.59	abcdefghijk	Climax
Castanopsis acuminatissima	0.59	abcdefghijkl	Climax
Quercus kingiana	0.58	abcdefghijkl	Climax
Styrax benzoides	0.58	abcdefghijkl	Pioneer
Eugenia cumini	0.57	abcdefghijkl	Climax
Castanopsis diversifolia	0.57	abcdefghijkl	Climax
Polyalthia cerasoides	0.57	abcdefghijkl	Pioneer
Eurya acuminata	0.56	bcdefghijkl	Pioneer
Wendlandia tinctoria	0.55	cdefghijklm	Pioneer
Sarcosperma arboreum	0.54	cdefghijklm	Climax
Semecarpus albescens	0.54	cdefghijklm	Pioneer
Antidesma sootepensis	0.53	defghijklm	Pioneer
Helicia nilagirica	0.53	defghijklm	Pioneer
Dalbergia cultrata	0.53	dfghijklm	Pioneer
Schima wallichii	0.53	efghijklmn	Pioneer
Phoebe lanceolata	0.52	fghijklmn	Climax
Magnolia hodgsonii	0.52	fghijklmno	Climax
Castanopsis lucida	0.51	ghijklmno	Climax
Aporosa villosa	0.51	ghijklmno	Climax
Phyllanthus emblica	0.50	hijklmnop	Pioneer
Polyalthia viridis	0.49	iklmnop	Climax
Eugenia fruticosa	0.49	jklmnop	Climax
Turpinia pomifera	0.49	klmnop	Climax
Sapindus rarak	0.48	lmnop	Climax
Ilex umbellulata	0.44	mnopq	Climax
Berrya mollis	0.44	mnopq	Climax
Archidendron clypearia	0.41	nopq	Pioneer
Canarium subulatum	0.41	opq	Climax
Albizia chinensis	0.40	pq	Pioneer
Ficus semicordata	0.36	q	Pioneer
Ficus fistulosa	0.24	r	Pioneer

The different letter showed significantly different.

Pioneer and climax species was classified based on Maxwell and Elliott (2001), Sinhaseni (2008), Vaidhayakarn and Maxwell (2010)

APPENDIX D

Description of 72 trees (136 destructive samples including coppice). No. is number of destructive sample, Site is study site; 4y is 4-year-fallow, 7y is 7-year-fallow, and SF is Secondary forest. Code is destructive inventory code, DBH is diameter at breast height in cm, H is height in m, WD is wood density from direct measurement in g/cm^3, WDa is wood density from average of WD in each species in g/cm^3, WDgwd is wood density from average of WD in each species from Global Wood Density database in g/cm^3, WDg is wood density from average of WD in each genus from Global Wood Density database in g/cm^3, Ws is dry weight of the stem in kg, Wb is dry weight of the branches, Wl is dry weight of the leaves. AGB is aboveground biomass in kg. %C is carbon concentration.

