SOIL CARBON SEQUESTRATION AND DYNAMICS OF NATURAL FOREST ECOSYSTEMS AND FOREST RESTORATION PLOTS IN MAE RIM DISTRICT, CHIANG MAI PROVINCE

NUTTIRA KAVINCHAN

DOCTOR OF PHILOSOPHY
IN BIODIVERSITY AND ETHNOBIOLOGY

GRADUATE SCHOOL
CHIANG MAI UNIVERSITY
DECEMBER 2013

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A THESIS SUBMITTED TO CHIANG MAI UNIVERSITY IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
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17 DECEMBER 2013

To

…My parents and great teachers…

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Nuttira Kavinchan

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LIST OF ABBREVIATIONS

3PG	Physiological Principles Predicting Growth
AET	annual actual evapotranspiration
AGC	above-ground carbon
BIO	Microbial Biomass
CAMAg	Carbon Accounting Model for Agriculture - Cropping and grazing
CAMFor	Carbon Accounting Model for Forestry
CH4	Methane
CO_2	Carbon dioxide
DDF	Dry Dipterocarpus Forest
DEF	Dry Evergreen Forest
DPM	Decomposable Plant Material
EC	European Commission
ECOSSE	Estimate Carbon in Organic Soils – Sequestration and Emissions
EU27	European Union 27 countries
FAO	FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
FORRU	Forest Restoration Research Unit
FullCAM	The Full Carbon Accounting Model
GENDEC	GENeral microbial mulch DECay model
GHGs	Green house gases
HUM	Humified Organic Matter
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MAP	mean annual precipitation
MAT	mean annual temperature
MDF	Mixed Deciduous Forest
MODIS	Moderate Resolution Imaging Spectroradiometer
N2O	Nitrous oxide
NPP	Net primary production
NRC	National Research Council
OC	organic carbon
RED	Reducing emissions from deforestation
REDD	Reducing emissions from deforestation and forest degradation
RFD	Royal Forest Department
NRC	National Research Council
OC	organic carbon
RED	Reducing emissions from deforestation
REDD	Reducing emissions from deforestation and forest degradation

LIST OF ABBREVIATIONS (continued)

RothC	Rothamsted Soil Carbon Model
RPM	Resistant Plant Material
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNPD	United Nations Population Division

ข้อความแห่งการริเริ่ม

1. ถึงแม้งานวิจัยทางด้านการกักเก็บคาร์บอนเหนือดินจะมีการรวบรวมแล้วทั้งส่วนของป่าธรรมชาติและป่าปลูก แต่ยังคงขาดข้อมูลของป่าที่เกิดจากการฟื้นฟู โดยเฉพาะความรู้ทางด้านคาร์บอนใต้ดิน
2. อินทรีย์คาร์บอนในดิน เป็นแหล่งกักเก็บคาร์บอนที่สำคัญ อีกทั้งยังมีส่วนช่วยในเรื่องความอุดมสมบูรณ์ของดิน การเจริญเติบโตของพืชและความสามารถในการฟื้นตัวของป่า
3. การสร้างความเข้าใจในกลไกของพลวัตเศษซากพืชและการสะสมในรูปแบบของอินทรีย์คาร์บอนในดิน นำไปสู่ประสิทธิภาพของการฟื้นฟูป่าที่ได้ผลมากขึ้น

STATEMENT OF ORIGINALITY

1. Although much research has been done on carbon sequestration in mature forests and in plantations particularly with regard to above ground carbon, little attention has been paid to the potential for forest restoration to sequester carbon, particularly in the soils.
2. Soil organic matter is a major contribution to the soil nutrient pool required for maintaining soil fertility, plant growth and ultimately the capacity for forest regeneration.
3. Increased understanding of the dynamics of litterfall and accumulation of soil organic matter can ultimately lead to better forest restoration strategies.

หัวข้อดุษฎีนิพนธ์ การสะสมและพลวัตคาร์บอนในดินของระบบนิเวศป่าธรรมชาติและ
แปลงฟื้นฟูป่า อำเภอแม่ริม จังหวัดเชียงใหม่

ผู้เขียน นางสาวณัฏฐิรา กำวินจันทร์

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	ผศ.ดร. จิตติ ปิ่นทอง	อาจารย์ที่ปรึกษาร่วม

บทคัดย่อ

การศึกษาคาร์บอนใต้ดินในป่าที่ฟื้นฟูด้วยวิธีพรรณไม้โครงสร้างโดยหน่วยวิจัยการฟื้นฟูป่า ซึ่งตั้งอยู่ในเขตหมู่บ้านแม่สาใหม่ อำเภอแม่ริม จังหวัดเชียงใหม่ ที่มีอายุการปลูกคือ 11, 7 และ 2 ปี เปรียบเทียบกะแปลงป่าธรรมชาติใกล้เคียง รวมถึงแปลงที่ไม่ได้รับการฟื้นฟู (แปลงควบคุม) การศึกษาการสะสมปริมาณเศษซากพืชโดยการใช้ตาข่ายขนาด 1 x 1 ตารางเมตรรองรับเศษซากพืชที่ร่วงหล่นในแปลงศึกษาเป็นเวลา 32 เดือน (มิถุนายน 2552 – มกราคม 2555) โดยปริมาณเศษซากพืชอยู่ในช่วง 1.54 – 17.61 ตัน/เฮกตาร์ โดยป่าธรรมชาติมีปริมาณเศษซากพืชที่ร่วงหล่นสูงสุด รองลงมาคือ แปลงอายุ 11, 7, แปลงควบคุมและแปลงอายุ 2 ปี ตามลำดับดังนี้ คือ 17.61, 13.98, 13.18, 6.24 และ 1.54 ตัน/เฮกตาร์ ส่วนปริมาณคาร์บอนในเศษซากพืช เท่ากับ 6.82, 4.96, 4.35, 2.08 และ 0.53 ตันคาร์บอนต่อเฮกตาร์ โดยป่าฟื้นฟูที่อายุมากจะมีแนวโน้มของเศษซากพืชและปริมาณคาร์บอนที่สะสมในเศษซากพืชมากกว่าแปลงที่อายุน้อย

การย่อยสลายเศษซากพืชที่เป็นตัวแทนของพรรณไม้โครงสร้าง 3 ชนิดได้แก่ ทองหลางป่า ก่อแป้นและมะเดื่อน้อย โดยพบว่า มะเดื่อน้อยมีการย่อยสลายสูงสุด รองลงมาคือ ทองหลางป่าและก่อแป้น และได้มีการศึกษาการย่อยสลายของเศษซากพืชโดยการใช้ถุงตาข่ายขนาดใหญ่ โดยพบว่าอัตราการย่อยสลายสูงสุดในแปลงอายุ 7 ปีรองลงมาคือ แปลงอายุ 11 ปี แปลงควบคุม แปลงป่าธรรมชาติและแปลงอายุ 2 ปี คือ 2.85, 1.27, 1.20, 1.12 และ 1.08 ตามลำดับ

นอกจากนั้น ยังมีการศึกษาคาร์บอนที่สะสมในดินจากผิวดินจนถึงระดับความลึก 200 เซนติเมตร โดยพบว่าแปลงอายุ 2 ปีมีปริมาณอินทรีย์คาร์บอนสะสมในดินสูงสุดรองลงมาคือ 254.40, แปลงอายุ 7 ปี แปลงป่าธรรมชาติ แปลงควบคุมและแปลงอายุ 11 ปีเท่ากับ 251.14, 244.96, 205.88 และ 161.82 ตันคาร์บอนต่อเฮกตาร์

Dissertation Title Soil Carbon Sequestration and Dynamics of Natural Forest
Ecosystems and Forest Restoration Plots in Mae Rim District,
Chiang Mai Province

Author Ms. Nuttira Kavinchan

Degree Doctor of Philosophy (Biodiversity and Ethnobiology)

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ABSTRACT

The study of below-ground carbon sequestration was conducted in a forest that was restored using framework species method of Forest Restoration Research Unit (FORRU), Ban Mae Sa Mai, Mae Rim district, Chiang Mai. Plots of three different ages: 11, 7 and 2 years since planted, natural forest and control (non-planted) plots were chosen. Litter traps (1 x 1 m^2) were set up and plant litter was collected for 32 months (during Jun. 2009 – Jan. 2012). Litterfall accumulation of a total of 32 months in all study sites ranged from 1.54 – 17.61 t/ha. The highest amount of litterfall was found in the natural forest plot next to the 11-year, 7-year, control and 2-year-old sites, 17.61, 13.98, 13.18, 6.24 and 1.54 t/ha, respectively and carbon content of litter were 6.82, 4.96, 4.35, 2.08 and 0.53 t/ha, respectively. An old-age forest restoration plot tends to have more litter accumulation and carbon stock in term of litterfall. Litter decomposition of three representative framework species (*Erythrina subumbrans*, *Castanopsis diversifolia* and *Ficus subincisa*) using litterbag method was studied. *Ficus subincisa* decomposed more rapidly than *Erythrina subumbrans* and *Castanopsis diversifolia*, respectively. The additional part of mixed litter decomposition using big litterbag was also determined. The highest decay rate coefficient was found in 7-year-old site next to 11, control, natural forest site and 2 year-old site, 2.85, 1.27, 1.20, 1.12 and 1.08, respectively.

Moreover, soil profile in each study was determined. Soil organic carbon until 200 cm. in depth was also determined and found that the highest soil organic carbon in 2-year next to 7-year-old, natural, control and 11-year-old site, 254.40, 251.14, 244.96, 205.88 and 161.82 tC/ha.

CHAPTER 1

Introduction

1.1 Principles, Theory, Rationale and/ or Hypotheses

Climate change is now recognized as one of the most serious challenges to the people, the environment and its economies of the world (EC, 2008). Most scientists agree that the anthropogenic cause of increment of green house gas (GHGs) in the atmosphere is the main cause of the - climate change incidences experienced (Robledo and Forner, 2005). The emissions of the GHGs that result from human activities, in particular land use changes such as deforestation in developing countries, and the burning of fossil fuels specifically from developed countries, are major causes. Emission of greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs) have grown since the industrial times, with an increase of 70% between 1970s and 2004 (IPCC, 2007). The rapid increase of atmospheric CO_2 in the recent decades is well documented and changes in the earth climate, due to the “enhanced greenhouse effect”, are of growing concern. Therefore, mitigating the increase in atmospheric concentrations of CO_2 necessitates identification of options including: (i) reduce emissions by using low-carbon or no-carbon fuel sources, (ii) enhance energy use efficiency by minimizing losses, and (iii) sequester atmospheric CO_2 into solid carbon reservoirs with secure storage and long residence time (Lal, 2008).

There is also evidence that with current climate change mitigation policies and related sustainable development practices, global GHGs emissions will continue to grow over the next few decades. The industrial lifestyles of rich countries accounts for the majority of majority fossil fuels burnt, contributing approximately 80% of total GHGs emissions into the atmosphere. In contrast people of poor countries contribute only about 20% of total emissions through the land use change and deforestation (Robledo and Forner, 2005; UNFCCC, 2007).

Forest degradation and deforestation are major contributors to global climate change accounting for at least 15% of total anthropogenic CO_2 emissions (Boucher, 2008). Tropical forests store about 17% of the total carbon contained in all of Earth's terrestrial vegetation. The pan-tropical average works out at about 240 tonnes of carbon stored per hectare, split more or less equally between the trees and soils (IPCC, 2000).

At the end of 2007, the parties to the United Nations Framework Convention on Climate Change (UNFCCC) confirmed their commitment to address the global climate challenge through the Bali Action Plan 6 and the Bali Road Map 7 for an agreement were completed at the Conference of the Parties (COP) to the UNFCCC in Copenhagen at the end of 2009. Their agreement includes reference to **emissions from deforestation and forest degradation - known as REDD**). Those discussions began with RED (i.e., limited to deforestation only) and expanded to REDD with consideration of forest degradation, then broadened to further consider forest conservation, sustainable forest management, and enhancement of forest carbon stocks (REDD+). Mitigation activities potentially included under REDD are changing in forest area (hectare) by reducing deforestation and enhancing afforestation and reforestation (Angelsen and Wertz-Kanounnikoff, 2008).

Whilst forest degradation and deforestation increase atmospheric carbon dioxide, forest restoration can absorb it and increase not only the current terrestrial carbon pool, but also the capacity for future carbon absorption. Forests play an important role in global carbon cycle. Carbon sequestration of by forests varies in different vegetation types and with forest age or successional status. Carbon storage in forest ecosystems includes both biomass and soil carbon. The soil carbon pool is twice as large as that of the atmosphere and is climate-dependent (IPCC, 2001). Forest soils play an important role in the global C cycle (Jobbagy and Jackson, 2000).

Inputs of carbon into the soil pool through litterfall is closely related to tree species composition, age structure, growth rate and productivity (Scherer- Lorenzen *et al.*, 2007). Litterfall increases rapidly in the first years of succession (Ewel, 1976); once the canopy is closed, however, there is no obvious trend in litterfall production with increasing stand age

(Ostertag *et al*., 2008), species richness (Scherer-Lorenzen *et al*., 2007), or diversity (Wardle *et al*., 1997). Litter input to forest soil can be derived from forest biomass with biomass turnover rates (e.g. Starr *et al*., 2005; Liski *et al*., 2006).

Although much research has been done on carbon sequestration in mature forests (Chidthaisong and Lichaikul, 2005; Janmahasatian *et al*., 2005; Pibumrung *et al*., 2008; Timpan, 2008; Khamyong, 2009; Phonchaluen, 2009; Satienpirakul *et al*., 2013; Chaiwong *et al*., 2013) and in plantations (Poolsiri, 2005; Chidthaisong and Lichaikul, 2005; Pumijumnong, 2007; Tangsinmankong, *et al*., 2007; Pibumrung *et al*., 2008; Meungpong *et al*., 2010) particularly with regard to above ground carbon, little attention has been paid to the potential for forest restoration to sequester carbon, particularly in the soils. Furthermore, soil organic matter is a major contribution to the soil nutrient pool required for maintaining soil fertility, plant growth and ultimately the capacity for forest regeneration. Therefore, increased understanding of the dynamics of litterfall and accumulation of soil organic matter can ultimately lead to better forest restoration strategies.

Therefore, my research was focused on below-ground accumulation of carbon in litter and soil in forest restoration plots, established by the framework species method, making use of a system of plots of known ages and species composition established by Chiang Mai University's Forest Restoration Research Unit annually since 1997.

Since 1994, the Forest Restoration Research Unit (FORRU) of Chiang Mai University has been assessing the suitability of the framework species approach for restoring seasonal evergreen forest (*sensu* Maxwell and Elliott, 2001) on degraded land in the highland of northern Thailand (FORRU, 1998, 2000). The framework species method involves planting a mixture of 20–30 pioneer and climax native tree species (Elliott *et al*., 2003). Furthermore, framework species should be easily propagated in nurseries, with features such as reliable seed availability, rapid and synchronous germination and growth of seedlings to a plantable size (50–60 cm) in less than 1 year (FORRU, 1998, 2006, 2008).

Best-performing framework tree species have been identified (Elliott *et al.*, 2003) and optimal silvicultural treatments determined, to maximize survival and growth rates after planting (Elliott *et al.*, 2000; FORRU, 2006). Essential characteristics of framework species are: (i) high survival and growth rates in open degraded site; (ii) spreading and dense crowns that shade out herbaceous weeds and (iii) providing fruits, nectar and nesting sites that attract seed-dispersing wildlife at an early age (Goosem and Tucker, 1995).

1.2 Objectives

The objectives of this research were to evaluate litter accumulation and determine soil carbon stock in forest restoration plots in different ages compared with both natural forest and non-restored sites. The objectives also included developing predictions of soil carbon stocks through forest restoration using the FullCAM model.

CHAPTER 2

Literature Reviews

2.1 Global warming crisis

The global warming crisis is the average temperature rising of earth's atmosphere and oceans since the late 19th century. Since the early 20th century, Earth's average surface temperature has increased by about 0.8 °C (1.4 °F), with about two-thirds of the increase occurring since 1980 (NRC, 2011). Warming is unequivocal, and more than 90% of scientists are certain that it is primarily caused by increasing concentrations of greenhouse gases produced by human activities such as burning of fossil fuels and deforestation (IPCC, 2007). These findings are recognized by the national science academies of all major industrialized nations. Climate model projections were summarized in the 2007 Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). They indicated that during the 21st century, the global surface temperature is likely to rise a further 1.1 to 2.9 °C (2 to 5.2 °F) for their lowest emissions scenario and 2.4 to 6.4 °C (4.3 to 11.5 °F) for their highest. The ranges of these estimates arise from the use of models with differing sensitivity to greenhouse gas concentrations. Future warming and related changes will vary from region to region around the globe (IPCC, 2007).

Hadley Centre (the UK’s leading centre studying climate change named after George Hadley) made the HadCM3 climate model for predicting temperature change in global scale (Fig. 2.1). The plotted colors show predicted surface temperature changes, expressed as the average prediction for 2070-2100, relative to the model's baseline temperatures in 1960-1990. The average change is 3.0°C, placing this model on the lower half of the Intergovernmental Panel on Climate Change's 1.4 - 5.8°C surface temperature changes, expressed as the average prediction for 2070-2100, relative to the model's baseline temperatures in 1960-1990. The average change is 3.0°C, placing this model on the lower half of the Intergovernmental Panel on Climate Change's 1.4 - 5.8°C predicted climate

change from 1990 to 2100 (IPCC, 2007). As can be expected from their lower specific heat, continents are expected to warm more rapidly than oceans, with average increases of 4.2°C and 2.5°C respectively. The lowest predicted warming is 0.55°C south of South America and the highest is 9.2°C in the Arctic Ocean (points exceeding 8°C are plotted as black).

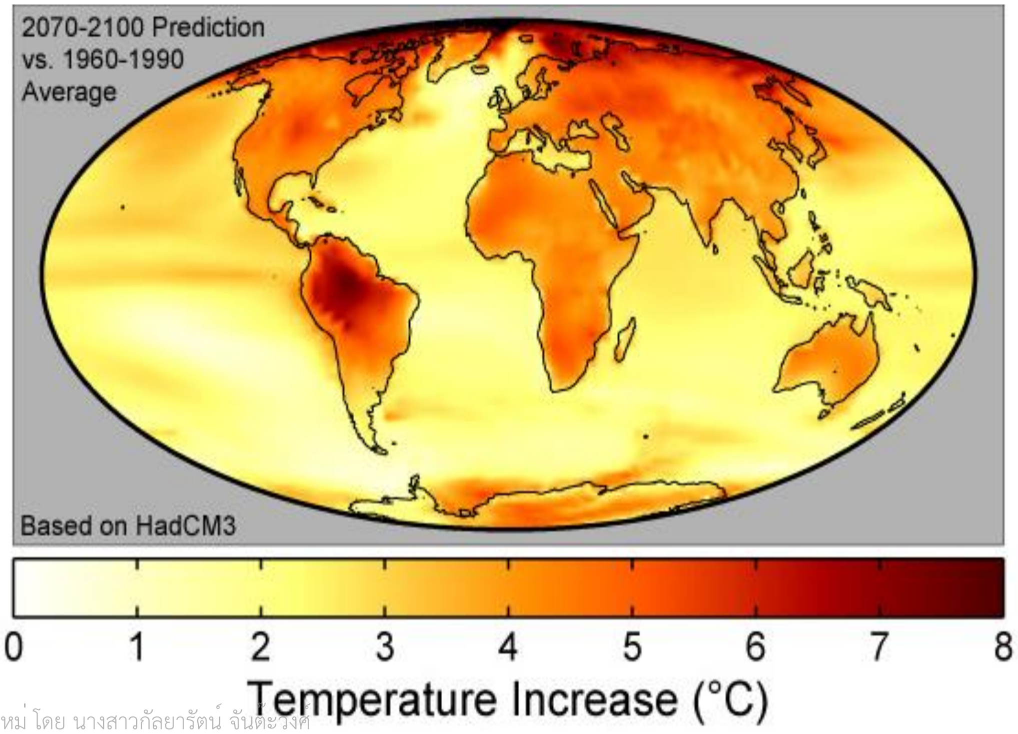


Figure 2.1 Global warming prediction

source: http://www.globalwarmingart.com/wiki

2.1.1 The effects of increasing global temperatures

(Lu *et al*., 2007; Battisti and Naylor, 2009)

- Continuing retreat of glaciers, permafrost, sea ice, associated with rising sea level.
- Frequent occurrence of extreme weather events, including heat waves, droughts and storms.
- Changes in the amount and distribution pattern of precipitation.
- Ocean acidification and species extinctions, due to shifting temperature regimes.
- Probable expansion of subtropical deserts.
- Threatened food security from decreasing crop yields.
- The loss of habitats from flooding.

2.1.2 Proposed policy responsibility

Proposed policy responses to global warming include mitigation by emission reduction, adaptation to its effects, and possible future geoengineering. Most countries are parties of the United Nations Framework Convention on Climate Change (UNFCCC), whose ultimate objective is to prevent dangerous anthropogenic (i.e., human-induced) climate change. The parties of the UNFCCC have adopted a range of policies, designed to reduce greenhouse gas emissions and to assist in adaptation to global warming (World bank, 2010; UNFCCC, 2011), and also agreed that deep cuts in emissions are required and that future temperature increases should not exceed 2.0 °C (3.6 °F) relative to pre-industrial level (UNFCCC, 2011). Reports published in 2011 by the United Nations Environment Programme (UNEP, 2011) and the International Energy Agency (IEA, 2011) suggest that efforts, as of the early 21st century to reduce emissions may be inadequate to meet the UNFCCC's 2 °C target.

2.2 Trend of CO_2 emission from 1960 – 2010

Three main components of the CO_2 budget by Ballantyne *et al*. (2012) are shown in Fig. 2.2. The top panel shows that the annual amount of CO_2 in the atmosphere is increasing. The middle panel shows the annual amount of CO_2 that is emitted into the atmosphere each year from human activities (fossil fuel use and land use changes). The amount that remains in the atmosphere (top panel) is only about 45% of the amount that is emitted by humans (middle panel). This means that 55% is being taken up by land and ocean sinks. This increasing sink is shown in the bottom panel, and the greater the negative value; the greater the carbon sink. This growth enhancement has led to the Earth's plants taking up an increasing amount of CO_2 from the atmosphere and turning it into biomass, where carbon is stored for days to hundreds of years (this mechanism accounts for a significant portion of the earth's land-based carbon sink). It seems the more CO_2 we pump into the atmosphere, the more CO_2 that plants take up to enhance their growth. The oceans also take carbon dioxide out of the atmosphere and can store it for long periods of time (thousands of years). It appears that this ocean carbon sink is also expanding as we emit more CO_2 into the atmosphere. Together, the land and ocean carbon sinks have been pretty much keeping up with the increasing anthropogenic carbon dioxide emissions. Consequently, the percentage of CO_2 injected into the atmosphere from human activities, that remains in the atmosphere, has remained pretty much constant for the last 50 years.

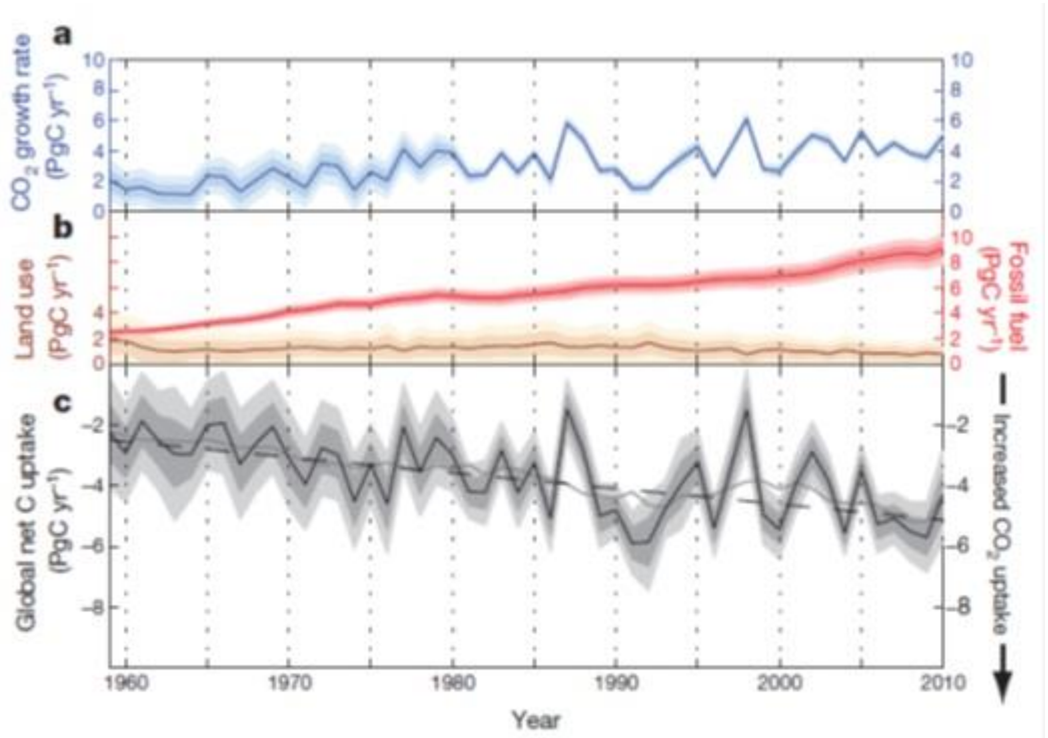


Figure 2.2 (Top) Annual accumulation of CO$_2$ in the atmosphere. (Middle) Annual CO$_2$ emissions from anthropogenic activities. (Bottom) Net CO$_2$ uptake by land and ocean sinks (Ballantyne *et al.*, 2012).

2.3 CO$_2$ emissions per country and per capita

Based on trends in global CO$_2$ emissions 2012 report (Oliver *et al.*, 2012), since 2002, annual economic growth in China accelerated from 4% to 11%, on average. CO$_2$ emissions increased by 150% in China, and in India by 75%. China is a developing country, but CO$_2$ emissions there are at the top of the chart (29 %), compared with other industrialized countries, such as United States and EU27 were 16%, 11%, respectively. India (6%) is the fourth largest CO$_2$ emitting country, followed by the EU27 and the Russian Federation (5%), closely followed by Japan (4%).

China, the world's most populous country, is now well within the 6 to 19 tonnes/person range spanned by the largest industrialized countries (Annex I countries under the Kyoto

Protocol, including the United States (which did not ratify the protocol)). In 2011, the United States was one of the largest CO_2-emitting countries with 17.3 tonnes per capita. Although per capita emissions in India have doubled since 1990, it is clear that with 1.6 tonnes in 2011 the country's per capita emissions are still much lower than those in industrialized countries.

When comparing CO_2 trends among countries over a decade or more, also trends in population numbers should be taken into account, since population growth rates differ considerably, also between Annex I countries, with the highest growth since 1990 seen in Australia (+32% between 1990 and 2011) and in the United States and Canada (both +24%). The population of the EU and Japan, however, increased much less (by 7% and 3%, respectively), and Russia saw a decline of 4% .Thailand is the ranked at the bottom but CO_2 emission per country and also per capita tended to be higher from 1990, 2000 and 2011. CO_2 emissions from fossil fuel and cement production per country and per capita were shown in Figs. 2.3 - 4.

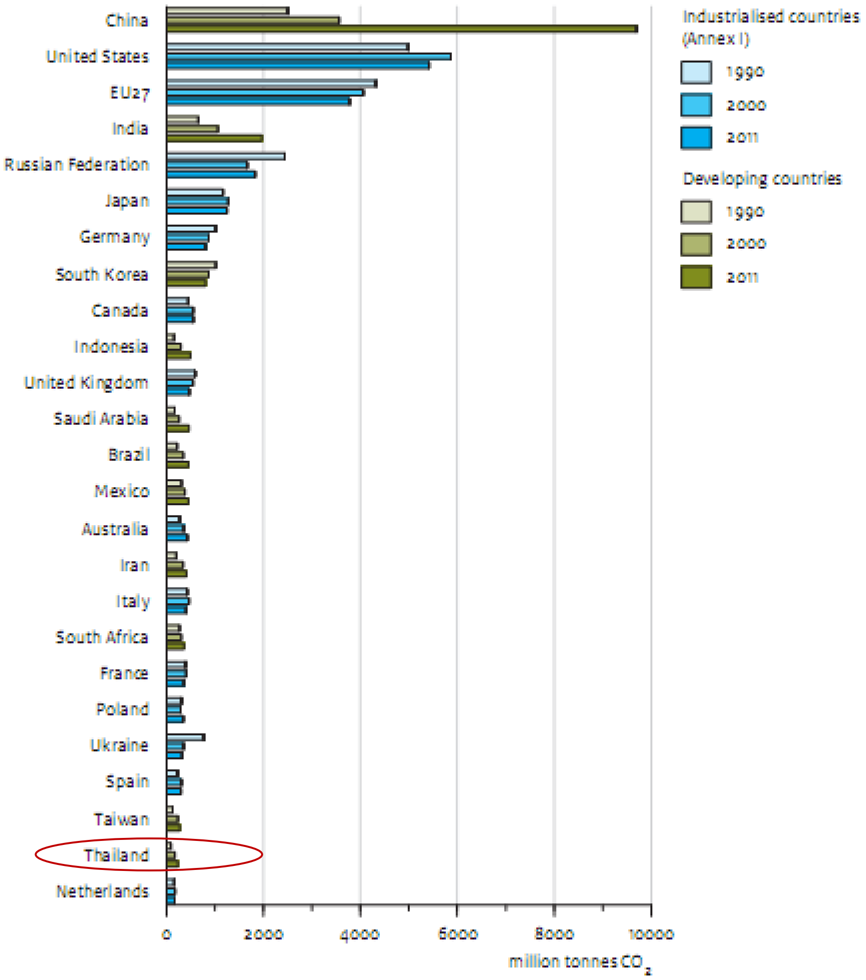


Figure 2.3 CO_2 emissions per country from fossil fuel and cement production

Source of population data: UNPD, 2010

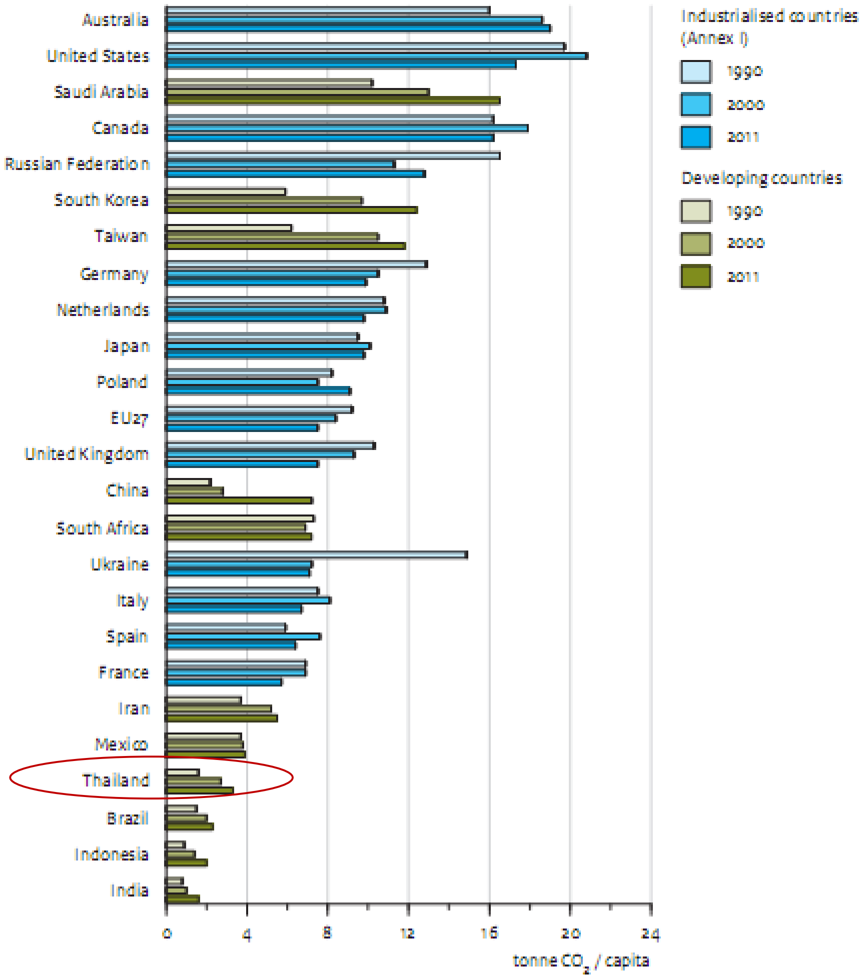


Figure 2.4 CO$_2$ emissions per capita from fossil fuel use and cement production

Source of population data: UNPD, 2010

2.4 Global major carbon pools

The five global C pools are interconnected (Fig. 2.5): atmospheric, geologic, oceanic pool, pedologic (1 m depth) and biotic pools. The flux among these pools is strongly influenced by anthropogenic perturbations. Gross primary production ranges from 90 to 130 $PgCy^{-1}$ (mean of 120 $PgCy^{-1}$), which is balanced by plant respiration of 40 to 60 Pgy^{-1} and decomposition of soil organic matter (SOM) of 40 to 68 $PgCy^{-1}$. Anthropogenic emissions involve two principal components: fossil fuel combustion of >7.5 $PgCy^{-1}$during 2000 s and land use conversion (deforestation) and soil cultivation of about 1.6 $PgCy^{-1}$.

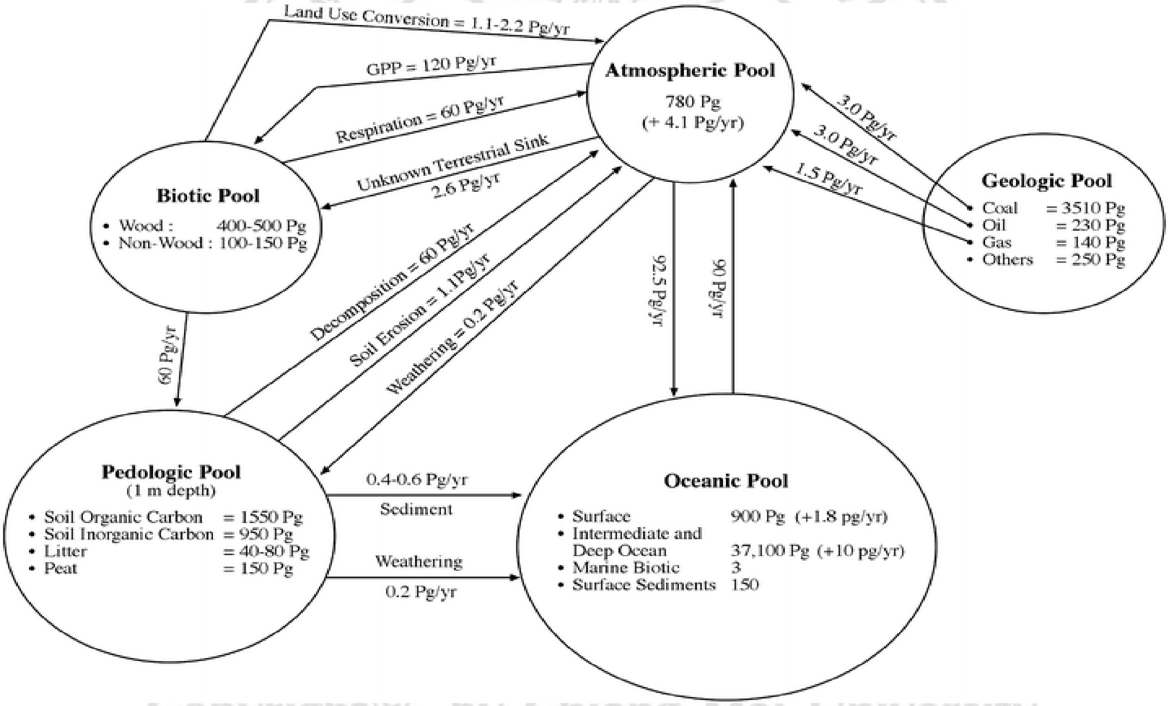


Figure 2.5 Global carbon pool (Lal, 2008)

2.5 Global carbon storage

A recent recalculation (Eglin *et al.*, 2011) of carbon storage values, including soil carbon stock estimates down to a depth of 3 m (Jobbágy and Jackson 2000), revealed significantly higher estimates in nearly all biomes, including an approximately threefold increase in soil organic carbon stocks estimates for tropical forests (Table 2.1).

Table 2.1 Summary of global carbon stocks

Biomes	Vegetation (GtC)	Soil (GtC)	Total (GtC)
Deserts and sclerophyllous shrubs	9	332	341
Crops	3.5	248	251.5
Tropical savannas	72.5	345	417.5
Temperate grassa Lands	16	172	188
Tundra	4	144	148
Tropical forests	276	692	968
Temperate forests	99	262	361
Boreal forests	72.5	150	222.5
Peatlands	15	400 – 500	415 – 515
Permafrost	-	1,024	1,024

Source: Eglin *et al*. (2011) provided mean values for soil C and ranges for vegetation C; the latter were then averaged to generate the estimates shown here for vegetation and total C respectively.

Based on data from Jobbagy and Jackson (2000) and Tarnocai *et al*., (2009), highest SOC content in 0 – 1 m in depth (MgCha^{-1}) was found in tropical evergreen forest. Tropical green forest was the major SOC storage (474 Pg) Total C stocks and C densities in different biomes were shown in Table 2.2.

Table 2.2 Total C stocks and C densities in different biomes in global scale

Biomes	Area (10^{12} m^2)	SOC content (MgCha^{-1}) 0 - 1 m	SOC content (MgCha^{-1}) 0 – 3 m	SOC storage (Pg) 0 – 1 m	SOC storage (Pg) 0 -3 m	uncertainty
Boreal forest	12	93	125	112	150	
Crops	14	112	177	157	248	
Deserts	18	62	115	112	208	
Sclerophyllous shrubs	8.5	89	146	76	124	U
Temperate deciduous forest	7	174	228	122	160	
Temperate evergreen forest	5	145	204	73	102	
Temperate grassland	9	117	191	105	172	
Tropical deciduous forest	7.5	158	291	119	218	U
Tropical evergreen forest	17	186	279	316	474	U
Tropical savanna/grasslands	15	132	230	198	345	U
Tundra	8	142	180	114	144	U
Total of above	121			1,502	2,345	
Peatland	3.5		1,140 - 1,430		400 - 500	U
Permafrost*	18.8		544		1,024	U

Source: Jobbagy and Jackson (2000) and Tarnocai *et al*., (2009), *partly includes peat lands, boreal forests and boreal grasslands. Assessment of stocks marked with U are particularly uncertain.

The global distribution of soil organic carbon (SOC) is spatially very uneven (Fig. 2.9). Estimates of SOC stocks per unit surface area (also called SOC inventories or SOC densities) by Jobbagy and Jackson (2000) and Tarnocai *et al*. (2009) up to a depth of 3.0 m vary between 291 MgCha^{-1} for tropical forests and 91 MgCha^{-1} for boreal forests. Boreal peat lands have carbon densities far exceeding those of other soil types (> 1,000 MgCha^{-1}). Croplands have, on average, a relatively low SOC density of ca. 177 MgCha^{-1} (Jobbagy and Jackson, 2000).

The distribution of SOC stocks is controlled by both natural and human factors. Soils can store large amounts of carbon when either decomposition rates are very low such as is the case in peatlands and/or primary productivity is high, such as in tropical rainforests. Low SOC densities, such as in deserts/shrubs and croplands, are explained by either a low C input rate (due to low primary productivity or the removal of plant organic matter at harvest) or a high SOM decomposition rate (e.g. due to a warm climate or soil disturbance) or a combination of both (Johnston *et al.*, 2009).

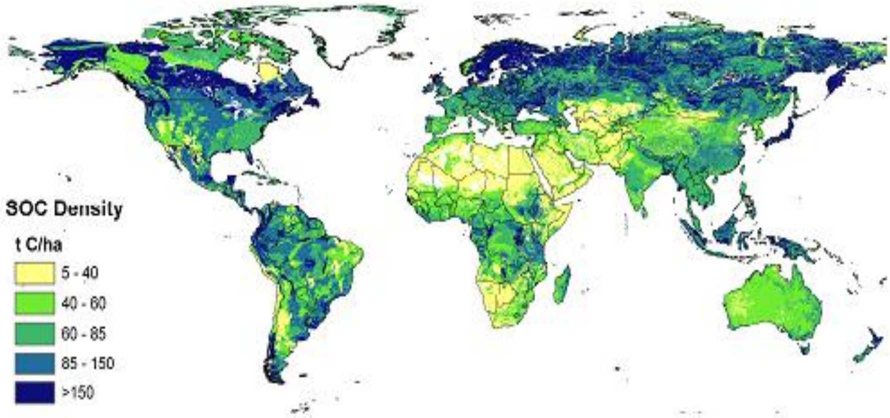


Figure 2.6 Global variation in SOC density, 0 - 1 m depth (MgCha^{-1}), own processing based on data from the amended Harmonized Soil Database (Hiederer and Kochyl, 2012; Panagos *et al*., 2012)

2.6 Response of soil carbon pools to climate change

Significant research have been focused on the response of soil carbon pools to climate change, although significant uncertainty remains (Eglin *et al*., 2011; Schmidt *et al*., 2011). The relationship between increased production and increased soil carbon sequestration is also uncertain; a recent study in tropical forests estimated that increased litterfall would actually increase soil carbon release, a so-called “priming effect” (Sayer *et al*., 2011). Increasing temperatures are thought to increase the rate of microbial decomposition and respiration by increasing the rate of enzymatic reactions in the soil and these processes are thought to be more sensitive to temperature than increased productivity, particularly at lower temperatures. These observations are supported by the higher proportion of soil carbon stocks in temperate, cooler climates compared to warmer tropical climates (Lal, 2006). Recent meta-analysis supports the theory that temperature increases, due to climate change, will result in increased soil respiration and potentially, although not necessarily, to increased fluxes to the atmosphere (Bond-Lamberty and Thomson, 2010).