No.	Site	Code	Type	Species name	Thai name	DBH	H	WD	WDa	WDgwd	WDg	Ws	Wb	Wl	AGB	%C
1	4y	4.1y	T	*Phyllanthus emblica* L.	มะขามป้อม	5.1	5.00	0.50	0.50	0.64	0.64	1.90	1.16	0.46	3.52	44.20
2	4y	4.1y	C	*Phyllanthus emblica* L.	มะขามป้อม	3.8	4.40	0.49	0.50	0.64	0.64	1.63	0.46	0.30	2.39	44.20
3	4y	4.1y	C	*Phyllanthus emblica* L.	มะขามป้อม	3.7	4.00	0.49	0.50	0.64	0.64	0.92	0.73	0.25	1.90	44.20
4	4y	4.2y	T	*Phyllanthus emblica* L.	มะขามป้อม	3.2	5.58	0.46	0.50	0.64	0.64	1.22	0.31	0.21	1.74	44.11
5	4y	4.2y	C	*Phyllanthus emblica* L.	มะขามป้อม	2.2	4.36	0.39	0.50	0.64	0.64	0.33	0.11	0.08	0.52	44.11
6	4y	4.2y	C	*Phyllanthus emblica* L.	มะขามป้อม	2.2	4.28	0.45	0.50	0.64	0.64	0.44	0.09	0.05	0.58	44.11
7	4y	4.2y	C	*Phyllanthus emblica* L.	มะขามป้อม	3.0	4.38	0.46	0.50	0.64	0.64	0.44	0.19	0.10	0.73	44.11
8	4y	4.2y	C	*Phyllanthus emblica* L.	มะขามป้อม	2.4	4.57	0.59	0.50	0.64	0.64	0.51	0.17	0.09	0.77	44.11
9	4y	4.2y	C	*Phyllanthus emblica* L.	มะขามป้อม	2.2	3.98	0.56	0.50	0.64	0.64	0.50	0.07	0.04	0.61	44.11
10	4y	4.3y	T	*Phyllanthus emblica* L.	มะขามป้อม	2.9	3.90	0.56	0.50	0.64	0.64	0.60	0.23	0.11	0.94	43.72
11	4y	4.3y	C	*Phyllanthus emblica* L.	มะขามป้อม	3.7	4.25	0.46	0.50	0.64	0.64	1.01	0.21	0.19	1.41	43.72
12	4y	4.3y	C	*Phyllanthus emblica* L.	มะขามป้อม	1.9	3.25	0.45	0.50	0.64	0.64	0.37	0.06	0.09	0.52	43.72
13	4y	4.3y	C	*Phyllanthus emblica* L.	มะขามป้อม	1.8	3.25	0.56	0.50	0.64	0.64	0.28	0.05	0.09	0.42	43.72
14	4y	4.3y	C	*Phyllanthus emblica* L.	มะขามป้อม	3.2	3.90	0.47	0.50	0.64	0.64	1.11	0.35	0.22	1.68	43.72
15	4y	4.3y	C	*Phyllanthus emblica* L.	มะขามป้อม	3.2	4.10	0.52	0.50	0.64	0.64	1.17	0.35	0.26	1.78	43.72
16	4y	4.3y	C	*Phyllanthus emblica* L.	มะขามป้อม	2.5	4.13	0.46	0.50	0.64	0.64	0.72	0.13	0.15	1.00	43.72
17	4y	4.3y	C	*Phyllanthus emblica* L.	มะขามป้อม	2.6	3.77	0.52	0.50	0.64	0.64	0.97	0.16	0.15	1.28	43.72
18	4y	4.7y	T	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	4.1	3.95	0.45	0.51	-	0.62	1.51	0.37	0.16	2.04	42.52
19	4y	4.7y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	3.4	4.18	0.43	0.51	-	0.62	1.25	0.46	0.17	1.88	42.52
20	4y	4.7y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	3.7	4.00	0.42	0.51	-	0.62	1.51	0.43	0.18	2.12	42.52
21	4y	4.7y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	3.4	4.10	0.58	0.51	-	0.62	0.99	0.33	0.16	1.48	42.52