2.7 Interaction between plants and soils

Plant species characteristics, such as life-span, biomass allocation, biomass productivity and tissue chemical composition have shown to have significant effects on soil organic carbon and soil nutrient dynamics (Matson, 1990). For example, in tropical plantations, different tree species affect the amount of soil carbon sequestered: stands with high proportion of nitrogen fixing tree species sequestered 2.3 t C ha^{-1} more than pure *Eucalyptus* stands after 17 years of afforestation in Hawaii (Kaye *et al.*, 2000). These results suggest that the amount of soil organic carbon depends on tree species composition. Consequently, the soil carbon sequestration potential cannot be determined without analyzing the characteristics of vegetation as well (Garcia-Oliva and Masera, 2004).

The presence of planted native and non-native species is likely to affect carbon dynamics also. Species composition and dominance impact the amount and mean residence time of carbon in the ecosystem through effects on plant growth rates, carbon allocation patterns, and carbon quality (Lugo, 1992). Therefore, understanding the long-term effects of reforestation on plant community characteristics and its impact on carbon dynamics is vital for the management for maximizing carbon sequestration and biodiversity (Silver *et al.*, 2004). More carbon can be stored below ground by increasing the input rate of organic matter, increasing the depth of carbon stock, increasing the carbon density in the soils, and decreasing the carbon turnover rate in soils (Post and Kwon, 2000).

2.8 Litter production

Litter on the forest floor is a source and reservoir of nutrients (Sundarapandian and Swamy, 1999). Nutrient and organic matter are returned to the soil through litterfall (Vitousek and Sanford, 1986), where leaves, twigs and other dead material abscise from trees and accumulate on the forest floor. Litter production is closely related to species composition, age structure, growth rate and productivity (Scherer- Lorenzen *et al*., 2007). Numerous studies have reported that litterfall productivity is higher in diverse mixed stands than in monoculture stands (Wang *et al*., 2007; Scherer-Lorenzen *et al*., 2007). It has also been reported that total litterfall is similar in primary and secondary forests, but lower in plantations (Barlow *et al*., 2007). Litterfall increases rapidly during the first years of succession (Ewel, 1976); once the canopy is closed, however, there is no obvious trend in litterfall production with increasing stand age (Ostertag *et al*., 2008), species richness (Scherer-Lorenzen *et al*., 2007), or diversity (Wardle *et al*., 1997).

Litterfall studies, in different types of plantations and forest type in Thailand and other countries, are listed in Tables 2.3 – 5.

Table 2.3a Litterfall studies in different types of plantation in Thailand

Location	plantation	Litter production (t/ha/yr)	Mean annual rainfall (mm)	References
Western Thailand (Prachinburi province)	Plantation (3-year-old) -*Eucalyptus camaldulensis* -*Acacia* hybrid (*mangium xauriculaemis)* -*Leucaena leucecephala*	11.43 13.67 10.56	1,540	Tanavat *et al*., 2011
Western Thailand (Kanchanaburi province)	Unthinned teak plantation -6-year-old -14-year-old -27-year-old	4.45 5.65 6.69	1,655	Sumantakul and Viriyabuncha, 2007
Eastern Thailand (Cha Choeng Sao province)	*Acacia mangium* -6-year-old *Eucalyptus camadulensis* -6-year-old -14-year-old	10.37 8.29 8.97		
Huey Bong Silvicutural Research Station, Chiang Mai Province	*Pinus caribaea* plantation (29-year-old)	4.68	1,100	Sangsathien *et al*.,2012
FORRU, northern Thailand	Forest restoration plot -4-year-old-plot -6-year-old-plot -8-year-old-plot Control (non-planted plot)	2.26 4.90 5.22 3.03	1,295	Gavinjan, 2005

Table 2.3b Litterfall studies in different types of plantation in Thailand

Location	plantation	Litter production (t/ha/yr)	Mean annual rainfall (mm)	References
The Mae Klong Watershed Research Station),Lintin, Thong Pha Phum, Kanchanaburi Province, western Thailand	The teak-gmelina stand (planted in 1977)	2.22	1,650	Takahashi *et al.*, 2012
The Huai Lam Kradon subwatershed in the Wang Thong watershed, in lower northern Thailand	Para rubber tree plantation	1.37	1,300 -1,700	Podong and Poolsiri, 2012

Table 2.4 Litter production in different forest type in Thailand

Location	Forest type	Litter production (t/ha/yr)	Mean Annual rainfall (mm)	References
Sakaerat environmental Research station, Nakhon Ratchasima	Dry evergreen forest (DEF)	7.67	1,000 – 1,500	Visaratana and Chernkhuntod, 2005
Mae Nam Phachi Wildlife Sanctuary, Ratchaburi province	Dry Dipterocarpus Forest (DDF)	7.89	959 – 1,285	Chaiyo *et al*., 2011
	Mixed Deciduous Forest (MDF)	3.29		
		4.96		
The Huai Lam Kradon subwatershed in the Wang Thong watershed, in lower northern Thailand	Secondary mixed deciduous forest	4.16	1,300 -1,700	Podong and Poolsiri, 2012
The Mae Klong Watershed Research Station),Lintin, Thong Pha Phum, Kanchanaburi Province, western Thailand	Mixed DeciduousForest (MDF)	2.38	1,650	Takahashi *et al*., 2012

Table 2.5 Litter production in plantations in other countries

Location	Forest type	Litter production (t/ha/yr)	Mean annual rainfall (mm)	References
Shasha Forest Reserve, Nigeria	Teak plantations planted since 1965,	6.7		Sale and Agbidye, 2011
	1970,	7.4		
	1975,	10		
	1980,	8.3		
	1985	6.8		
	semi-decidous tropical lowland rainforest	7.0		
North – east Brazilian Amazon	-Primary forest	7.8		Barlow *et al*., 2007
	-14 -19 –year-old secondary forest	6.8		
	-4-5-year-old *Eucalyptus urophylla*	4.5		
Hui tong Experimental Station of Forest Ecology, Chinese Academy of Sciences	-pure *Cunninghamia* lanceolata stand	2.44 – 7.88	1,200	Wang *et al*., 2008
	-mixed stand o f *C. lanceolata* and *Michelia macclurei*	4.45 – 10.41		
Xinkou Experimental Forestry Centre of Fujian Agricultural and Forestry University, Sanming, Fujian, China	33-year-old plantations of two coniferous trees, Chinese fir (*Cunninghamia lanceolata*, CF)	5.47	1,749	Yang *et al*., 2004
	Fokienia hodginsii (FH	7.29		
	Ormosia xylocarpa (OX)	5.69		
	Castanopsis kawakamii (CK	9.54		
	natural forest of *Castanopsis kawakamii*	11.01		
Las Cruces Biological Station Coto Brus county in southern Costa Rica	young secondary forest (7–9-yr-old natural regeneration).	7.3		Celentano *et al*., 2011
	Planted species included two native timber-producing hardwoods (*Terminalia amazonia* and *Vochysia guatemalensis*) interplanted with two N-fixing species (*Inga edulis* and *Erythrina poeppigiana*).	6.3	3,500	

2.9 Litter decomposition

Litter decomposition is also correlated closely with plant species composition and plant species traits (Vivanco and Austin, 2008). Plant species and their community have the potential to influence decomposition process through altering plant species interactions, plant-decomposer interactions, and biotic factors such as bacteria and fungi and abiotic environments such as the microclimate (Vivanco and Austin, 2008) and physical forces such as leaching, and fragmentation.

Nevertheless, tree species alter litter chemistry and influence decomposition (Xuluc-Tolosa *et al*., 2003), which in turn affect nutrient availability and successional pathways (Vitousek and Walter, 1989). Faster decomposition rates were found for high quality litter (i.e., low lignin content and lignin:nutrient ratios) and lower for poor quality litter (i.e., high lignin content and lignin:nutrient ratios) (Martinez-Yrizar *et al*., 2007). At the ecosystem scale, litter quality is most often related to chemical characteristics of litter, for example, carbon: nitrogen ratio and /or lignin content (Aerts, 1997). Theoretically, the optimum ratio of C/N for microbial growth is about 25, but fungi and bacteria can decompose resources with far higher ratios. Dead plant materials may contain between about 5% and 0.1% N, resulting in C/N ratios ranging from 20 to 500. Only animal and microbial tissues with high protein content have C/N ratios below this range. Materials with C/N ratios of < 20 decompose rapidly, often with the release of ammonia, because nitrogenous compounds are metabolized as C sources (Heal *et al*., 1997).

Heal *et al*. (1997) stated that the decomposition constant, or *k* value and the mechanistic explanation of *k*, describing how the decay rates of substrates, which comprise litter, i.e. litter quality, combine to determine the overall decomposition rate.

Factors that regulate *k* values have been identified (Zhang, 2008):

- (i) Climatic factors such as mean annual temperature (MAT), mean annual precipitation (MAP) and annual actual evapotranspiration (AET)
- (ii) Litter quality, e.g. nitrogen content (N) carbon:nitrogen ratio (C:N), lignin content (LIGN) and lignin:N ratio (LIGN:N)
- (iii) Vegetation and litter

2.10 Carbon sequestration

Carbon sequestration is when carbon taken out of the atmosphere or absorbed and stored in a terrestrial or aquatic body. Such bodies can be classified as carbon sinks, but only in their absorption years. For example, old growth forests, are in equilibrium with the atmosphere, naturally release as much CO_2 in death as they absorb during growth. Carbon content is measurable, but the quantity sequestered is interdependent on the species of trees planted, the trees survival rates, soil characteristics, climatic conditions, and the final use of the tree and how it is managed during its growth (Vidler, 1998). On a global basis, soils are the largest carbon pool in terrestrial ecosystems, three times higher than the carbon pool in vegetation (Post *et al*., 1990; Schlesinger, 1990, 1991) and have been estimated to have one of the largest potentials to sequester carbon worldwide (Garcia-Oliva and Masera, 2004).

2.11 Soil Carbon Sequestration

Soil carbon sequestration is a process in which CO_2 is removed from the atmosphere and stored in the soil carbon pool. This process is primarily mediated by plants through photosynthesis, with carbon stored in the form of SOC (Lal, 2008). Soil carbon stocks are much larger than carbon sequestered in biomass (Lal, 2004). Overall fluxes between the atmosphere and soils are an order of magnitude larger than anthropogenic emissions (IPCC, 2000). However, nearly all climate change mitigation projects and policies focus on above-ground carbon and forest biomass carbon, in particular. While there are historical and scientific rationales for this focus, the generally weaker understanding of soil carbon dynamics, and the difficulty in soil carbon measurement, also contribute to the above-ground biomass focus (Epple, 2012). Nevertheless, recent research have informed the understanding of soil carbon dynamics and, combined with improved modelling approaches, allows for a greater consideration of soil carbon in climate change mitigation.

Soil carbon can be examined from two angles: (i) stocks of carbon in soils and (ii) active sequestration of additional carbon into soils. Tropical soils are highly diverse (Richter and Babbar, 1991) and each type has a different soil carbon sequestration capacity. Among the soil characteristics, soil texture strongly affects soil carbon dynamics (Parton *et al.*, 1994). In general terms, fine-textured soils have a higher soil carbon content than coarse-textured soils (Hassink, 1994), and the residence times of carbon associated with clays and silts are higher than carbon associated with sand size-fraction (Franzluebers, 2000). This is because fine size fractions are usually better aggregated and protect soil organic carbon from microbial decomposition (van Veen and Kuikman, 1990).

Carbon in soils can be divided into two major pools: organic carbon (SOC) and inorganic carbon (SIC) (Lal, 2009):

Organic carbon is derived from organic matter and is also more important in soil fertility;

Inorganic carbon can be classified into two types:

- (i) carbonates derived from weathering of rocks (lithogenic)
- (ii) carbonates derived from the direct absorption of carbon dioxide into the soils (pedogenic).

Soil inorganic carbon (SIC) sequestration rates are generally an order of magnitude lower than those of soil organic carbon (SOC), but soil inorganic carbon can be a significant carbon pool and has been estimated as high as 930-1,738 Gt C globally, with significant concentrations in arid regions and in degraded ecosystems (Lal, 2009). However, the soil inorganic pool is relatively stable, and is thought not to be a net sink nor to be strongly affected by land management and therefore not as relevant to climate change mitigation (Walcott *et al*., 2009). Recent research however points to SIC sequestration in certain ecosystems, for example, limestone karsts, as potentially relevant (Yan *et al*., 2011).

2.12 Soil organic carbon

Soil organic carbon (SOC) dynamics are driven by changes in climate and land cover or land use. In natural ecosystems, the balance of SOC is determined by the gains through plant and other organic inputs and losses due to the turnover of organic matter (Smith *et al*., 2008). Soil is a significant terrestrial carbon (C) reservoir which plays a notable role in the global carbon cycle, it contains about 1,500 Pg C (1 Pg = 1 billion tons) in the surface meter of soil (Lal, 2002) and 684 Pg C in the upper 30cm layer (Batjes, 1996). Moreover, Batjes (1996) estimates a 60% increase in the global soil organic carbon (SOC) storage with depth extended to 2.0 m.

Changes in organic carbon (OC) content of soils correlate with changes in the structural form and stability of soils and the change in structural characteristics is often strongly dependent on soil structure (Bicheldey and Latushkina, 2010). Three major factors controlling the levels of SOC: (i) the first factor is *climatic* such as temperature and moisture conditions (Lal, 2002, 2003), (ii) the second one is *biological* as residue input and plant composition (Quideau *et al.,* 1998) and (iii) the third factor is *physico-chemical* for instance soil structure and texture, clay content and mineralogy, acidity and organic matter content (Paustian *et al.*, 1997).

Accumulation of soil organic carbon is the result of the balance between inputs of carbon to the soil in organic matter from primary productivity and outputs from soil respiration (De Deyn *et al*., 2008). Abiotic factors, temperature and soil moisture are important in determining this balance, but many other factors also influence it, including soil biota diversity and composition (Nielsen *et al*., 2011).

2.12.1 Soil carbon measurement

While above-ground biomass can be estimated using remote sensing (Goetz *et al*., 2009), the measurement of soil organic carbon stocks over large areas is much more difficult. Verifying changes in soil organic matter due to management is even more problematic. Measurement techniques for assessing soil organic matter (SOM), and by extension soil carbon, are relatively straightforward: established methods are available and individual samples are on the order of USD 20. The measurement of soil carbon requires the assessment of three variables: (i) soil carbon content; (ii) soil depth; and (iii) soil bulk density. Depth and bulk density together estimate soil mass per unit area, and soil carbon content determines what proportion of the mass is carbon.

2.12.2 Soil organic carbon and land-use change

Empirical studies of the effect of land-use change on soil carbon stocks are common, but exhibit high variability and inconsistent methodology. However, using meta-analysis, several authors have drawn broad, general conclusions about which land-use changes affect soil carbon stocks. In the tropics, Powers *et al*. (2011) conducted a meta-analysis of 80 published studies and concluded that sampling was biased across precipitation regimes and soil types which classified by clay mineral class effects on soil carbon contents (including 0- to 30-cm sampling depths) and concluded that, with significant qualifications:

(a) Conversion of forest to pasture increased soil carbon stocks in low-activity clay soils, but decreased soil carbon in high-activity clay soils, related with effect of mean annual precipitation;

(b) Conversion of pasture to secondary forest increased carbon stocks

(c) Conversion of forest to cropland decreased carbon stocks, except in high-activity clay soils.

Another recent meta-analysis of soil organic carbon change in response to tropical land-use change reported similar results, with greater consideration of depth of soil carbon measurement (Don *et al*., 2011). The study reported that SOC decreases with the following land-use transitions: primary forest to grassland, primary forest to cropland, primary forest to perennial cropland,

primary to secondary forest, secondary forest to grassland, and grassland to cropland. The following land-use changes were reported as increasing carbon stocks: grassland to secondary forest, cropland to secondary forest, cropland to grassland, and cropland to fallow. Only a single transition, primary forest to secondary forest, had contradictory SOC changes depending on soil depth: in this transition, while upper layers of soil lost carbon, deeper layers were reported to have gained carbon. The greatest magnitude of SOC change involved transitions to and from cropland.

The study of Guo and Gifford (2002) reported the same result and concluded that SOC stocks decreased in the following conversions: pasture to plantation, native forest to plantation, native forest to crop, and pasture to crop. Land-use conversions that increased soil carbon stocks were: forest to pasture, crop to pasture, crop to plantation, and crop to secondary forest.

Other studies support the general conclusion that the clearing of forest land for cropland decreases soil carbon stocks, but that conversion to pasture does not (Murty *et al*., 2002). Lal (2008) asserts that conversion of natural ecosystems to agricultural ecosystems depletes soil carbon over a period of 20 to 50 years in temperate climates and 5 to 10 years in the tropics; he also reports that cultivated soils contain on average 50 to 70 per cent of the carbon content of undisturbed soils. Degraded ecosystems and those affected by desertification are widely reported to contain less soil carbon (Lal, 2004; Lal, 2009).

2.12.3 Management to increase soil carbon

The feasibility of increasing the concentration of carbon in soils depends on the ecosystem, type of soil and condition. Generally, management practices that tip the balance of production and respiration: increasing net primary production (NPP) for instance through irrigation, fertilizers, revegetation or modifications that reduce carbon loss from soils for instance re-wetting wetlands. The rate of carbon sequestration in soils depends on many factors but is generally faster in cooler soils and slower in warmer soils. Wetter soils also sequester more carbon as do clayey soils when compared to drier, sandier soils. Because degraded soils have depleted soil carbon stocks, they have some of the largest potential for enhancing carbon sequestration, which has been estimated at approximately 1 $GtCyr^{-1}$ in the global drylands (Lal, 2009).

2.12.4 Soil carbon studies

Soil carbon studies in various types of forest, plantations and other land-use types in northern, central and western Thailand and other countries are shown in Tables 2.6 - 8.