Continued

No.	Site	Code	Type	Species name	Thai name	DBH	H	WD	WDa	WDgwd	WDg	Ws	Wb	Wl	AGB	%C
22	4y	4.7y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	2.5	3.62	0.53	0.51	-	0.62	0.72	0.22	0.11	1.05	42.52
23	4y	4.7y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	2.2	2.10	0.54	0.51	-	0.62	0.38	0.14	0.04	0.56	42.52
24	4y	4.8y	T	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	2.9	3.17	0.47	0.51	-	0.62	0.68	0.39	0.19	1.26	42.6
25	4y	4.8y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	3.2	3.71	0.53	0.51	-	0.62	0.95	0.25	0.30	1.50	42.6
26	4y	4.8y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	1.9	2.89	0.46	0.51	-	0.62	0.36	0.25	0.13	0.74	42.6
27	4y	4.8y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	1.9	3.10	0.45	0.51	-	0.62	0.34	0.27	0.16	0.77	42.6
28	4y	4.8y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	2.6	3.68	0.48	0.51	-	0.62	0.64	0.29	0.20	1.13	42.6
29	4y	4.8y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	1.4	2.44	0.51	0.51	-	0.62	0.25	0.10	0.07	0.42	42.6
30	4y	4.9y	T	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	2.9	3.53	0.49	0.51	-	0.62	0.82	0.23	0.14	1.19	42.98
31	4y	4.9y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	2.3	3.53	0.55	0.51	-	0.62	0.62	0.09	0.10	0.81	42.98
32	4y	4.9y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	2.6	3.31	0.54	0.51	-	0.62	0.58	0.12	0.14	0.84	42.98
33	4y	4.9y	C	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	1.6	3.09	0.48	0.51	-	0.62	0.33	0.06	0.06	0.45	42.98
34	4y	4.10y	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	3.1	4.33	0.51	0.65	-	0.67	1.03	0.25	0.37	1.65	45.38
35	4y	4.10y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	5.7	4.63	0.55	0.65	-	0.67	3.45	1.15	0.97	5.57	45.38
36	4y	4.10y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	6.4	4.32	0.53	0.65	-	0.67	4.23	1.96	1.27	7.46	45.38
37	4y	4.10y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	4.3	4.31	0.53	0.65	-	0.67	2.03	0.88	0.87	3.78	45.38
38	4y	4.10y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	4.1	4.11	0.56	0.65	-	0.67	1.82	0.42	0.41	2.65	45.38
39	4y	4.10y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	1.4	3.05	0.64	0.65	-	0.67	0.27	0.08	0.11	0.46	45.38
40	4y	4.10y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	1.2	3.12	0.72	0.65	-	0.67	0.20	0.12	0.15	0.47	45.38
41	4y	4.10y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	1.0	2.3	0.70	0.65	-	0.67	0.11	0.05	0.04	0.20	45.38
42	4y	4.11y	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	4.5	4.63	0.60	0.65	-	0.67	2.40	0.62	0.80	3.82	45.18
43	4y	4.11y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	3.7	4.68	0.58	0.65	-	0.67	2.09	0.53	0.67	3.29	45.18
44	4y	4.11y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	2.2	3.68	0.49	0.65	-	0.67	0.66	0.14	0.31	1.11	45.18
45	4y	4.12y	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	3.2	3.20	0.55	0.65	-	0.67	1.14	0.33	0.31	1.78	44.6
46	4y	4.12y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	2.0	3.11	0.61	0.65	-	0.67	0.58	0.13	0.15	0.86	44.6
47	4y	4.12y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	1.3	2.74	0.50	0.65	-	0.67	0.2	0.06	0.09	0.35	44.6
48	4y	4.13y	T	*Ilex umbellulata* (Wall.) Loes.	เน่าใน	3.8	4.20	0.51	0.44	-	0.56	2.03	0.77	0.10	2.90	44.93
49	4y	4.13y	C	*Ilex umbellulata* (Wall.) Loes.	เน่าใน	1.0	2.30	0.39	0.44	-	0.56	0.24	0.06	0.07	0.37	44.93
50	4y	4.14y	T	*Ilex umbellulata* (Wall.) Loes.	เน่าใน	4.1	4.73	0.42	0.44	-	0.56	1.74	0.59	0.54	2.87	44.69
51	4y	4.14y	C	*Ilex umbellulata* (Wall.) Loes.	เน่าใน	2.4	3.85	0.47	0.44	-	0.56	0.52	0.25	0.17	0.94	44.69
52	4y	4.14y	C	*Ilex umbellulata* (Wall.) Loes.	เน่าใน	1.0	2.34	0.39	0.44	-	0.56	0.37	0.05	0.05	0.47	44.69
53	4y	4.15y	T	*Ilex umbellulata* (Wall.) Loes.	เน่าใน	3.9	4.62	0.44	0.44	-	0.56	1.72	0.83	0.42	2.97	45.31
54	4y	4.15y	C	*Ilex umbellulata* (Wall.) Loes.	เน่าใน	3.5	4.83	0.41	0.44	-	0.56	1.46	0.50	0.32	2.28	45.31

Continued

No.	Site	Code	Type	Species name	Thai name	DBH	H	WD	WDa	WDgwd	WDg	Ws	Wb	Wl	AGB	%C
55	4y	4.16y	T	*Eugenia fruticosa* (DC.) Roxb.	หว้าขี้กวาง	2.7	3.02	0.41	0.44	-	0.56	0.65	0.18	0.18	1.01	44.79
56	4y	4.16y	C	*Eugenia fruticosa* (DC.) Roxb.	หว้าขี้กวาง	2.5	3.06	0.52	0.44	-	0.56	0.67	0.25	0.24	1.16	44.79
57	4y	4.16y	C	*Eugenia fruticosa* (DC.) Roxb.	หว้าขี้กวาง	1.6	2.21	0.43	0.44	-	0.56	0.33	0.09	0.11	0.53	44.79
58	4y	4.16y	C	*Eugenia fruticosa* (DC.) Roxb.	หว้าขี้กวาง	1.1	2.36	0.47	0.44	-	0.56	0.13	0.01	0.01	0.15	44.79
59	4y	4.17y	T	*Canarium subulatum* Guillaumin	มะกอกเกลื้อน	2.7	3.76	0.32	0.41	-	0.49	0.44	0.04	0.10	0.58	43.61
60	4y	4.18y	T	*Wendlandia tinctoria* (Roxb.) DC.	แข้งกวาง	2.1	3.57	0.63	0.55	-	0.69	0.54	0.06	0.12	0.72	45.86
61	4y	4.18y	C	*Wendlandia tinctoria* (Roxb.) DC.	แข้งกวาง	1.4	2.84	0.52	0.55	-	0.69	0.22	0.05	0.10	0.37	45.86
62	4y	4.19y	T	*Schima wallichii* Choisy	ทะโล้	4.1	5.18	0.54	0.53	0.56	0.56	2.44	1.07	0.47	3.98	45.83
63	4y	4.19y	C	*Schima wallichii* Choisy	ทะโล้	3.5	4.80	0.58	0.53	0.56	0.56	1.95	0.83	0.35	3.13	45.83
64	4y	4.19y	C	*Schima wallichii* Choisy	ทะโล้	3.2	5.10	0.52	0.53	0.56	0.56	1.58	0.56	0.28	2.42	45.83
65	4y	4.19y	C	*Schima wallichii* Choisy	ทะโล้	2.2	3.90	0.58	0.53	0.56	0.56	0.51	0.20	0.06	0.77	45.83
66	4y	4.20y	T	*Styrax benzoides* W. G. Craib	กำยาน	4.1	5.28	0.53	0.58	-	0.42	2.27	0.67	0.81	3.75	45.22
67	4y	4.21y	C	*Phoebe lanceolata* (Nees) Nees	ตองหอม	3.6	3.8	0.49	0.52	0.69	0.69	0.88	0.40	0.3	1.58	45.86
68	4y	4.22y	C	*Ficus semicordata* Buch.-Ham. ex Sm.	มะเดื่อปล้องหิน	2.1	3.9	0.31	0.36	-	0.41	0.43	0.03	0.03	0.49	41.26
69	4y	4.22y	C	*Ficus semicordata* Buch.-Ham. ex Sm.	มะเดื่อปล้องหิน	3.3	4.00	0.40	0.36	-	0.41	1.04	0.46	0.34	1.84	41.26
70	4y	4.23y	T	*Castanopsis acuminatissima* (Blume) A.DC.	ก่อเดือย	5.2	4.54	0.45	0.59	-	0.55	2.54	1.11	0.46	4.11	45.42