Table 2.6 Soil carbon studies in different forest type in Thailand

Study site	Vegetation type	Soil organic carbon ($tCha^{-1}$)	Soil depth (cm)	References
Doi Inthanon National park (Keaw Mae Pan area)	Upper montane forest	262.47 – 288.80	0 -100	Timpan, 2008
Sakearat environmental research station, Nakornratchasrima Province and Maeklong forest, Kanchanaburi Province	Dry evergreen forest (DEF) Mixed deciduous forest (MDF)	210.89 223.91	0-100	Janmahasatien *et al.*, 2005
Sakaerat environmental research station, Nakornratchasrima Province	Dry evergreen forest (DEF)	118	0-50	Chidthaisong and Lichaikul, 2005
Num Yao sub-watershed, Nan province	Hill evergreen and Mixed deciduous forest	196.24±22.81	0-100	Pibumrung *et al.*, 2008
Doi Suthep-Pui national park, Chiang Mai province	Dry evergreen forest (DDF) Mixed deciduous forest (MDF) Dry evergreen forest (DEF) Pine forest (PF) Montane forest (MF)	67.99 136.57 139.01 123.20 133.03	0 -100 0-100 0-160 0-160 0-120	Khamyong, 2009
Boakaew watershed station, Chiang Mai province	Fragmented Montane forest Dominated by - *Pinus kesiya* - *Castanopsis accuminattissima* - *Castanopsis diversifolia* - *Shima wallichii*	 84.33 93.07 – 150.78 107.99 263.87	0 -100	Satienpirakul, 2013
Huay Kha Khaeng Wildlife Sanctuary and teak plantation of Thai Plywood Co., Ltd. Lansak, Uthaithani Province	Mixed deciduous forest	70.96	0-100	Tangsinmankong, *et al.*, 2007
Ban Sai Thong Community forest, Lamphun Province	DDF old conservation area DDF new conservation area MDF old conservation area MDF new conservation area	42.95 16.16 40.49 86.11	0- 80 0 – 20 0 – 110 0 - 100	Phonchaluen, 2009
Huai Hong Khrai Royal Development Study Center (HHK), Chiang Mai Province, Northern Thailand	Dry dipterocarp forest (DDF) Mixed deciduous forest (MDF)	29.57 39.88	0 -100 0 - 160	Chaiwong *et al.*, 2013
Petrified wood forest park, Tak province	Dry dipterocarp forest (DDF)	31.22	0 -100	Wongin, 2011

Table 2.7 Soil carbon studies in different plantations and other land uses type in Thailand

Study site	Vegetation type	soil organic carbon (t C ha^{-1})	Soil depth (cm)	References
Num Yao sub-watershed, Nan province	Reforestation planted since 1979 (exotic+ native species) :*Gmelina aborea,Eucalyptus camaldulensis, Tectona grandis,Pterocarpus macrocarpus ,Afzelia xylocarpa,Pterocarpus macrocarpus, Acacia catechu*	146.83±7.22	0 - 100	Pibumrung *et al*., 2008
Huay Kha Khaeng Wildlife Sanctuary and teak plantation of Thai Plywood Co., Ltd. Lansak, Uthaithani Province	Teak plantation			Tangsinmankong *et al*., 2007
	24-year-old	105.67		
	15-year-old	78.78	0 - 100	
	6-year-old	157.03		
Central Thailand	Teak plantation			Pumijumnong *et al*., 2007
	- 28-year-old	66.83		
	- 27-year-old	105.67	0 – 100	
	- 18-year-old	78.78		
	- 14-year-old	61.72		
	- 10-year-old	157.03		
Sakaerat environmental research station, Nakornratchasrima Province	Reforest			Chidthaisong and Lichaikul, 2005
	Acacia mangium (16 –year-old)	66	0 - 50	
	Agriculture maize	60		
Prachuap Khiri Khan Silvicultural Research Station, Southern Thailand	Native and exotic species plantation (14-15-year-old)			Meungpong *et al*., 2010
	- *Acacia crassicarpa*	58.63		
	- *Azadirachta indica*	44.49	0 - 50	
	- *Pterocarpus*	46.78		
	macrocarpus	62.64		
	- *Shorea roxbyrghii*	56.77		
	- *Tectona grandis*	49.00		
	- *Xylia xylocarpa*	49.90		
North – east (Nongkhai province)	Rubber plantation			Saengruksawong *et al*., 2012
	- 1-year-old	14.26		
	- 5-year-old	16.83	0 - 100	
	- 10-year-old	18.52		
	- 15-year-old	16.05		
	- 20-year-old	13.37		

Table 2.8a Soil carbon studies in plantations in other countries

Location	Type	Location	SOC (tC/ha)	Soil depth (m)	Elevation (m)	Mean annual rainfall (mm)	References
Sarawak, Malaysia	Rehabilitated forest 1– 7 year-old		36.96 – 75.03	0- 60			Ch’ng *et al*., 2011
Sarawak, Malaysia	Rehabilitated forest - 1991 (19-year-old) - 1999 (10-year-old) - 2008 - Natural forest		34.9 41.9 26.7 31.9	0 - 50			Roland *et al*., 2012
	Rehabilitated forest - 16- year-old		144.18	0 - 40			Leng *et al*., 2009
Luquillo Experimental forest, Northeastern, Puerto Rico	*Pinus caribeaeb* dominated plantation	18^{0} 18’ N, 65^{0}50’W		0 - 10	400	3,920	Li *et al*., 2005

Table 2.8b Soil carbon studies in plantations in other countries

Location	Type	Location	SOC (tC/ha)	Soil depth (m)	Elevation (m)	Mean annual rainfall (mm)	References
Garhwal Himalayan Region of India	*Eucalyptus* spp. *Pinus roxburghii* *Tectona grandis* *Dalbergia sissoo*	$74^0$34’36’’ E – $78^0$18’22’’E	54.03 46.07 41.07 40.80	0 - 30	381 – 1, 729		Gupta and Sharma, 2011
Kouilou, Congo	*Terminalia superba* -7-year-old -12-year-old -48-year-old	$4^0$31’S, $12^0$4’E	2.24 2.32 3.41	0 - 10	300	1,250	Goma-Tchimobakala, 2009
Brazilian Agricultural Research Company, State of Rio de Janeiro	Mixed plantation Pure plantation - *Eucalyptus grandis* - *Pseudosamanea guachapele*	$22^0$40’S, $43^0$41’W	23.83 17.19 14.20	0 - 40	33	1,250	Munishamappa *et al.*, 2012
Taiwan	Broad-leaf plantation Conifer plantation		96 120	0 - 100		1,850 - 2,700 2,500 – 3,250	Tsai *et al.*, 2009

2.13 Forest restoration

One forest restoration method, which Forest Restoration Research Unit (FORRU) have been developing since 1994, and which shows considerable promise as a means of maximizing carbon storage, whilst accelerating biodiversity recovery, is the framework species method (FORRU, 2006, 2008). Originally conceive in Australia, (Goosem and Tucker, 1995; Tucker and Murphy, 1997; Tucker, 2000), this restoration concept has been adapted to the forest ecosystems of Thailand and neighbouring countries, by Chiang Mai University's (FORRU). It involves planting mixtures of 20–30 indigenous tree species (both pioneer and climax species) in a single step, where natural regeneration is too sparse to achieve rapid canopy closure. Essential characteristics of framework species are: (i) high field performance (high survival and growth rates) in open degraded sites; (ii) spreading, dense crowns that shade out herbaceous weeds and (iii) provision of resources that attract seed-dispersing wildlife (e.g. fruits, nectar, nesting sites, etc.) at an early age (Goosem and Tucker, 1995). Furthermore, framework species should be easily propagated in nurseries, with features such as reliable seed availability, rapid and synchronous germination and growth of seedlings to a plantable size (50–60 cm) in less than 1 year (FORRU, 1998, 2006, 2008). Best-performing framework tree species have been identified (Elliott *et al*., 2003) and optimal silvicultural treatments determined, to maximize survival and growth rates after planting (Elliott *et al*., 2000; FORRU, 2006). With those species and treatments, canopy closure can now be achieved within 3 years after planting to bring tree density up to 3,000/ha. Natural seedling recruitment of 73 species non-planted was reported by Sinhaseni (2008). Forest restoration also increased the species richness of the bird community, from about 30 before planting, to 88 after 6 years, representing about 54% of bird species recorded using the same methods in nearby mature forest (Toktang, 2005).

Before planting, plots were cleared of weeds by slashing and spraying with glyphosate, taking care not to damage any existing natural regeneration. Tree saplings, of 20-30 species, derived from locally collected seed and raised in local tree nurseries in 9 x 2½" polybags in 50:50, forest soil:organic matter, were planted randomly across the plots, averaging 1.8 m apart (3,000/ha). Various fertilizer, mulching and weeding regimes were applied as experimental treatments during the first two rainy seasons after planting. Fire breaks were cut every January and fire prevention patrols worked throughout the dry season.

2.14 FullCAM Model

There are many models used for assessment and predicting carbon pools in various types of landuse for example:

- Century is used for simulating the dynamics of carbon (C), nitrogen (N), phosphorus (P), and sulfur (S) for different plant-soil systems including grasslands, agricultural lands, forests, and savannas (Parton *et al*., 1996).

- RothC (the Rothamsted Soil Carbon Model) was originally developed and parameterized to model the turnover of organic carbon in arable soils under a range of soil and climatic conditions. (Coleman and Jenkinson, 1999)
- ECOSSE (Estimate Carbon in Organic Soils – Sequestration and Emissions) was developed from concepts originally derived for mineral soils in the ROTHC (Coleman and Jenkinson, 1996)
- FullCAM (Richards *et al*., 2001)

The Full Carbon Accounting Model (FullCAM) () was developed under the Australian National Carbon Accounting System to integrate data on land cover change, land use and management, climate, plant productivity, decomposition and soil carbon over time and accounting tools to provide a single model capable of carbon accounting in transitional (e.g. afforestation, reforestation and deforestation) and mixed (e.g. agroforestry) systems. The exchanges of carbon, loss and uptake, between the terrestrial biological system and the atmosphere are also accounted for. FullCAM consistes of five constituent models:

1. CAMFor (Carbon Accounting Model for Forestry)

    Models carbon and nitrogen cycling in a forest, including in: trees, debris, soil, minerals, and wood products. Forest growth can be included as yield curves, empirical growth formula, and process modeling.

2. CAMAg (Carbon Accounting Model for Agriculture - Cropping and grazing systems)

    Models carbon and nitrogen cycling in an agricultural system, including in: crops, debris, soil, minerals, and agricultural products.

3. 3PG (Physiological Principles Predicting Growth)

    Models tree growth and turnover in trees. A variant of this model is used to calculate a forest productivity index (potentially variable over both space and time) to support empirical growth formula.

4. GENDEC (GENeral microbial mulch DECay model)

    Models carbon and nitrogen cycling in mulch.

5. RothC (ROTHamsted Institute active soil Carbon model)

    Models carbon cycling in the active soil.

Under fullCAM model, RothC model version 26.3 was focused on simulating soil carbon mass. In this model, soil organic carbon is split into four active compartments and a small amount of inert organic matter (IOM). The four active compartments are Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM). Each compartment decomposes by a first-order process with its own characteristic rate. The IOM compartment is resistant to decomposition. Incoming plant carbon is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming plant material. For most agricultural crops and improved grassland, DPM/RPM ratio of 1.44, i.e. 59% of the plant material is DPM and 41% is RPM, for unimproved grassland and scrub (including savanna) a ratio of 0.67 is used. For a deciduous or tropical woodland a DPM/RPM ratio of 0.25 is used, so 20% is DPM and 80% is RPM and also applied for this study. All incoming plant material passes through these two compartments once. Both DPM and RPM decompose to form CO_2, BIO and HUM. The proportion that goes to CO_2 and to BIO + HUM is determined by the clay content of the soil. The BIO + HUM is then spitted into 46% BIO and 54% HUM. BIO and HUM both decompose to form more CO_2, BIO and HUM (Coleman and Jenkinson, 1999).The structure of the model is shown in Fig. 2.7.

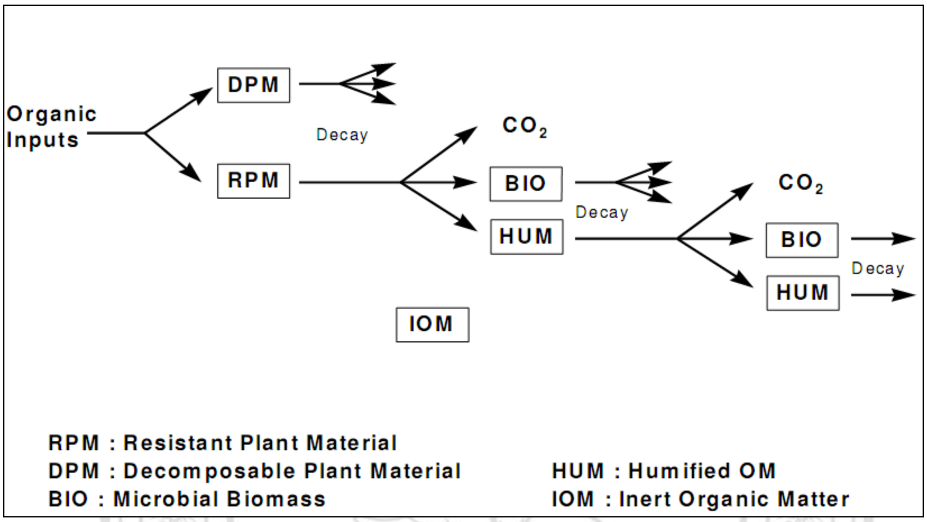


Figure 2.7 Structure of RothC model version 26.3 under fullCAM model (Coleman and Jenkinson, 1999)

For above-ground study in Australia, Preece *et al*. (2012) assessed the accuracy of the two accepted allometric methods (FullCAM and the Keith *et al*. (2000) to estimate carbon stocks in rainforest stands in north-eastern Queensland, Australia, and also compared their estimates across three reforestation methods (Brown, 1997; Keith *et al*., 2000; Chave *et al*., 2005) with the FullCAM modelled estimates for the same sites. Small stems (<10 cm) were collected which accounted for 15.1% of above-ground carbon (AGC) in plantings <20 years old. They found that the estimates using the Keith allometric were 19.5% greater than those of FullCAM; the Chave allometric, 40.4% greater; and the Brown allometric, 54.9% greater. Therefore, the Chave allometric function was recommended because it provides intermediate values, is based on the widest range of tropical trees and has been shown to be accurate away from the sites used for its development. For above and below-ground carbon mass, Norris *et al*. (2010) studied in Victoria publicly managed land including various forest types e.g. Alpine ash, Mountain ash, Mountain mix species, etc. Then, they summarized that the movement of carbon stocks for the sum over time (1930 – 2009) especially complete carbon mass and onsite carbon mass are stable at about 750 million of carbon.

RothC is a sub-module under FullCAM model used for stimulated soil carbon mass and worldwide used. It can be used in small scale plot up, national and even global scale. In Australia, Paul *et al*. (2003) used a complete carbon (C) accounting model for forest systems, GRC3 which links a C tracking model (CAMFor) with independently verified models of forest growth (3PG), litter decomposition (GENDEC) and soil C turnover (RothC). GRC3 was tested in seven regional case studies of eucalypt or *Pinus radiata* plantations in Australia to predict rates of change in soil C after afforestation and to determine controlling factors. The model was calibrated as far as possible to above-ground growth of plantations, litterfall, accumulation of litter and in some cases root biomass, and was then run to determine expected change in soil C. They summarized that actual trends in soil C may vary according to site and management conditions, but the main controlling factors will be different between pasture and plantation in the amount and allocation of net primary productivity (NPP), and the quantity and quality of residue inputs to soil. Changes in soil C were small compared with other forest pools and fluxes—after 40 years of afforestation less than 3% of the cumulative NPP was predicted to accumulate in soil. It is debatable whether it will be feasible or cost-effective to directly measure change in soil C over short-time frames (such as 5 years) for the purpose of claiming C credits under an emissions trading scheme**.** Modelling provides a useful alternative and at the very least can be used to identify sites and time frames where investment in soil C measurement may be warranted.

In Japan, Hashimoto *et al*. (2011) estimated plant litter input to a depth of 30 cm in the mineral soil in a Japanese forest using RothC and an average value of soil organic carbon (SOC) content, and also compared with estimated litter inputs from the NPP dataset from Moderate Resolution Imaging Spectroradiometer (MODIS). Finally, they found that the litter carbon input calculated using RothC and that derived from MODIS NPP were positively correlated, but the mean estimated litter input from RothC was 17.2% smaller than that estimated from MODIS.

In Mexico**,** Gonzalez *et al.* (2010) compared changes in estimated SOC in three regions of the Sierra Norte of Oaxaca, Mexico (which included multiple land-use e.g. agricultural land, plantations, oak forest, pine forest, tropical evergreen, sub-evergreen forests tropical deciduous and sub-deciduous forest, mountain cloud forest, etc.) with the method proposed by the Intergovernmental Panel on Climate Change (IPCC) and the RothC model fed with spatial information from the IPCC method. Changes were estimated for the periods 1980-2000 and 1990-2000. The SOC balance in the study regions resulting from the two methods indicates losses in the range of 342-1509 Gg in the first period and 29-1052 Gg in the second. Changes in SOC estimated with both methods, in general, exhibited the same trend for the two periods. The correlation coefficients varied between 0.86 and 0.99. This study showed that the RothC model used with partial information from the IPCC method is a useful tool for predicting changes in estimated SOC on a regional scale in the hillside systems studied. Gonzalez-Molina *et al.* (2011) investigated the changes in SOC in short term (not more than 20 years) in various land use types : farming with residues added and no added, pure forest stands , grassland and rangeland. The adjustment coefficients for site modeling had R^2 values of 0.77 – 0.95 and model efficiency (EF) was -0.6 to 0.93 when RothC performance was evaluated by a system R^2 value were 0.06 – 0.92 and EF were -0.24 – 0.90 the low R^2 and EF values in rangelands were attributed to the fact that these systems are complex became of heterogeneous vegetation but the evaluation of RothC model indicates that it can be useful in simulating SOC changes in temperate and warm climate sites and in farming, forest and grassland systems in Mexico.

In Brazillan Amazon, Cerri *et al.* (2007) studied the simulating SOC changes in land use change chronosequences from Brazilian Amazon with RothC and Century models. The chronosequences comprised an area of forest (used for reference) and a series pasture sites established at different time. And also predicted the forest clearance and conversion to well managed pastured would cause an initial in soil C stocks (0-20 cm in depth). The model provided reasonable estimates (coefficient of correction = 0.8) when compared with available measured data.

In Thailand, Gnanavelrajah *et al.* (2007) estimated and mapped carbon stock of different agricultural land uses in a sub – watershed of Thailand. RothC carbon model was used to project the soil carbon of present land-uses in the coming 10 years and based on which the sustainability of land-use was predicted. The total carbon stock of agricultural land–use was estimated to be 20.5 Tg, of which 41.49 % was biomass carbon and 58.51 % was soil carbon. Among the land-use, para rubber had the highest average biomass C (136.34 MgCha^{-1}) while paddy had the lowest (7.08 MgCha^{-1}). Such information on carbon stock could be valuable to develop viable land-use options for agricultural sustainability and carbon sequestration.

On a global scale, Gottschalk *et al.* (2012) used the RothC model to examine the impacts of future climate on global soil organic carbon (SOC) stocks. The results suggested an overall global increase in global SOC stocks by 2100 under all scenarios, but with a different extent of increase among 5 the climate model and emissions scenarios. Their simulations, including changes in climate, land use and NPP, suggested that aggregate global SOC stocks continuously increase from 1971 up to 2100 with varying intensity in all scenarios. Hotspots of SOC losses of more than 20 Cha^{-1} are central and north-eastern Scandinavia, Northeast China and North- and South-Korea, a belt stretching from central China along its south-west border to northern India, the east coast of Canada and15 some small patches at Canada’s south west corner. Areas of medium SOC losses of less than 20 tCha^{-1} cover the boreal zones of northern and eastern Europe, eastern Canada and Alaska, mid and northern India, central China and patchy regions in South America and South Africa and Australia. Prominent SOC stock increases occur in east Brazil while all remaining areas largely show a moderate increase from 0–20 tha^{-1}up20 to 20–40 tha^{-1}in smaller regions.

CHAPTER 3

Methodology

3.1 Study site

The study site was located in the field trial plot system, set up to test the framework species method of forest restoration. Plots had been established annually, every rainy season since 1997, ranging in size from 1.4 to 3.2 hay^{-1} and planted with varied combinations of 20 - 30 candidate framework tree species, in the Upper Mae Sa Valley (18’ 52^{0}N, 98’ 51^{0}E, 1,207 – 1,310 m elevation) of Doi Suthep-Pui National Park (Elliott *et al*., 2012). The forest restoration plots were established near Ban Mae Sa Mai, Mae Rim district Chiang Mai province, Thailand (Figs. 3.1a - b), a Hmong hill tribe community (around 36.3 km. away from Chiang Mai University). In the past, the Hmong farming system consisted of swidden farming, mainly growing maize, opium, and upland rice. During the 1970’s, opium was cultivated as a cash crop, maize for stock feed, and mainly rained rice for subsistence (Irwin, 1976) and then lychee orchards became the main cultivation. Nowadays, the lychee orchard area is declining to accommodate multiple cash crop e.g. cabbage, radish and also high quality vegetables, using green-house chambers, which some of them were supported by Mae Sa Mai Royal Project.