71	4y	4.23y	C	*Castanopsis acuminatissima* (Blume) A.DC.	ก่อเดือย	5.1	4.95	0.48	0.59	-	0.55	2.82	0.52	0.41	3.75	45.42
72	4y	4.24y	T	*Ficus fistulosa* Reinw. ex Blume	ชิ้งขาว	1.9	3.30	0.23	0.24	-	0.41	0.23	0.03	0.08	0.34	39.43
73	4y	4.24y	C	*Ficus fistulosa* Reinw. ex Blume	ชิ้งขาว	1.7	3.20	0.25	0.24	-	0.41	0.21	0.04	0.06	0.31	39.43
74	4y	4.24y	C	*Ficus fistulosa* Reinw. ex Blume	ชิ้งขาว	1.3	3.05	0.25	0.24	-	0.41	0.13	0.02	0.06	0.21	39.43
75	7y	7.1y	T	*Quercus kingiana* Craib	ก่อแดง	32.9	13.6	0.62	0.58	-	0.70	338.48	393.23	15.82	747.53	45.38
76	7y	7.2y	T	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	15.2	9.25	0.55	0.51	-	0.62	37.05	8.35	0.99	46.39	43.67
77	7y	7.3y	T	*Quercus kingiana* Craib	ก่อแดง	18.5	10.33	0.65	0.58	-	0.70	86.52	36.23	5.33	128.08	45.18
78	7y	7.4y	T	*Eugenia fruticosa* (DC.) Roxb.	หว้าขี้กวาง	15.1	8.74	0.5	0.49	-	0.73	31.67	12.78	2.49	46.94	45.42
79	7y	7.5y	T	*Dalbergia cultrata* Benth.	กระพี้เขาควาย	10.8	8.90	0.51	0.53	0.77	0.77	17.61	5.31	0.36	23.28	44.5
80	7y	7.6y	T	*Quercus kingiana* Craib	ก่อแดง	10.5	9.30	0.60	0.58	-	0.7.0	24.95	3.49	1.87	30.31	45.23
81	7y	7.7y	T	*Phoebe lanceolata* (Nees) Nees	ตองหอม	6.7	6.57	0.64	0.52	0.69	0.69	8.04	3.51	1.13	12.68	45.98
82	7y	7.8y	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	7.6	6.60	0.66	0.65	-	0.67	10.04	2.96	1.06	14.06	45.1
83	7y	7.9y	T	*Quercus semiserrata* Roxb.	ก่อกระดุม	10.8	8.70	0.63	0.63	-	0.70	21.54	7.37	1.01	29.92	44.7
84	7y	7.10y	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	8.3	8.10	0.67	0.65	-	0.67	15.82	3.00	1.64	20.46	45.24
85	7y	7.10y	C	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	9.3	8.50	0.68	0.65	-	0.67	18.51	4.91	2.30	25.72	45.24
86	7y	7.11y	T	*Quercus kingiana* Craib	ก่อแดง	7.3	5.25	0.52	0.58	-	0.70	7.03	0.68	0.38	8.09	44.36