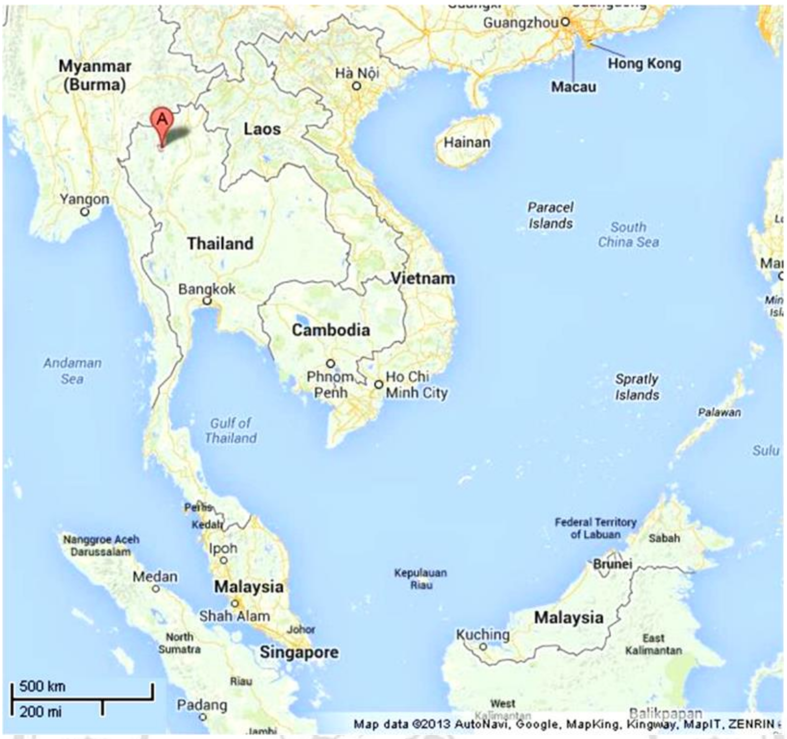


Figure 3.1a Location of Chiang Mai, Thailand (Google, 2013)

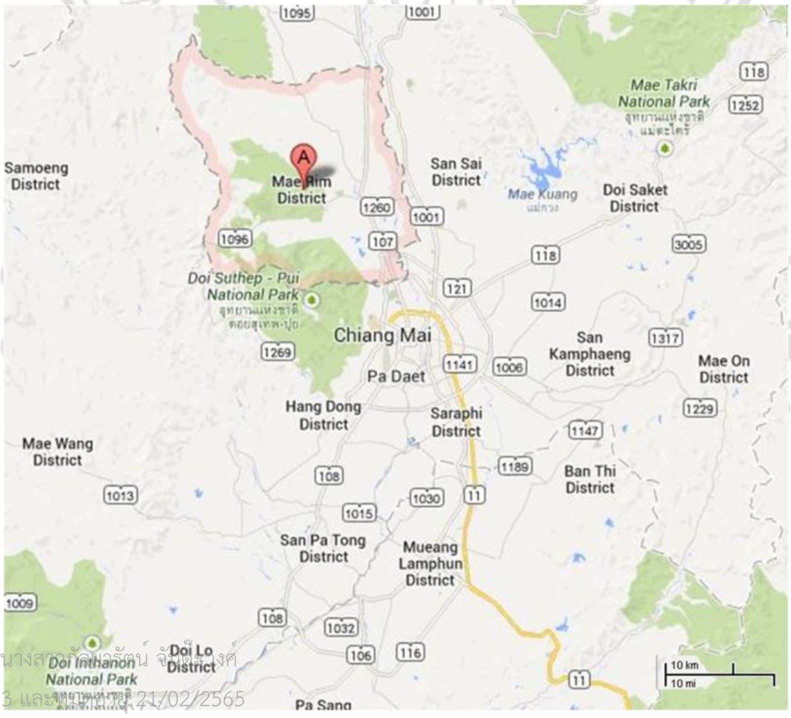


Figure 3.1b Location of Mae Rim District, Chiang Mai, Thailand (Google, 2013)

Fifteen subplots measuring 40 x 40 m^2 were set up in forest restoration plots of 3 different ages, since planting: 2, 7, and 11 years old (at the start of this study), planted in 2007, 2002 and 1998 (Figs. 3.4 - 6). The locations of the subplots in restored forest and in control sites (excluding the natural forest site) are shown in Fig 3.2. The plots planted in 1998 (11 years old) were split into 3 locations (1998.1, 1998.2 and 1998.3) and together with adjacent control plots (control 1, control 2 and control 3). The 2002 and 2007 plots were the larger and were split into 3 subplots.

Three control sites (Fig. 3.3), dominated by herbaceous weeds, where no trees had been planted and no restoration treatment applied, were used as an indicators of initial conditions. This site was dominated by the grasses: *Thysanolaena latifolia*, *Phragmites vallatoria* and *Imperata cylindrical* (Toktang, 2005).

Plots had been planted with mixtures of 20–30 selected indigenous framework species (Appendix A).

Secondary forest east of Ban Mae Sa Mai was also included in the study, as the least disturbed forest in the vicinity (Fig. 3.7). Although never clear cut, this area had been disturbed by local villagers, including selective tree felling for construction, fire wood collection and clearance of small patches for opium cultivation about 40-50 years previously. This “community” forest had been protected from disturbance for at least 20 years by local rules, enforced by the village environment committee. Throughout this thesis it is referred to as “natural forest” to distinguish it from “restored forest”. Situated at 1,300 m a.s.l., this natural forest was dominated by trees and seedlings of *Castanopsis diversifolia* (Family Fagaceae) (Jinto, 2009).

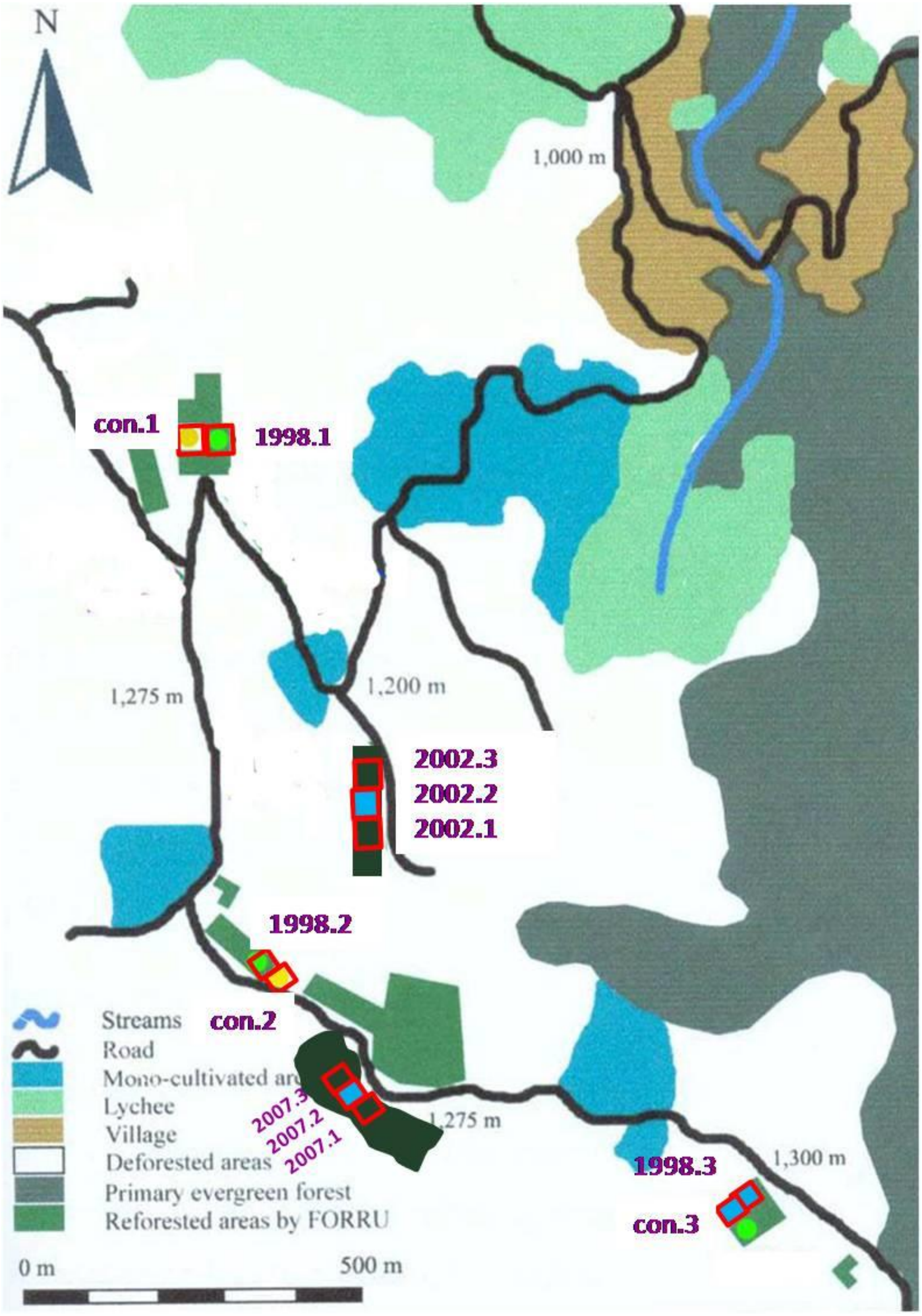


Figure 3.2 Map of forest restoration study plots and the position of soil pedon (subplot with blue color) at Ban Mae Sa Mai, Mae Rim district, Chiang Mai

Figure 3.3 Control site

Figure 3.4 2-year-old site (2007 site)

Figure 3.5 7-year-old site (2002 site)

Figure 3.6 11-year-old site (1998 site)

Figure 3.7 Natural forest nearby Ban Mae Sa Mai, Mae Rim district, Chiang Mai province

According to the geological map of Northern Thailand (German Geological Mission, 1979), the petrography of Mae Sa Mai consists of 87% migmatites from Palaeozoic granites and 13% Precambrain paragneiss. Schuler (2008) found that the soils of the Mae Sa Mai area are dominated by Acrisols and Cambisols based on soil mapping.

3.2 Climate data

The data of rainfall (mm), minimum and maximum temperature (^{0}C) were taken from the nearest meteorogical station, Ban Mae Sa Mai Royal Project to the study around 3 km., during June 2009 – January 2012 (Fig. 3.8). Minimum and maximum temperature ranged from 14.68 – 20.52 and 16.14 – 36.79 ^{0}C, respectively. Annual rainfall in year 1 (June 2009 – May 2010) and year 2 (June 2010 – May 2011) of this study was 764 and 1,336 mm, respectively.

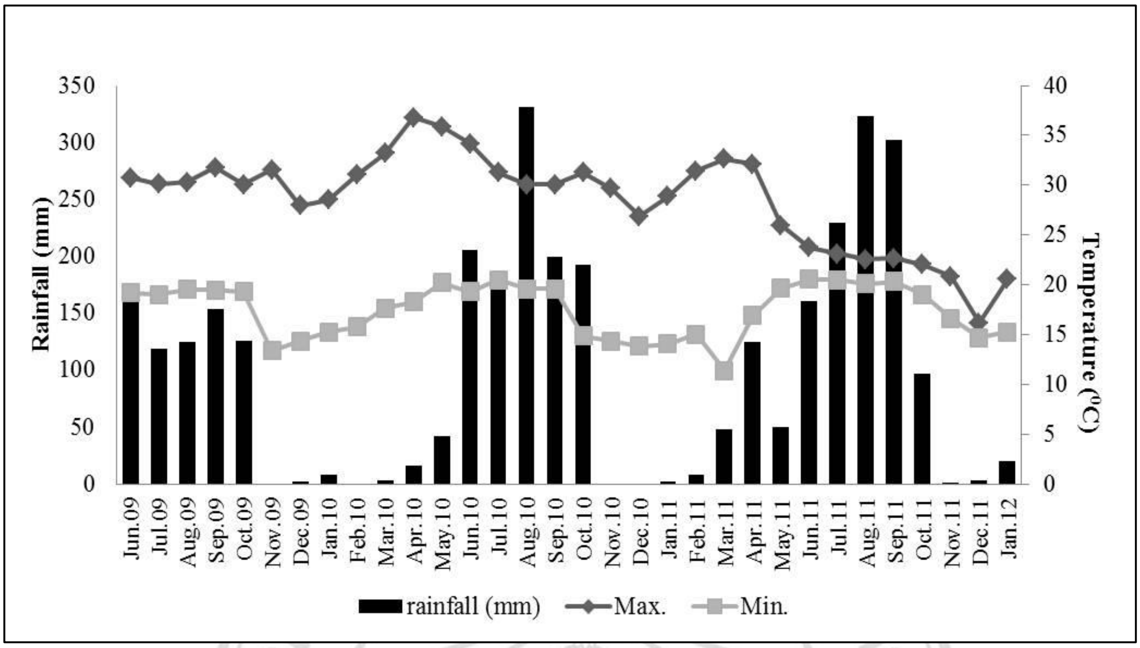


Figure 3.8 Rainfall, minimum and maximum temperatures from the nearest meteorogical station of Ban Mae Sa Mai Royal project. (Ban Mae Sa Mai meteorogical station, 2009 -2012)

3.3 Method

3.3.1 Litterfall

Six 1 x 1 m^2 litter traps were set up in each subplot (Fig. 3.9) (total litter traps = 6 traps x 15 subplots = 90 traps) for collecting litter monthly for 32 months (June 2009 – January 2012). The collected litter was oven-dried at 80^0C to constant weight and sorted into 4 major parts (leaves, wood, reproductive organ and other parts) before weighing (Weerakkody and Parkinson, 2006).

The dry litter in each study site was analyzed for organic carbon concentration in a laboratory and carbon in the litter was estimated using formula:

$$\text{Carbon in litter (tC/ha)} = \text{dry mass (t/ha)} \times \text{C concentration (\%)}/100$$

% carbon concentration in litter from lab analysis was compared with the 50 % value mass, suggested by many previous research (Jina *et al*., 2008 and Lewis *et al*., 2009).

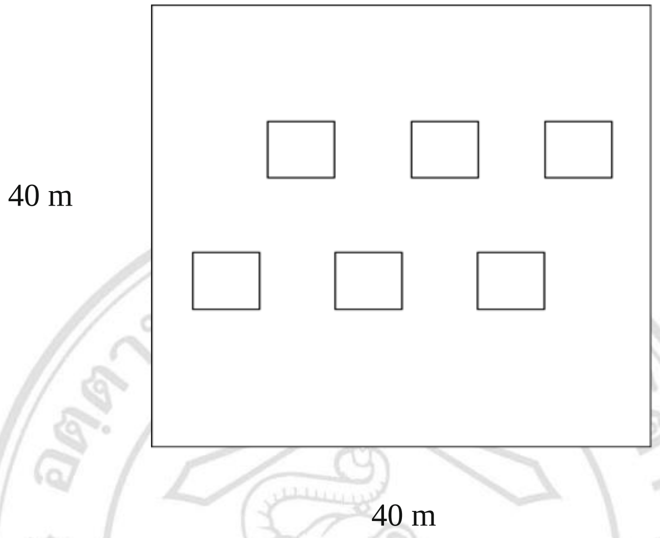


Figure 3.9 Diagram of litter traps in each subplot (40 x 40 m^2)

3.3.2 Litter accumulation

At all nine points, forest floor without soil was collected within a ring of 30 cm diameter (Fig. 3.10) and dry weight was also determined.

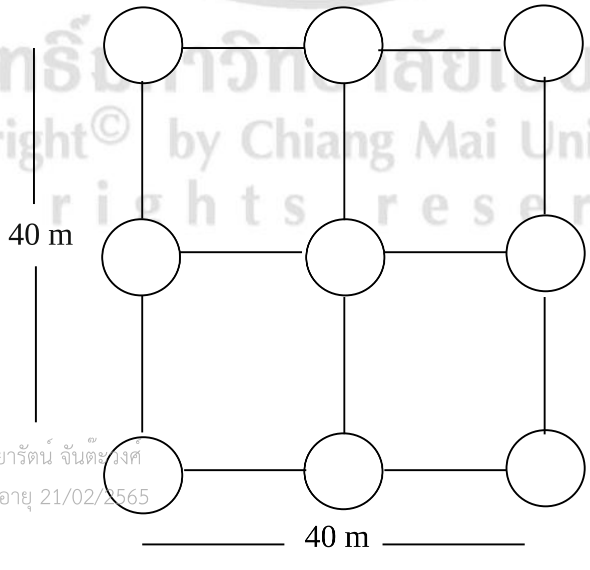


Figure 3.10 Diagram of sampling plot for soil and litter sampled in each site

3.3.3 Litter decomposition of three species

Senescent leaves of 3 important framework tree species *Erythrina subumbrans*, *Ficus subinsica* and *Castanopsis diversifolia* were collected and air-dried. Because the characteristics of *Erythrina subumbrans* (Family Leguminosae (Papilionoideae) and *Ficus subinsica* (Family Moraceae) provided (nectar rich and flowers, fruits respective that attract seed dispersers, from an early age (within 4 years). *Castanopsis diversifolia* (Family Fagaceae) is a common species characteristic of natural forest with edible fruites. Therefore, it was also selected for litter decomposition study.

This experiment was conducted from October 2010 – March 2011. Two grams of dried leaves of each species was placed in nylon litterbags (2-mm mesh size) (Berg *et al.*, 1993). Three hundred and sixty bags for all the species, were placed *in situ* in all the study sites (October 2010). Twenty-four bags were placed in each subplot. Four litterbags were collected after 2 weeks (October 2010), 1 (November 2010), 2 (December 2010), 3 (January 2011), 4 (February 2011) and 5 months (March 2011). Then, washed and oven-dried at 70^0C to constant weight.

Percentage remaining mass of each of the species and the total remaining mass of each species and mixed-three species were calculated using formula:

$$\% \text{ mass loss} = \frac{(W1 - W2)}{W1} \times 100$$

where W1 is the original dry mass of litter,
W2 is dry mass of litter after time t

$$\% \text{ mass remaining} = 100 - \% \text{ mass loss}$$

Freshly senescent leaves of the three species: *Erythrina subumbrans*, *Ficus subinsica* and *Castanopsis diversifolia* at the beginning phase (October 2010), decomposed litter at middle after 3 months (December 2010) and late phase after 5 months (March 2011) were analyzed for organic carbon by Walkley-Black method and total nitrogen by micro-Kjeldahl digestion technique (Cromack and Monk, 1975) at Central laboratory, Faculty of Agriculture.

Decay rate of three species, i.e., *k* values (units = year^{-1}) after 5 months were calculated (Olson, 1963) using the formula:

$$\ln\left(\frac{Xt}{X_0}\right) = -kt$$

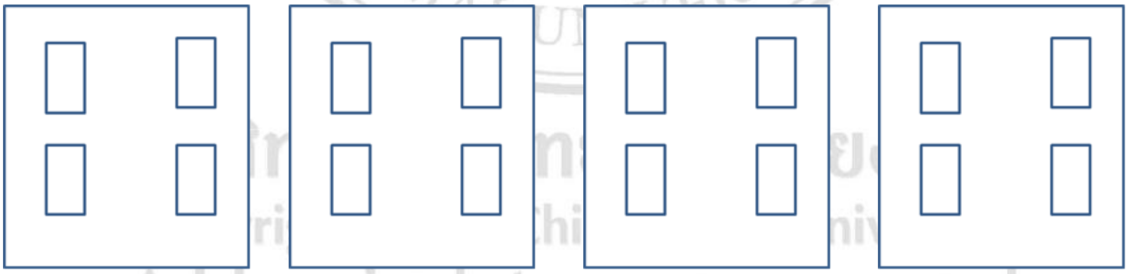
where X_0 is the original mass of litter,

Xt is the amount of litter remaining after time t,

t is the time (year) and *k* is the decomposition rate (year^{-1})

3.3.4 Decomposition of natural litter using big bag

Mixed litter of each study site in natural condition was used for this experiment. Mixed framework species was used in restored forest, grass in control site and mixed plant species in natural forest site. Around 500 g (wet weight) of material in natural condition was placed in each big bag (50 x 50 cm^2) (Fig.3.11).



Setting point	1 collection	2 collection	3 collection
April 2011	August 2011	November 2011	February 2012
	(rainy season)	(cool season)	(cool dry season)

Figure 3.11 Diagram of litter bags containing mixed species

Setting (Apr.11)

- wet weight 500g was put in each litterbag and 10% of the whole sample was collected

1st and 2nd collection

- collected 10% of sample

3rd collection

- collected whole sample

Each period, measure wet weight (mass loss during time), carbon content, decomposition rate and C:N ratio. 10% (subsample) of litter in litterbag was collected at the setting point (April 2011), rainy season (August 2011), cool season (November 2011) and cool dry season (February 2011). The subsamples were used to measured moisture content and calculated for percentage of mass remaining and analyzed for organic carbon by Walkley-Black method and total nitrogen by micro-Kjeldahl digestion technique (Cromack and Monk, 1975). Decay rate was also determined.

3.3.5 Soil sampling

3.3.5.1 Soil moisture

Top soil samples were collected 0 – 10 cm in depth monthly from June 2009 – January 2012 at six random points in each site. The wet weight and dry weight (after oven-drying at 80^0C to constant weight) were determined for each sample.