Continued

No.	Site	Code	Type	Species name	Thai name	DBH	H	WD	WDa	WDgwd	WDg	Ws	Wb	Wl	AGB	%C
87	7y	7.11y	T	*Quercus kingiana* Craib	ก่อแดง	9.4	8.32	0.61	0.58	-	0.70p	15.76	1.78	1.55	19.09	44.36
88	7y	7.12y	T	*Quercus kingiana* Craib	ก่อแดง	6.9	6.29	0.5	0.58	-	0.7	6.37	0.98	0.81	8.16	44.77
89	7y	7.13y	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	5.0	5.51	0.58	0.65	-	0.67	4.01	0.86	0.75	5.62	46.46
90	7y	7.14y	T	*Wendlandia tinctoria* (Roxb.) DC.	แข้งกวาง	5.2	5.58	0.59	0.55	-	0.69	4.22	1.87	0.94	7.03	45.68
91	7y	7.15y	T	*Quercus kingiana* Craib	ก่อแดง	11.1	6.60	0.57	0.58	-	0.7	17.55	12.26	2.63	32.44	44.92
92	7y	7.16y	T	*Dalbergia cultrata* Benth.	กระพี้เขาควาย	5.8	5.08	0.55	0.53	0.77	0.77	4.79	0.44	0.45	5.68	43.74
93	7y	7.17y	T	*Castanopsis acuminatissima* (Blume) A.DC.	ก่อเดือย	11.1	7.26	0.69	0.59	-	0.55	24.57	15.45	1.86	41.88	45.16
94	7y	7.17y	T	*Castanopsis acuminatissima* (Blume) A.DC.	ก่อเดือย	5.6	4.07	0.66	0.59	-	0.55	3.95	0.65	0.29	4.89	45.16
95	7y	7.18y	T	*Quercus kingiana* Craib	ก่อแดง	8.0	4.93	0.52	0.58	-	0.7	5.44	1.52	0.86	7.82	45.22
96	7y	7.19y	T	*Canarium subulatum* Guillaumin	มะกอกเกลื้อน	7.0	6.68	0.45	0.41	-	0.49	4.62	0.69	0.35	5.66	43.08
97	7y	7.20y	T	*Dalbergia cultrata* Benth.	กระพี้เขาควาย	5.2	5.00	0.51	0.53	0.77	0.77	3.72	0.49	0.31	4.52	43.24
98	7y	7.21y	T	*Phyllanthus emblica* L.	มะขามป้อม	5.6	5.55	0.53	0.5	0.64	0.64	4.83	1.16	0.40	6.39	44.24
99	7y	7.22y	T	*Dalbergia cultrata* Benth.	กระพี้เขาควาย	9.4	7.72	0.53	0.53	0.77	0.77	13.72	2.69	0.63	17.04	44.08
100	7y	7.23y	T	*Styrax benzoides* W. G. Craib	กำยาน	10.5	7.90	0.55	0.58	-	0.42	20.47	11.22	3.16	34.85	45.77
101	7y	7.23y	C	*Styrax benzoides* W. G. Craib	กำยาน	7.0	6.79	0.57	0.58	-	0.42	10.35	4.30	0.80	15.45	45.77
102	7y	7.24y	T	*Schima wallichii* Choisy	ทะโล้	17.8	12.19	0.54	0.53	0.56	0.56	77.76	22.27	5.22	105.25	41.98
103	7y	7.24y	C	*Schima wallichii* Choisy	ทะโล้	6.0	6.80	0.46	0.53	0.56	0.56	7.91	2.74	1.09	11.74	41.98
104	7y	7.25y	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	12.3	5.80	0.65	0.65	-	0.67	16.00	5.98	2.01	23.99	46.42
105	SF	2F	T	*Castanopsis diversifolia* (Kurz) King ex Hook.f.	ก่อแป้น	8.3	11.68	0.52	0.57	-	0.55	15.09	1.62	0.81	17.52	45.01
106	SF	3F	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	7.2	8.26	0.74	0.65	-	0.67	11.06	7.53	0.79	19.38	45.22
107	SF	4F	T	*Helicia nilagirica* Bedd.	เหมือดคนตัวผู้	8.9	12.40	0.49	0.53	0.64	0.64	18.56	4.10	0.84	23.5	44.47
108	SF	5F	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	8.8	6.90	0.75	0.65	-	0.67	16.58	10.61	0.46	27.65	45.32
109	SF	6F	T	*Helicia nilagirica* Bedd.	เหมือดคนตัวผู้	5.1	5.90	0.61	0.53	0.64	0.64	3.08	0.59	0.26	3.93	42.39
110	SF	7F	T	*Castanopsis diversifolia* (Kurz) King ex Hook.f.	ก่อแป้น	6.4	5.90	0.55	0.57	-	0.55	5.54	2.31	1.06	8.91	44.27
111	SF	8F	T	*Helicia nilagirica* Bedd.	เหมือดคนตัวผู้	6.6	6.80	0.53	0.53	0.64	0.64	4.76	0.87	0.48	6.11	43.93
112	SF	9F	T	*Castanopsis tribuloides* (Sm.) A.DC.	ก่อใบเลื่อม	6.4	7.30	0.64	0.6	-	0.55	8.57	2.24	0.95	11.76	45.04
113	SF	10F	T	*Canarium subulatum* Guillaumin	มะกอกเกลื้อน	6.4	7.10	0.47	0.41	-	0.49	5.98	0.46	0.17	6.61	44.23
114	SF	11F	T	*Schima wallichii* Choisy	ทะโล้	11.2	14.6	0.52	0.53	0.56	0.56	44.44	5.41	2.87	52.72	46.19
115	SF	12F	T	*Canarium subulatum* Guillaumin	มะกอกเกลื้อน	4.8	7.70	0.48	0.41	-	0.49	2.77	0.18	0.20	3.15	44.22
116	SF	13F	T	*Castanopsis diversifolia* (Kurz) King ex Hook.f.	ก่อแป้น	5.1	6.43	0.64	0.57	-	0.55	4.29	1.42	0.65	6.36	44.76
117	SF	15F	T	*Canarium subulatum* Guillaumin	มะกอกเกลื้อน	14.3	11.6	0.32	0.41		0.49	27.72	2.93	0.59	31.24	43.96
118	SF	16F	T	*Schima wallichii* Choisy	ทะโล้	17.8	17.00	0.52	0.53	0.56	0.56	113.75	16.18	3.51	133.44	46.31