3.3.5.2 Soil investigation and description

A soil pit was dug (in each study site) down to 2 m depth (Fig. 3.12). Soil descriptions were written according to the “Field Book for Describing and Sampling Soils” (USDA-NRCS, 2002). The soil type was assigned using “Soil Taxonomy USDA 11th Edition” (USDA, 2010). Study site topography of each soil pit was recorded, e.g. elevation, slope and position. Then, the soil samples from each layer: 0 -5, 5-10, 10 – 20, 20 – 30, 30 – 40, 40 – 60, 60 – 80, 80 – 100, 100 -150 and 150 -200 cm. in depth were collected for analysis at Central Laboratory, Faculty of Agriculture, CMU (Fig. 3.13)

Figure 3.12 Soil pit

Figure 3.13 Soil sample collection

3.3.5.3 Soil analysis in laboratory

Soil physical properties

- Soil color using Munsell color system
- Soil texture using hydrometer method (Gee and Bauder, 1986)
- Bulk density using core method (Blake and Hartge, 1986)

Soil chemical properties

- pH (soil : H_2O = 1:1) (Mclean, 1982)
- Organic matter (O.M.) using Wet Oxidation Walkley and Black (Nelson and Sommers, 1996)
- Total nitrogen using Micro Kjeldahl method (Bremner and Mulvaney, 1982)
- Extractable P using Bray II and Colorimetric method (Olsen and Sommer, 1982)
- Extractable K and Na using Ammonium acetate (1 N, pH 7.0) and Flame photometer (Knudsen *et al.*, 1982)
- Extractable Ca and Mg using Ammonium acetate (1 N, pH 7.0) and Atomic absorption (Lanyon and Heald, 1982)
- Cation exchange capacity (CEC) extracted by 1 M Ammonium acetate (pH 7.0) (Rhoader, 1982).

3.3.5.4 Soil sampling and soil organic carbon

Soil samples from depth ranging from 0 to 200 cm were collected at 4 points from each study site (which have soil pit) using a soil auger. Four points in each layer was mixed and sub-sampled into 3 replicates. Soil properties (pH, N, P, K and CEC) were also determined (Figs. 3.14 - 15). Organic matter and bulk density were determined using the Walkley-Black method (Nelson and Sommers, 1996) and core method (Black and Hartge, 1986), respectively.

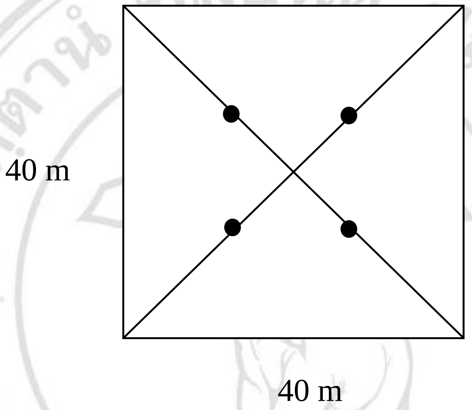


Figure 3.14 Diagram of point for collecting soil samples by soil auger

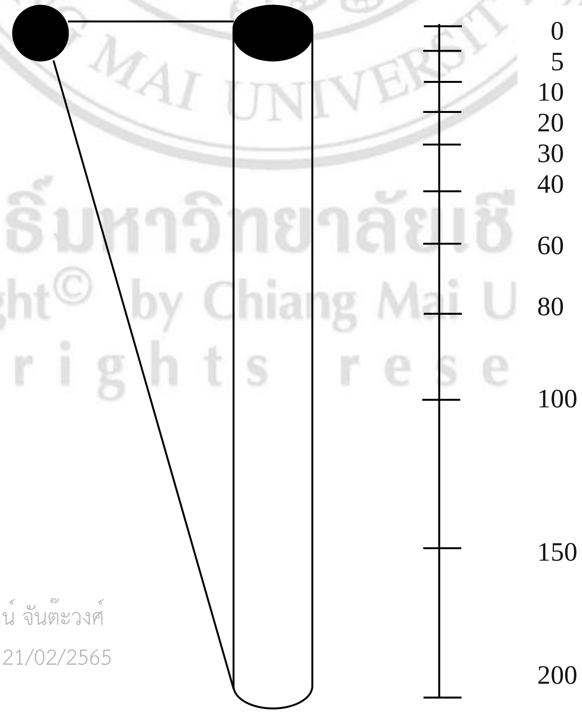


Figure 3.15 10 layers of soil depth

Soil organic carbon stock at depths ranging from 0 to 200 cm was calculated by the formula:
Soil organic carbon stock = OC (g/100g) x soil bulk density(g cm^{-3}) x soil depth (cm) (tC/ha)

3.3.6 Statistic analysis

3.3.6.1 Litterfall and carbon content in litter

The amounts of the litterfall in 32 months (June 2009 – January 2012) and their fractions were analyzed for differences among the study sites using one-way ANOVA (Guo *et al.*, 2004). Tukey's test was used in conjunction with an ANOVA to figure out which study site means were significantly different from one another, amounts of litterfall and carbon content in litter among the study sites. The relationships between total litter (t/ha) and age since planting and between total litterC (tC/ha) and age since planting were determined, using correlation analysis.

3.3.6.2 Litter decomposition of mixed three species and mixed species using big bag

Tukey's test was used to determine differences in decay rate among study sites and in different periods. Mass remaining (%) and carbon remaining (%) in different periods were also determined. Linear regression equation and R^2 of all study sites used for calculating predicted mass remaining (%) in 1 year.

3.3.6.3 Soil analysis

Differences in soil pH, N, P, K CEC and OM among study sites were tested. Pearson correlation was used for determined among parameters. Regression analysis was used to detect a relationship between organic carbon (%).

3.3.7 Model

FullCAM model tool (Richards *et al*., 2005)

FullCAM model 3.13.8 (Research version) was used for estimating soil carbon mass of each study site (control, 2-year-old, 7-year-old, 11-year-old and natural site). Some climate data were derived from Ban Mae Sa Mai Royal Project meteorogical station e.g. rainfall (mm), evaporation (mm) and average air temperature (^{0}C). Measured specify data e.g. plant residues (tC/ha), clay percentage were collected from our study sites from January 2010 – December 2011. Each plot was described and used the following criteria and assumptions for all of sites:

Table 3.1 Input data for simulating soil carbon mass in each study site

Parameter	Data	Resources
Plot type	Forest soil	
Simulate	Carbon	
Simulation steps	Yearly	
Year	2010 – 2020 (next 10 years)	
Climate data	Rainfall (mm), open-pan evaporation (mm) and average air temperature (^{0}C)	Climate data from the nearest meteorogical station that called Ban Mae Sa Mai Royal Project during January 2010 – December 2011x
Specify data	Plant residues	Measured litterC in each study sites 2010 -2011 (tC/ha)
	DPM to RPM 0.25	Typical value of forest type
	HUM encapsulation: 0.005	Typical value
	Depth of soil sampling: 200 cm	Maximum soil depth of our study
	Clay percentage	Clay percentage from soil texture analysis
	Carbon masses (tC/ha)	Assumption 20% DPM and 80%RPM of litterC of each site

CHAPTER 4

Results

4.1 Rainfall and average soil moisture

The relationship between rainfall and average soil moisture in each month during June 2009 – January 2012 is shown in Figs. 4.1a – e. Rainfall ranged from 0 – 323.3 mm. Maximum soil moisture (%) of all study sites were ranged from 34.05 – 37.63 % during rainy season. While minimum soil moisture (%) of all study sites were ranged from 6.46 – 16.48 %.

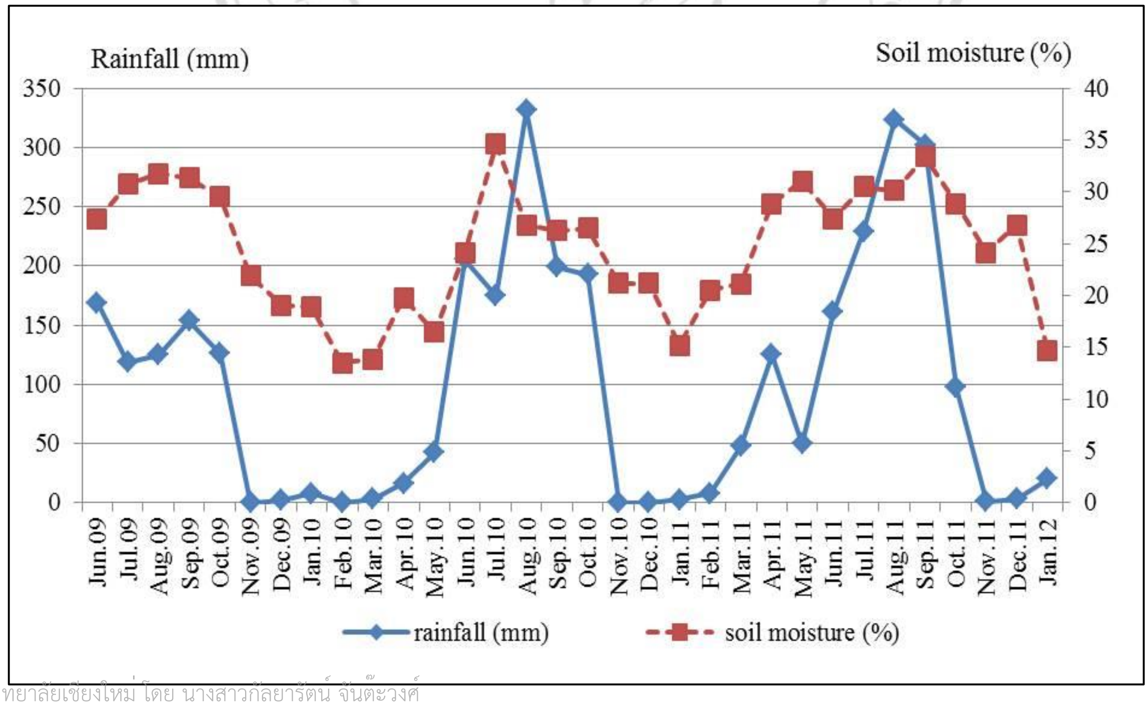


Figure 4.1a Rainfall (mm) and average soil moisture (%)
during June 2009 – January 2012 in control site

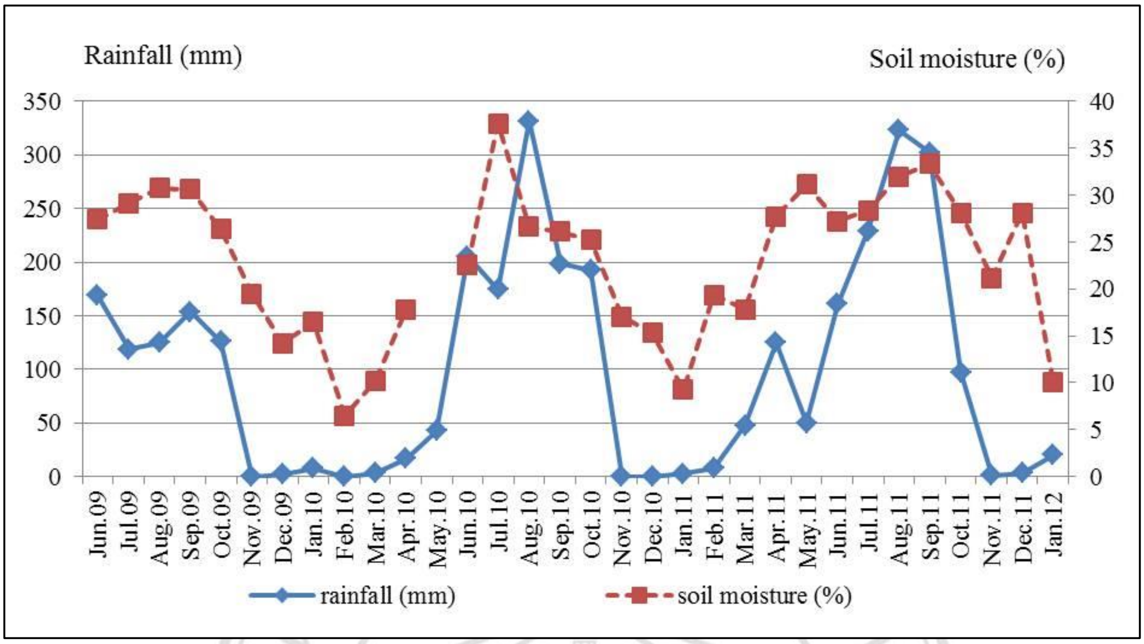


Figure 4.1b Rainfall (mm) and average soil moisture (%)

during June 2009 – January 2012 in 2-year-old site

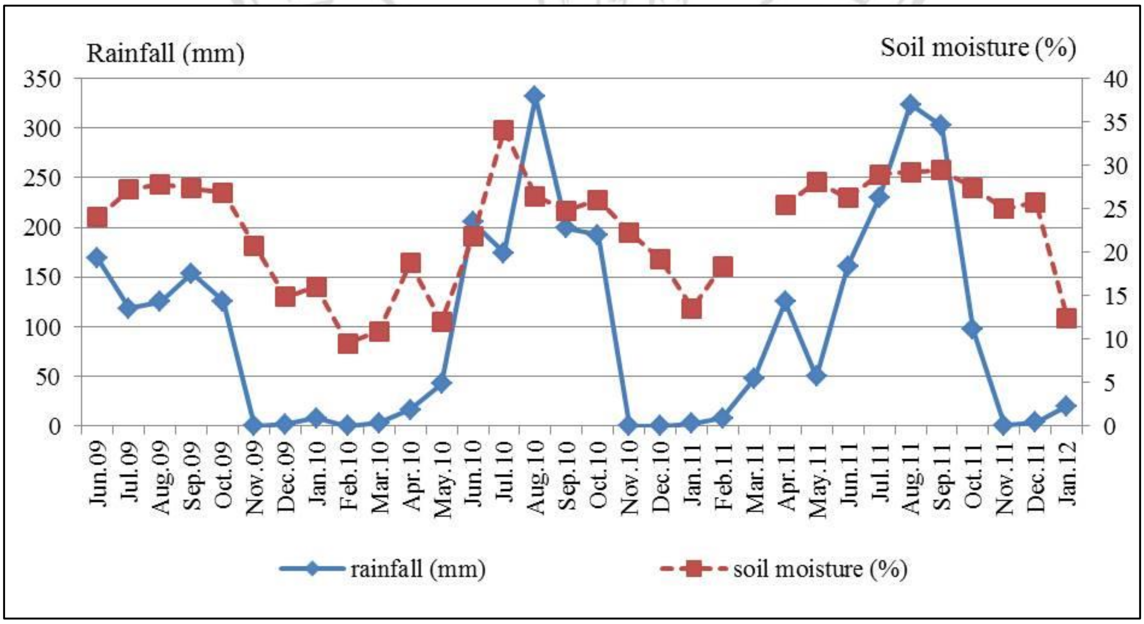


Figure 4.1c Rainfall (mm) and average soil moisture (%)

during June 2009 – January 2012 in 7-year-old site

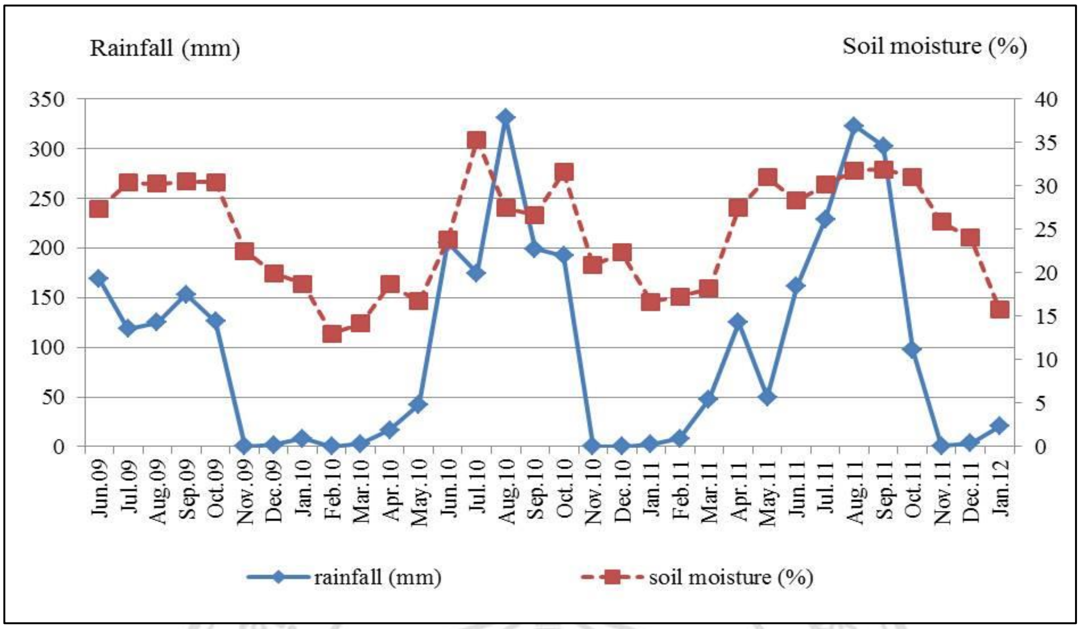


Figure 4.1d Rainfall (mm) and average soil moisture (%)

during June 2009 – January 2012 in 11-year-old site

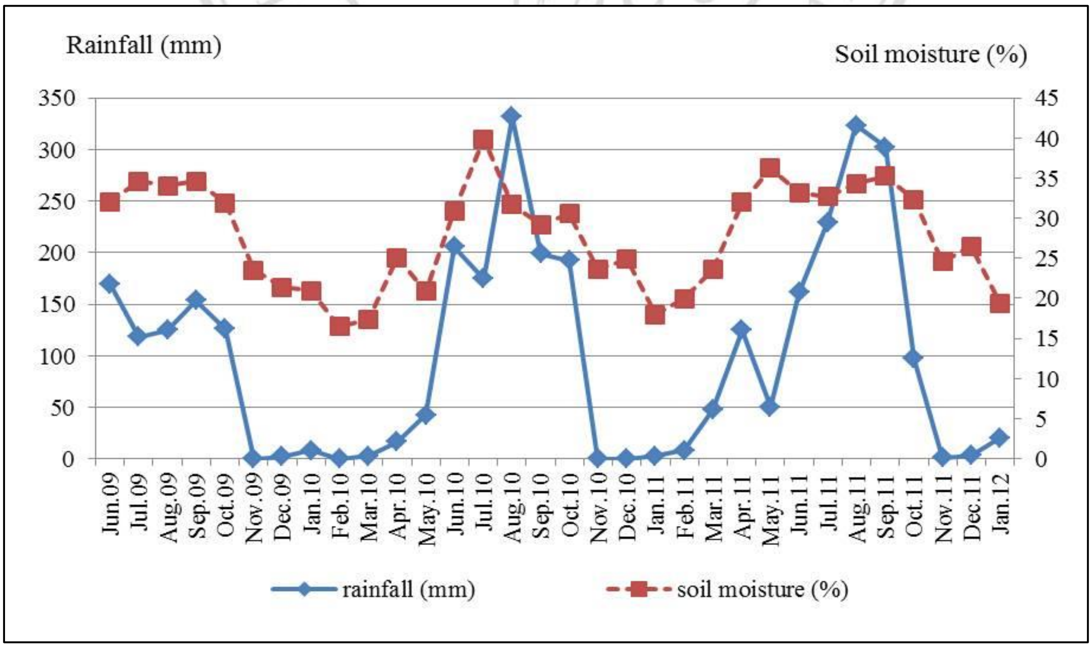


Figure 4.1e Rainfall (mm) and average soil moisture (%)

during June 2009 – January 2012 in natural site

4.2 Litterfall and rainfall

The highest amount of litterfall was found in the natural forest site followed by 11-year-old, 7-year-old, control, and 2-year-old site. The pattern of litterfall dry mass and rainfall in 32 months (June 2009 –January 2012) is shown in Fig.4.2. The amount of litterfall increased at the beginning of cool-dry season from November until March. In the second year (June 2010 – May 2011), the natural forest site had the highest peak in February 2011 and tended to produce more litterfall, but in the other study sites tended to be the same pattern of litterfall. The pattern of the litterfall in two years in restored forest site was quite similar, except in the 2-year-old site. Data from the 2-year-old site from April – September 2010 are drop to zero, because a forest fire occurred around the second week of March 2010.