Continued

No.	Site	Code	Type	Species name	Thai name	DBH	H	WD	WDa	WDgwd	WDg	Ws	Wb	Wl	AGB	%C
119	SF	17F	T	*Castanopsis tribuloides* (Sm.) A.DC.	ก่อใบเลื่อม	7.8	11.88	0.65	0.6	-	0.55	18.39	2.17	0.85	21.41	45.47
120	SF	18F	T	*Castanopsis tribuloides* (Sm.) A.DC.	ก่อใบเลื่อม	4.8	6.49	0.58	0.6	-	0.55	4.29	1.38	0.76	6.43	45.45
121	SF	19F	T	*Albizia chinensis* (Osbeck) Merr.	กางหลวง	21.6	19.30	0.42	0.4	0.30	0.30	170.8	23.05	3.67	197.52	45.52
122	SF	20F	T	*Canarium subulatum* Guillaumin	มะกอกเกลื้อน	30.9	15.10	0.32	0.41	-	0.49	162.66	65.22	4.05	231.93	44.54
123	SF	21F	T	*Styrax benzoides* W. G. Craib	กำยาน	5.8	8.15	0.58	0.58	-	0.42	7.20	0.76	0.31	8.27	45.08
124	SF	22F	T	*Phyllanthus emblica* L.	มะขามป้อม	13.1	10.70	0.56	0.5	0.64	0.64	46.34	24.8	1.25	72.39	44.94
125	SF	23F	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	18.1	16.80	0.70	0.65	-	0.67	140.19	98.26	4.96	243.41	45.43
126	SF	24F	T	*Sapindus rarak* DC.	มะซัก	16.2	15.50	0.48	0.48	0.51	0.51	90.31	15.59	2.08	107.98	46.22
127	SF	25F	T	*Archidendron clypearia* (Jack) I.C.Nielsen	มะขามแป	5.9	5.92	0.43	0.41	0.32	0.32	2.89	0.41	0.15	3.45	46.67
128	SF	26F	T	*Castanopsis tribuloides* (Sm.) A.DC.	ก่อใบเลื่อม	15.3	16.50	0.54	0.6	-	0.55	78.01	13.63	3.2	94.84	45.38
129	SF	27F	T	*Aporosa villosa* (Lindl.) Baill.	เหมือดโลด	11.3	11.31	0.48	0.51	-	0.62	24.88	2.38	0.38	27.64	43.24
130	SF	28F	T	*Sarcosperma arboreum* Hook.f.	มะยาง	6.1	7.20	0.53	0.54	0.41	0.41	7.32	2.00	0.63	9.95	45.35
131	SF	29F	T	*Helicia nilagirica* Bedd.	เหมือดคนตัวผู้	19.1	13.40	0.55	0.53	0.64	0.64	93.04	15.69	0.74	109.47	45.59
132	SF	30F	T	*Eugenia fruticosa* (DC.) Roxb.	หว้าขี้กวาง	10.8	7.78	0.43	0.49	-	0.73	15.71	4.07	1.05	20.83	45.19
133	SF	31F	T	*Castanopsis diversifolia* (Kurz) King ex Hook.f.	ก่อแป้น	11.5	14.60	0.58	0.57	-	0.55	34.98	8.21	2.14	45.33	45.24
134	SF	32F	T	*Phoebe lanceolata* (Nees) Nees	ตองหอม	12.6	15.52	0.45	0.52	0.69	0.69	51.17	3.33	1.52	56.02	45.15
135	SF	33F	T	*Lithocarpus polystachyus* (Wall. ex A.DC.) Rehder	ก่อนก	6.7	12.10	0.68	0.65	-	0.67	18.82	2.16	0.53	21.51	45.3
136	SF	34F	T	*Wendlandia tinctoria* (Roxb.) DC.	แข้งกวาง	8.5	11.69	0.44	0.55	-	0.69	14.43	1.10	0.51	16.04	46.1