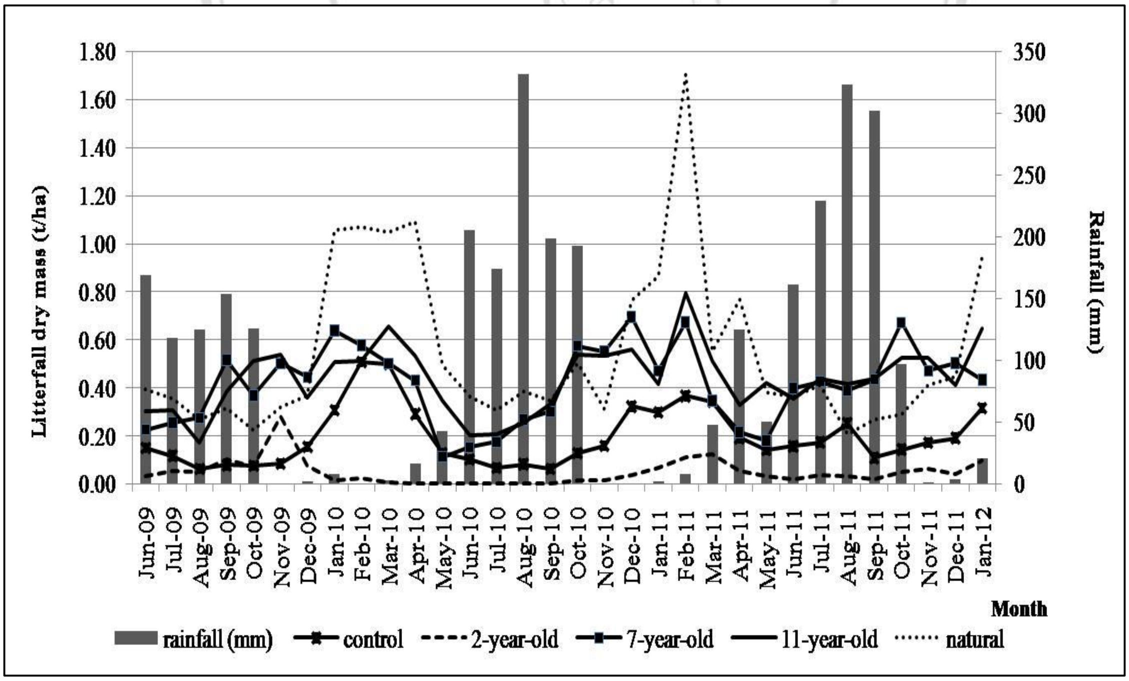


Figure 4.2 The total litterfall (t/ha/month) of all study sites with rainfall (mm) during June 2009 – January 2012

In the first year of collection from June 2009 to May 2010, the ranged of litterfall in the control, 2, 7, 11-year-old and the natural site were 0.06 – 0.51, 0 – 0.13, 0.11 – 0.64, 0.17 – 0.65 and 0.27 – 1.07 t/ha/month, respectively (Table 4.1a). In the second year of collection from June 2010 to May 2011 the ranges were 0.06 – 0.34, 0 - 0.13, 0.17 – 0.69, 0.20 – 0.80, and 0.31 – 1.71 t/ha/month, respectively (Table 4.1b). The annual litterfall in the first year of 2, 7, 11-year-old and the natural site 2.46, 0.71, 4.85, 5.13 and 7.01 (t/ha/yr), respectively, and in the second year were 2.27, 0.46, 4.60, 5.09 and 7.26 (t/ha/yr), respectively. Moreover, additional data in the third year were collected from June 2011 to January 2012. High amounts of litter in most study sites (control, 2, 11-year-old and natural sites) were found in January 2012: 0.32, 0.11, 0.65 and 0.95 t/ha, respectively, except in the 7-year-old site in October (Table 4.1c). However, there was a fire in the 2-year-old plot in early March 2010, so the amount of the litterfall in this plot was low from February to September 2010. Moreover, total litterfall collected from June 2009 until January 2012 (32 months) in control, 2, 7, 11-year-old and natural site were 6.24, 1.54, 13.18, 13.98 and 17.62 t/ha, respectively.

Table 4.1a The amount of litterfall dry mass in year1 during June 2009 – May 2010

Study site	Amount of litter (t/ha)												Total
	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	
	2009							2010					
control	0.15 cd	0.12 cd	0.06 b	0.08 c	0.08 d	0.09 d	0.16 b	0.31 c	0.51 b	0.50 b	0.29 bc	0.13 b	2.46
2-year-old	0.03 d	0.06 d	0.05 b	0.10 c	0.07 d	0.28 c	0.08 b	0.02 d	0.02 c	0.00 c	0.00 c	0.00 c	0.71
7-year-old	0.23 bc	0.26 bc	0.28 a	0.52 a	0.37 b	0.50 ab	0.44 a	0.64 b	0.58 b	0.50 b	0.43 b	0.11 b	4.85
11-year-old	0.30 ab	0.31 ab	0.17 ab	0.39 b	0.51 a	0.54 a	0.36 a	0.51 bc	0.51 b	0.65 b	0.53 b	0.35 b	5.13
natural	0.39 a	0.35 a	0.27 a	0.31 b	0.23 c	0.32 bc	0.37 a	1.05 a	1.07 a	1.05 a	1.09 a	0.49 a	7.01

Note: Value are means± SD (n=18). Means followed by different letters on the same column indicate significant differences among study sites at $P<0.05$ based on Tukey's test

Table 4.1b The amount of litterfall dry mass in year2 during June 2010 – May 2011

Study site	Amount of litter (t/ha)												
	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Total
	2010							2011					
control	0.10 b	0.07 c	0.08 c	0.06 b	0.13 b	0.16 bc	0.32 b	0.30 b	0.37 cd	0.34 ab	0.19 bc	0.14 c	2.27
2-year-old	0.00 c	0.00 c	0.00 c	0.00 b	0.02 b	0.02 c	0.04 c	0.07 c	0.11 d	0.13 b	0.05 c	0.03 c	0.46
7-year-old	0.15 b	0.17 b	0.27 ab	0.30 a	0.57 a	0.55 a	0.69 a	0.47 b	0.67 bc	0.35 ab	0.22 b	0.18 bc	4.60
11-year-old	0.20 b	0.20 ab	0.25 b	0.33 a	0.54 a	0.53 a	0.56 ab	0.42 b	0.80 b	0.51 a	0.33 b	0.42 a	5.09
natural	0.37 a	0.31 a	0.39 a	0.35 a	0.50 a	0.31 b	0.77 a	0.87 a	1.71 a	0.55 a	0.77 a	0.38 ab	7.26

Note: Value are means± SD (n=18). Means followed by different letters on the same column indicate significant differences among study sites at *P*<0.05 based on Tukey’s test.

Table 4.1c The amount of litterfall dry mass in year3 during June 2011 – January 2012

Study site	Amount of litter (t/ha)							
	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.
	2011							2012
control	0.16 c	0.17 b	0.25 bc	0.11 c	0.14 bc	0.17 b	0.19 bc	0.32 de
2-year-old	0.02 c	0.04 b	0.03 d	0.02 c	0.05 c	0.06 b	0.04 c	0.11 e
7-year-old	0.40 b	0.43 a	0.39 ab	0.44 a	0.67 a	0.47 a	0.50 a	0.43 cd
11-year-old	0.35 a	0.44 a	0.42 a	0.44 a	0.53 a	0.52 a	0.41 ab	0.65 bc
natural	0.36 b	0.41 a	0.21 c	0.27 b	0.29 b	0.41 a	0.45 a	0.95 a

Note: Value are means± SD (n=18). Means followed by different letters on the same column indicate significant differences among study sites at *P*<0.05 based on Tukey’s test.

4.3 Litter component

The average different components of litter: leaf, branch, flower/fruit and the others (t/ha/yr) in the study sites, and percentage of litter component are shown in Table 4.2. Leaf litter was the major component of all study sites overall the year. (Fig.4.3). Leaf component in control, 2, 7 and 11-year-old and natural site were 2.10, 0.47, 4.07, 4.27 and 4.51 t/ha/yr, respectively.

Percentage of leaf tended to be lower from control site to natural site. In contrast, other component such as fruit/flower, branch and small fractions in natural site higher than other site followed by 11, 7, 2-year-old and control site.

Table 4.2 Litter in different component (t/ha/yr) and percentage

Site	Leaf (%)	Branch (%)	Flower/fruit (%)	Other (%)	Total (%)
control	2.1 (89.4)	0.1 (5.5)	0.1 (4.3)	0.02 (0.8)	2.4 (100)
2-year-old	0.5 (81.4)	0.1 (15.2)	0.01 (2.6)	0.005 (0.8)	0.6 (100)
7-year-old	4.1 (81.2)	0.6 (12.4)	0.2 (4.7)	0.08 (1.7)	5.0 (100)
11-year-old	4.3 (80.8)	0.7 (14.0)	0.2 (4.2)	0.05 (1.0)	5.3 (100)
natural	4.5 (70.1)	1.2 (19.3)	0.6 (8.5)	0.13 (2.1)	6.4 (100)

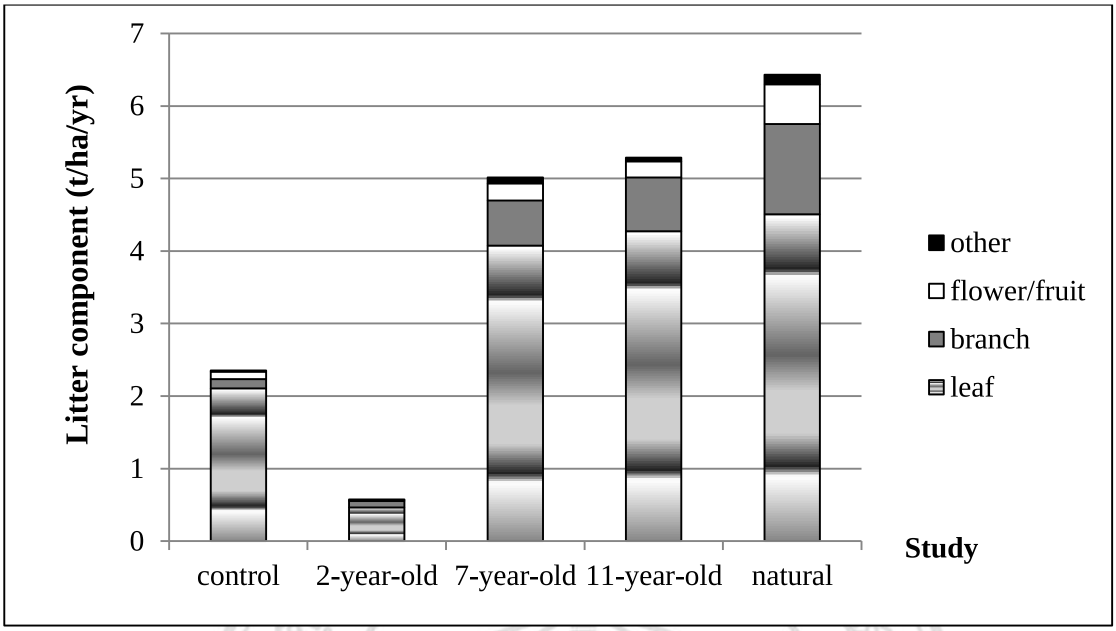


Figure 4.3 Mean litter of 3 years in different component (t/ha/yr)

4.4 Carbon through litterfall

The highest amount of organic carbon was found in natural site (38.72 g/100g), in contrast lowest amount of organic carbon was found in 7-year-old site (32.97 g/100g) (Table 4.3).

Litter carbon (litterC) in Year1 and Year2 ranged from 0.25 – 2.71 tC/ha/yr and 0.16 – 2.81 tC/ha/yr, respectively. LitterC in natural site was higher than other sites significantly. Among restored forest site, the high value of litter carbon was found in oldest site (11-year-old) next to 7-year-old, control and 2-year-old site (Table 4.3). The pattern of litter in terms of carbon similar to the pattern of litterfall which was collected in the study sites (Fig. 4.5).

Moreover, in the third year of collection from June 2011 – January 2013 (8 months), the total litterfall and litter carbon ranged from 0.55 – 5.63 t/ha and 0.19 – 2.00 tC/ha. However, in the third collection was not covered in one year. So, annual litter and litterC in the third year were calculated by multiplying average litterfall with 12. Mean annual litterfall over 3 years are shown in Table 4.4. The amount of litterfall was highest in the natural forest but not different significantly with the old restored forest sites (7 and 11-year-old). LitterC was the same trend as litterfall which ranged from 0.20 to 2.49 tC/ha.

Table 4.3 Annual litterfall (t/ha/yr) and litterC (tC/ha/yr)

Study site	OC g/100g	Year1		Year2		Year3	
		Litter (t/ha/yr)	LitterC (tC/ha/yr)	Litter (t/ha/yr)	LitterC (tC/ha/yr)	Litter (t/ha/yr)	LitterC (tC/ha/yr)
control	33.29±1.95 **b**	2.46	0.82 **cd**	2.27	0.75 **cd**	2.27	0.76
2-year-old	34.74±2.13 **ab**	0.71	0.25 **d**	0.46	0.16 **d**	0.55	0.19
7-year-old	32.97±2.74 **b**	4.85	1.60 **bc**	4.60	1.52 **bc**	5.59	1.84
11-year-old	35.50±1.50 **ab**	5.13	1.82 **ab**	5.09	1.81 **b**	5.63	2.00
natural	38.72±0.39 **a**	7.01	2.71 **a**	7.26	2.81 **a**	5.02	1.94

Note: Values in column 1 is mean of OC± SD (n= 3). In Column 3 and 5 are means of carbon in litter in year1 and year2 followed by different letters on the same column indicate significant differences at $P<0.05$ among study sites.

Table 4.4 Mean litterfall (t/ha/yr) in all study sites over 3 years and litterC (tC/ha/yr)

Site	Mean annual litterfall (t/ha/yr)	LitterC (tC/ha/yr)
control	2.33 ± 0.11 **b**	0.78 ± 0.04 **c**
2-year-old	0.57 ± 0.13 **c**	0.20 ± 0.05 **d**
7-year-old	5.01 ± 0.51 **a**	1.65 ± 0.17 **b**
11-year-old	5.28 ± 0.30 **a**	1.88 ± 0.11 **b**
natural	6.43 ± 1.23 **a**	2.49 ± 0.48 **a**

Note: Values are mean ± SD (n = 3) with different superscripts within columns are significantly different among study site at *P*<0.05 based on Tukey's test.

4.5 Litter accumulation and carbon in litter

Highest amount of litter accumulation was highest in natural forest (5.89 t/ha) but not significantly higher than 7-year-old (5.26 t/ha) and 11-year-old (4.89 t/ha). While the lowest amount of litter accumulation was found in 2-year-old site (1.94 t/ha). Carbon in litter was highest in natural forest next to 11, 7, control and 2-year-old were 2.28, 1.74, 1.73, 1.09 and 0.67 tC/ha (Table 4.5).

Table 4.5 Litter accumulation (t/ha) and carbon in litter (tC/ha)

Site	Litter accumulation (t/ha)	Carbon in litter (tC/ha)
control	3.27 ±1.6 **b**	1.09 ± 0.53 **c**
2-year-old	1.94 ± 1.4 **c**	0.67 ± 0.50 **d**
7-year-old	5.26 ± 1.5 **a**	1.73 ± 0.49 **b**
11-year-old	4.89 ± 1.5 **a**	1.74 ± 0.53 **b**
natural	5.89 ± 1.8 **a**	2.28 ± 0.78 **a**

Note: Values are mean ± SD (n = 27) with different superscripts within columns are significantly different among study site at *P*<0.05 based on Tukey's test.

4.6 Relationship between total litterC (tC/ha) and age since planted

The relationship between total litterC and age since planted was determined and are shown in Fig. 4.4. The equation derived from the data to describe the relationship was y = 0.90741ln(x) – 0.3187 (R^2 = 0.9757).

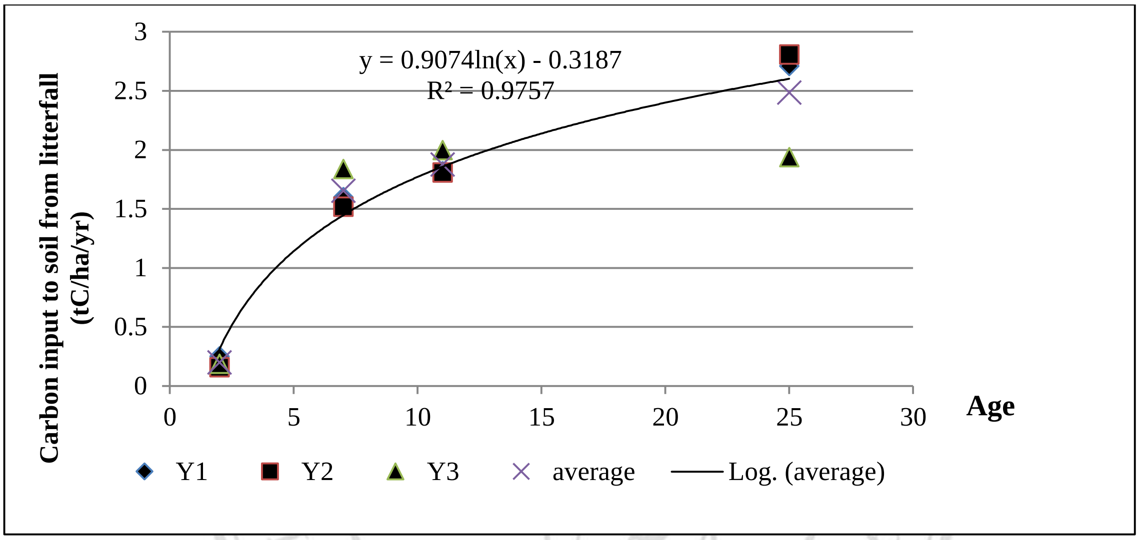


Figure 4.4 Relationship between total litterC (tC/ha/yr) and age since planted

4.7 Leaf litter decomposition of mixed three species

Ficus subincisa leaves decomposed the fastest (c80% in 5 months), *Erythrina subumbrans* leaves decomposed at a moderate rate (c50% in 5 months) and *Castanopsis diversifolia* leaves decomposed the slowest (c20% in 5 months) (Figs. 4.5a – d).