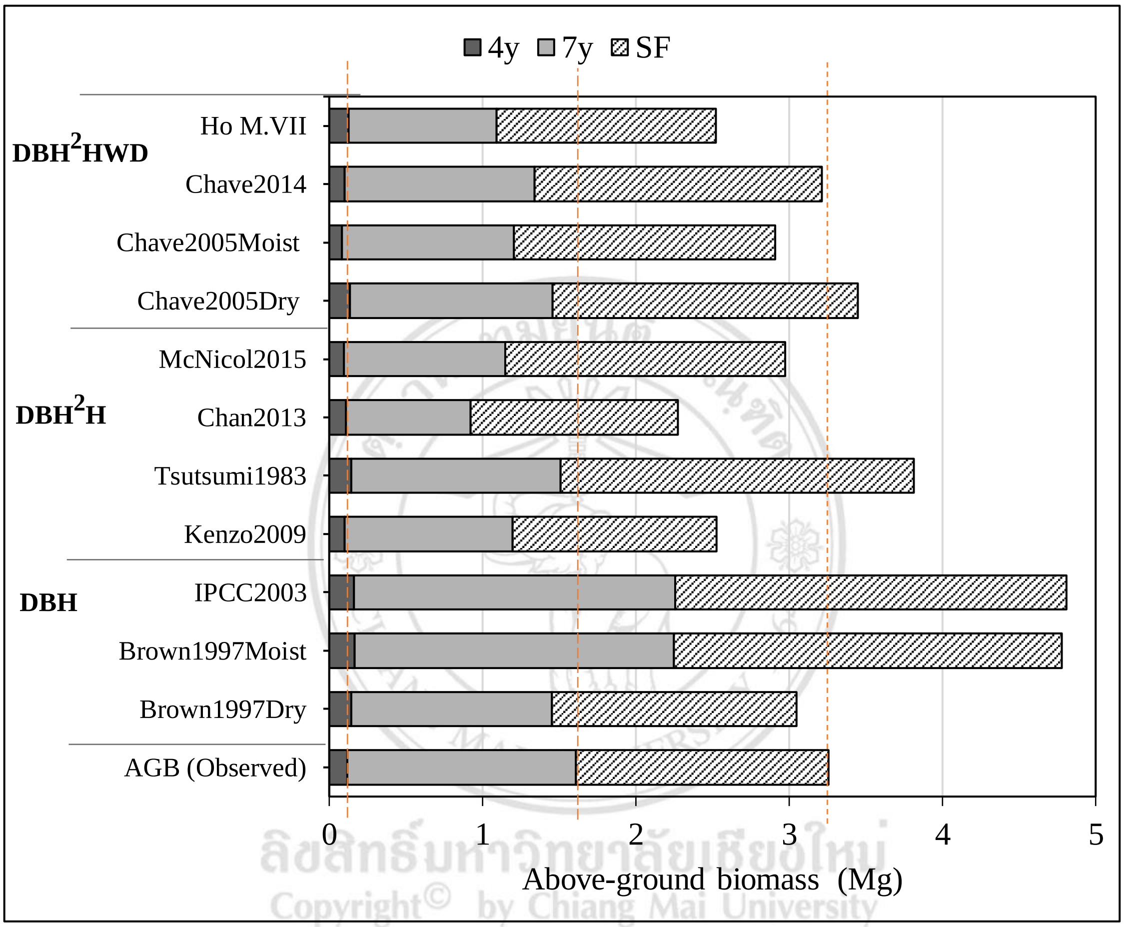
APPENDIX E

Table 4.14 Mean carbon concentration (%) across species

Species	Family	Average (%C±SD)
Archidendron clypearia	Leguminosae	46.73±2.08
Sapindus rarak	Sapindaceae	46.22±1.58
Schima wallichii	Theaceae	46.03±1.06
Wendlandia tinctoria	Rubiaceae	45.88±0.86
Phoebe lanceolata	Lauraceae	45.65±1.35
Styrax benzoides	Styracaceae	45.62±1.51
Albizia chinensis	Leguminosae	45.52±1.16
Castanopsis tribuloides	Fagaceae	45.37±0.73
Lithocarpus polystachyus	Fagaceae	45.37±1.39
Sarcosperma arboreum	Sapotaceae	45.35±1.04
Castanopsis acuminatissima	Fagaceae	45.28±0.73
Eugenia fruticosa	Myrtaceae	45.19±0.71
Quercus kingiana	Fagaceae	45.03±1.11
Ilex umbellulata	Aquifoliaceae	44.97±0.88
Castanopsis diversifolia	Fagaceae	44.89±0.53
Quercus semiserrata	Fagaceae	44.70±0.61
Helicia nilagirica	Proteaceae	44.32±1.48
Phyllanthus emblica	Phyllanthaceae	44.32±0.76
Canarium subulatum	Burseraceae	44.00±1.02
Dalbergia cultrata	Leguminosae	43.97±0.88
Aporosa villosa	Phyllanthaceae	43.04±2.08
Ficus semicordata	Moraceae	41.26±3.16
Ficus fistulosa	Moraceae	39.43±3.87
Average across species		44.84±1.63

APPENDIX F

Comparison of AGB (observed) and AGB (predicted) from the best fit equations developed in this study and other reported allometric equation.



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