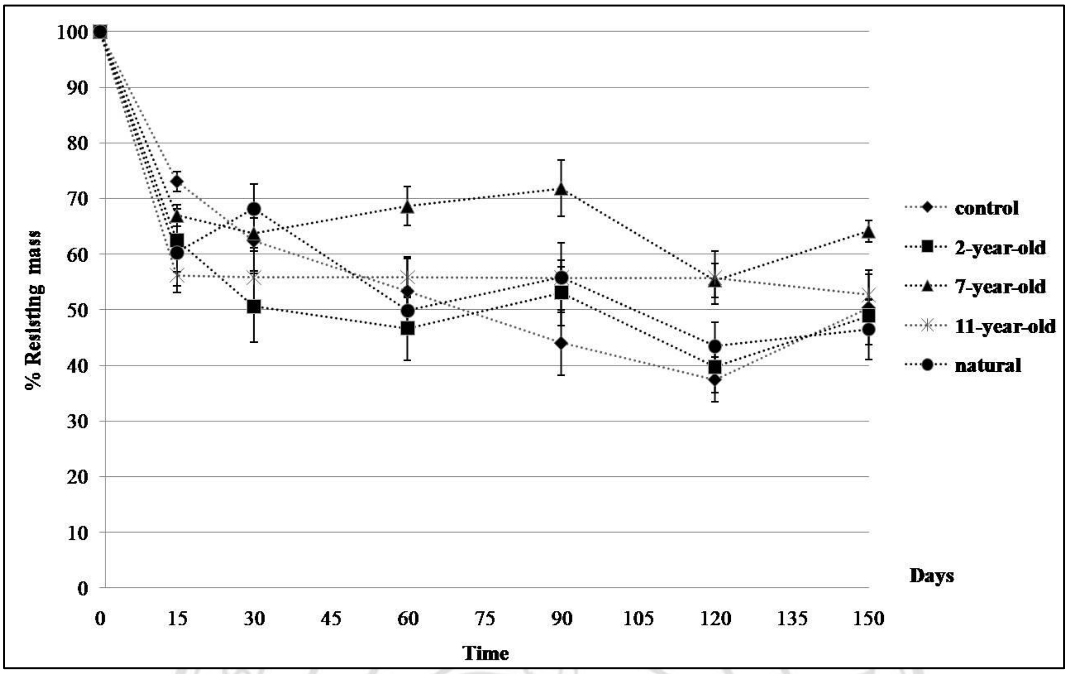


Figure 4.5a Percentage of resisting mass of *Erythrina subumbrans*

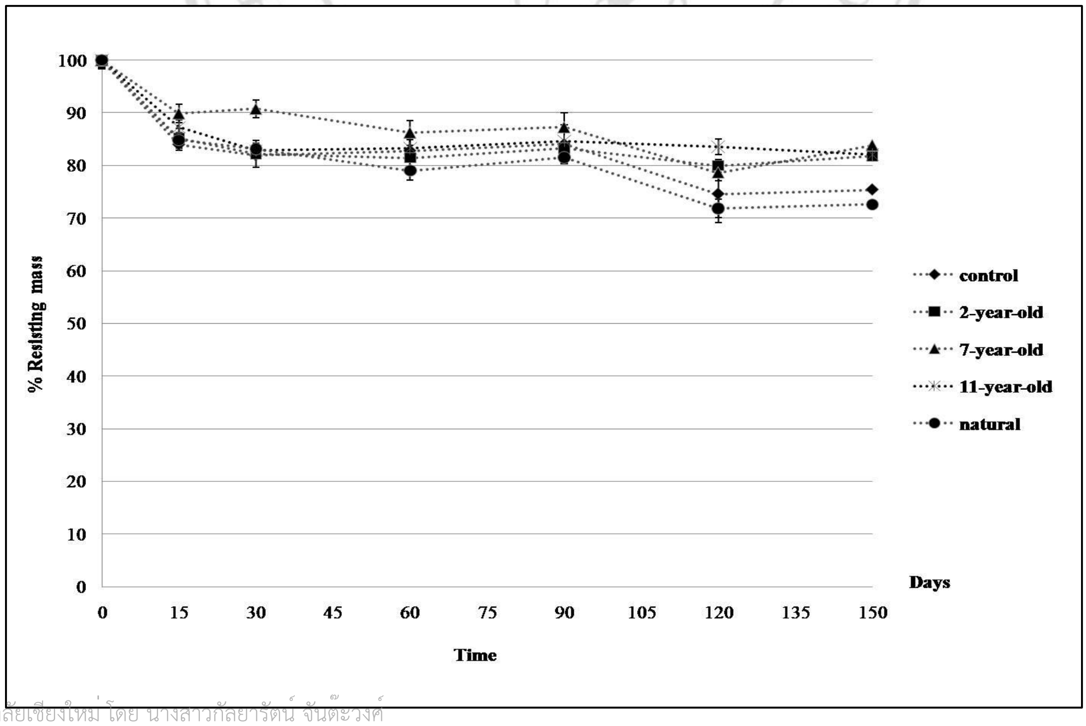


Figure 4.5b Percentage of resisting mass of *Castanopsis diversifolia*

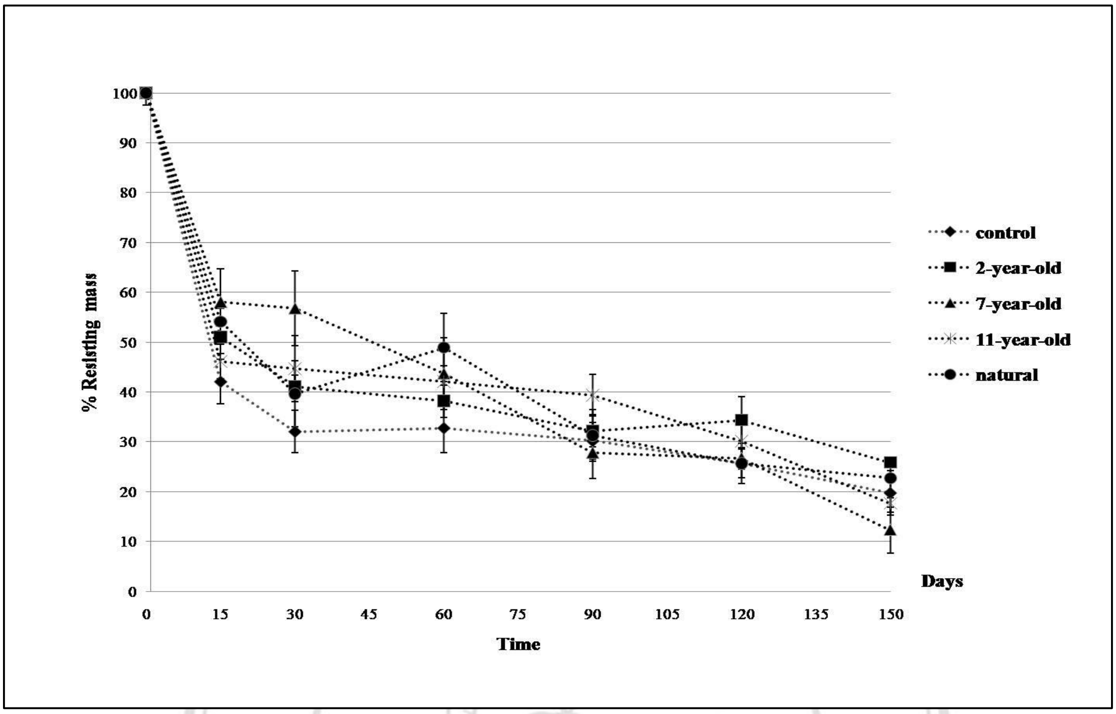


Figure 4.5c Percentage of resisting mass of *Ficus subincis*

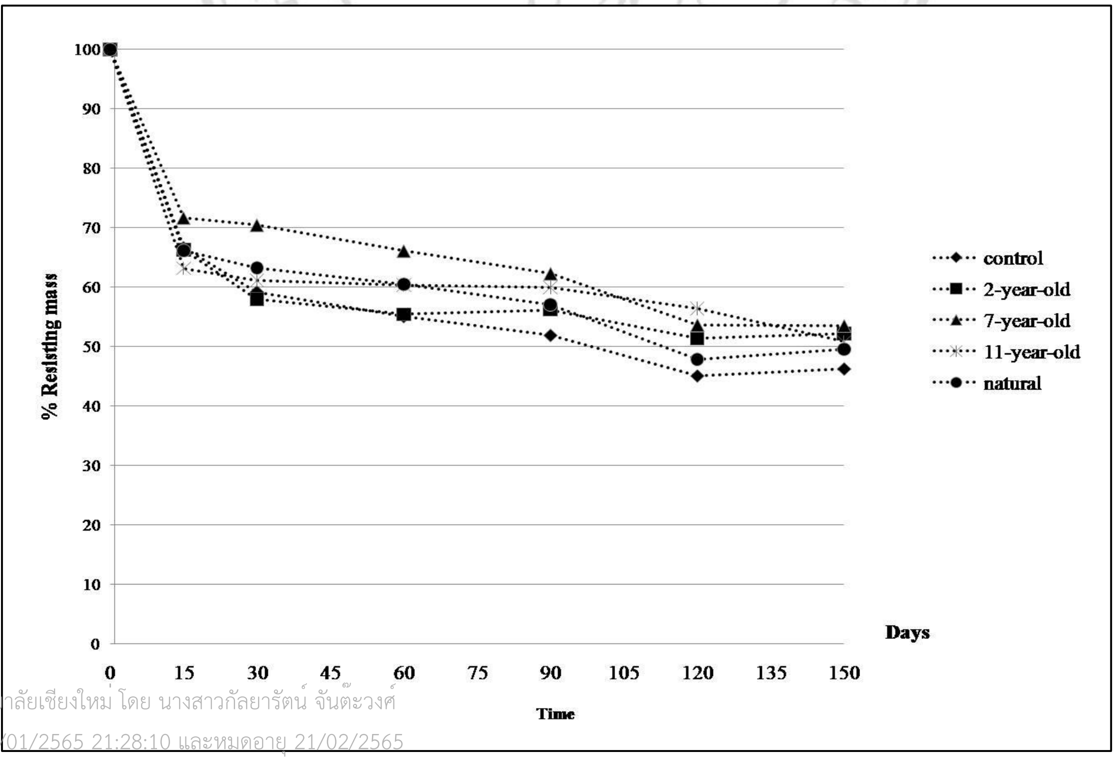


Figure 4.5d Percentage of resisting mass of mix three species

K values of three species in all study sites were shown in Table 4.6. *K* value of *Erythrina subumbrans* ranged 1.05 – 2.12, *Castanopsis diversifolia* ranged 0.41 – 0.87, *Ficus subincisa* ranged 1.21 – 4.15 and mix species ranged 1.46 – 1.87. *K* value in each species were not significantly different among study sites but high *k* value was found in *Ficus subincisa* compared with *Erythrina subumbrans* and *Castanopsis diversifolia*. The highest *k* value was found in 11-year-old site (4.15) site whereas the lowest *k* value was found in 7-year-old site (0.41). Moreover, *k* value of mix species ranged 1.46 – 1.87 and were not differ among study sites at $P<0.05$.

Table 4.6 *K* values of three species in all study sites

Study site	*k*			
	Erythrina subumbrans	*Castanopsis diversifolia*	*Ficus subincisa*	Mix species
control	AB 2.12±0.48 **a**	C 0.87±0.27 **a**	A 3.27±0.69 **a**	AB 1.87±0.21 **a**
2-year-old	AB 1.67±0.09 **a**	C 0.47±0.03 **a**	A 2.42±0.44 **ab**	B 1.51±0.05 **a**
7-year-old	AB 1.05±0.11 **a**	B 0.41±0.04 **a**	AB 1.21±0.45 **b**	A 1.46±0.07 **a**
11-year-old	B 1.88±0.50 **a**	C 0.46±0.04 **a**	A 4.15±0.25 **a**	B1.59±0.10 **a**
natural	B 1.66±0.19 **a**	B 0.66±0.06 **a**	A 3.27±0.49 **a**	B 1.63±0.07 **a**

Note: Value are means± SD (n= 12). Means followed by different letters on the same column on the right indicate significant differences at $p < 0.05$ among study sites and different letters on the same row on the left indicate significant differences at $P<0.05$ among three species.

Carbon nitrogen ratio (C:N) in three species were determined and showed in Table 4.7. C:N ratio was much higher for *C. diversifolia* than for the other 2 species. *F. subincisa* and *E. subumbrans* had similar C:N ratios

Table 4.7 Carbon nitrogen ratio in three species at beginning, middle (2 months) and late phase (5 months)

Study site	Species	Beginning phase C:N	Middle phase C:N	Late phase C:N
control	*Erythrina subumbrans*	20:1	15:1	15:1
	Castanopsis diversifolia	35:1	21:1	23:1
	Ficus subincisa	22:1	15:1	15:1
2-year-old	*Erythrina subumbrans*	20:1	13:1	13:1
	Castanopsis diversifolia	35:1	22:1	24:1
	Ficus subincisa	22:1	15:1	14:1
7-year-old	*Erythrina subumbrans*	20:1	16:1	14:1
	Castanopsis diversifolia	35:1	23:1	21:1
	Ficus subincisa	22:1	17:1	14:1
11-year-old	*Erythrina subumbrans*	20:1	16:1	14:1
	Castanopsis diversifolia	35:1	-	21:1
	Ficus subincisa	22:1	16:1	15:1
natural	*Erythrina subumbrans*	20:1	14:1	14:1
	Castanopsis diversifolia	35:1	20:1	21:1
	Ficus subincisa	22:1	15:1	15:1

4.8 Litter decomposition of mixed species using big bag

Decomposition of natural leaf litter in each study site was investigated during May 2011 to February 2012 over 4 periods were conducted. The early rainy season (May 2011), rainy season (August 2011), cool season (November 2011) and cool dry season (February 2012) from the starting date: 0, 103, 187 and 286 days. In each period, 10% of wet weight of each litter bag from all study sites was sub-sampled. The mass remaining of all study sites decreased rapidly from the beginning period to rainy season (Aug. 2011). The mass decreased around 20 – 30 % over 103 days in all study sites. From rainy season (Aug. 2011) to cool season (Nov. 2011) mass remaining (%) was increased in the 11-year-old and natural site (Table 4.8). In contrast, litter mass of in the 2 and 7-year-old sites decreased. In the last period, litter mass decreased in all study sites. Especially in 7-year-old site, the mass decreased rapidly in all periods (Fig.4.6). Moreover, mass remaining (%) of 7-year-old site in the last period of was 30.57% significantly and less than that at other sites (*P*<0.05). Moreover mass remaining with trend line was also shown in Fig.4.6 and predicted mass remaining (%) in 1 year using equation from linear regression is also shown in Table 4.9.

Table 4.8 Mass remaining (%) in different periods

Period / Site	1	2	3	4
	0 day Early rainy (May.11)	103 days Rainy (Aug.11)	187 days Cool (Nov.11)	286 days Cool dry (Feb.12)
control	100	A 76.12±14.85 **a**	A 71.43±27.97 **a**	A 67.42±22.59 **a**
2-year-old	100	A 75.09±13.76 **a**	A 66.65±22.36 **a**	A 68.18±21.58 **a**
7-year-old	100	A 79.50±14.42 **a**	AB 57.55±18.52 **a**	B 30.57±25.75 **b**
11-year-old	100	A 69.13±20.66 **a**	A 71.51±34.69 **a**	A 61.66±18.46 **a**
natural	100	A 75.36±13.07 **a**	A 79.82±24.45 **a**	B 53.06±11.11 **ab**

Note: Value are means± SD (n= 12). Means followed by different letters on the same column on the right indicate significant differences at *P*<0.05 among study sites and different capital letters on the same row on the left indicate significant differences at *P*<0.05 among periods.

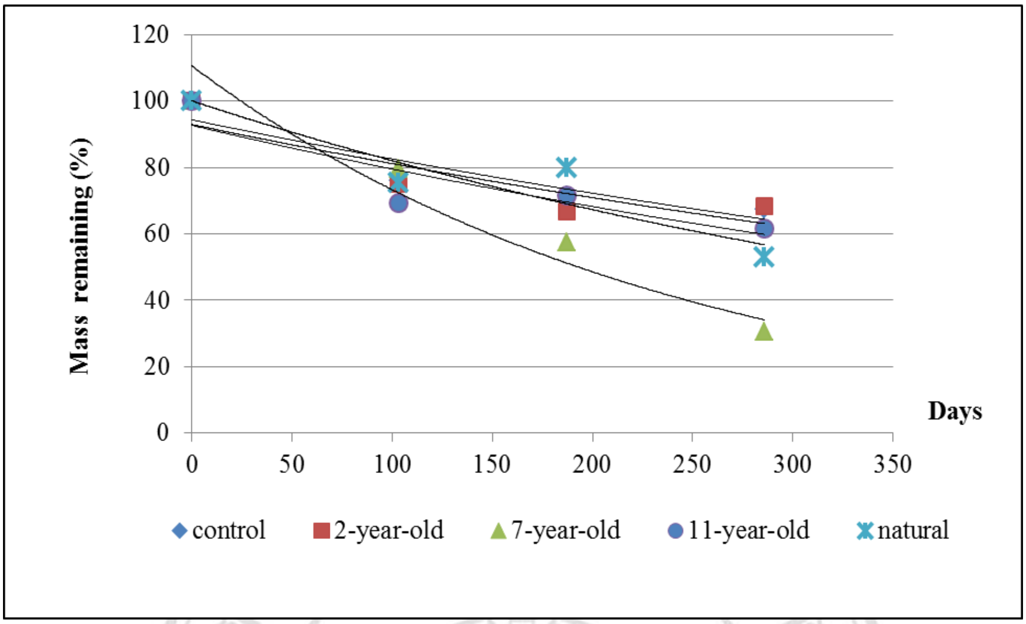


Figure 4.6 Litter mass remaining with trend line in different periods

Table 4.9 Linear regression equation and R^2 of all study sites

site	Equation	R^2	Predicted mass remaining (%) in 1 year
control	$y = 94.287^{e-0.001x}$	0.87	65.45
2-year-old	$y = 92.863^{e-0.001x}$	0.78	64.47
7-year-old	$y = 110.53^{e-0.004x}$	0.94	25.67
11-year-old	$y = 92.608^{e-0.002x}$	0.80	44.63
natural	$y = 99.996^{e-0.002x}$	0.85	48.19

Remaining mass in control, 2, 7, 11-year-old and natural site was calculated as 1.53, 0.37, 1.29, 2.36 and 3.10 t/ha/yr, respectively. In contrast, mass loss in control, 2, 7, 11-year-old and natural site were 0.81, 0.20, 3.73, 2.93 and 3.33 t/ha/yr, respectively (Fig.4.7). And percentage of remaining and loss per year were shown in Fig. 4.8. Percentage of remaining and loss mass in control and the youngest sites were around 65:35. In 11-year-old and natural site were 50:50. But in 7-year-old site, percentage of loss mass was 74.33 while percentage of remaining mass was just 25.67.

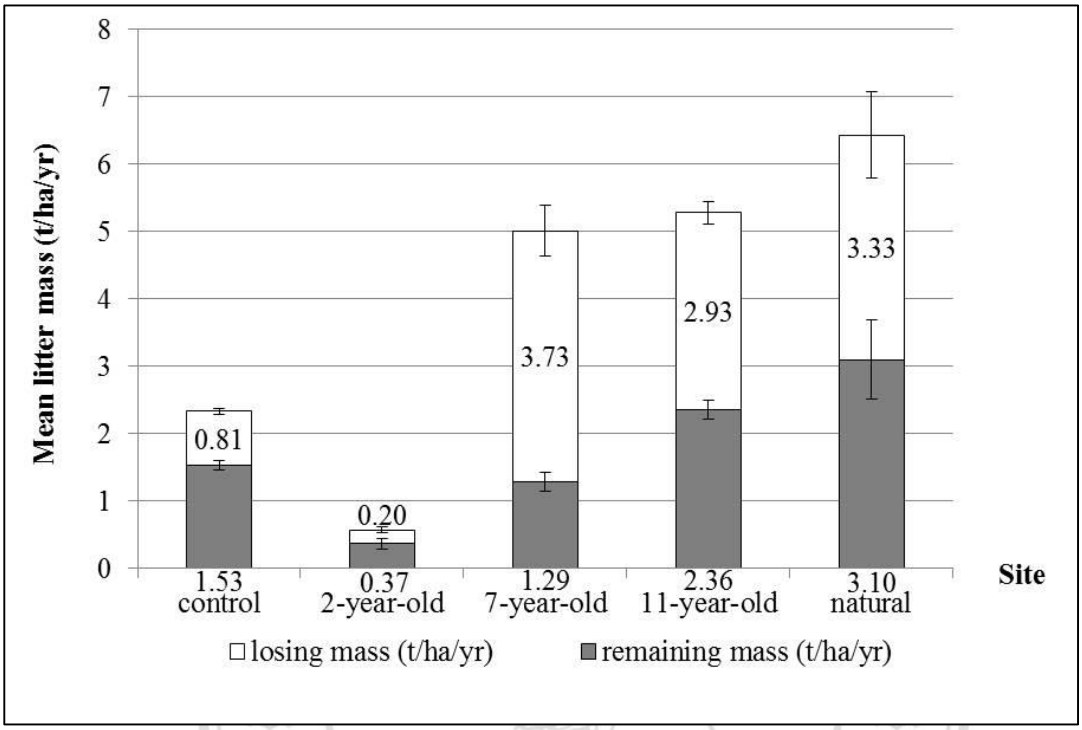


Figure 4.7 Litter mass remaining and loss (t/ha/yr)

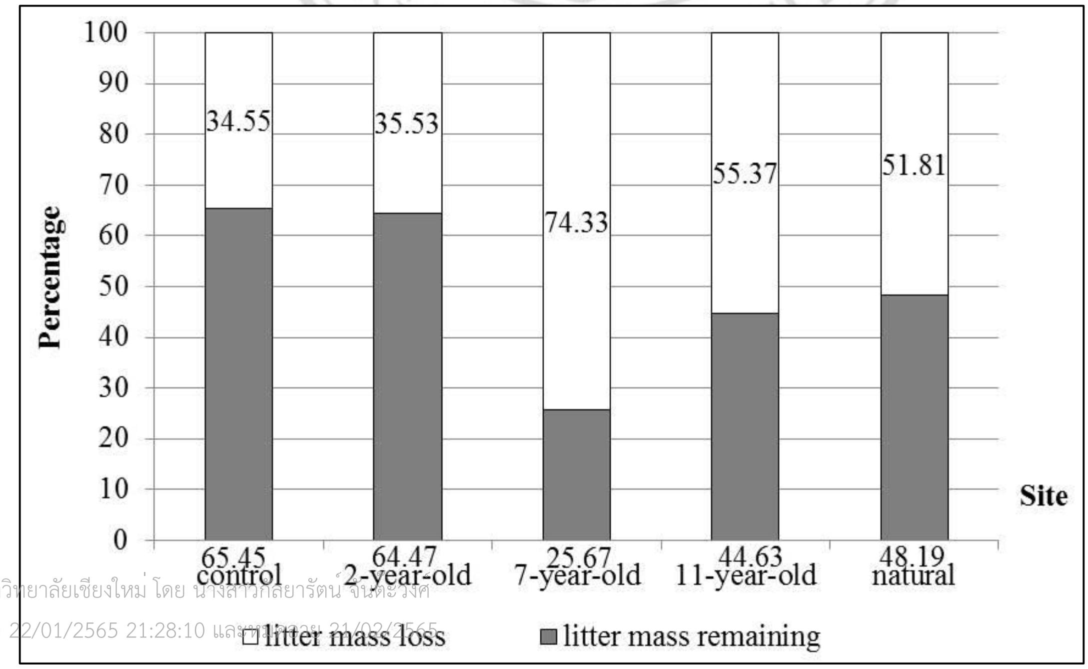


Figure 4.8 Percentage of mass remaining and loss

4.9 Carbon

Carbon content in litter was determined after collected in each period. Duration times were 0, 103, 187 and 286 days. Organic matter was determined and converted to organic carbon using 0.58. Carbon in litter decreased gradually from the beginning period to the last period. Significant differences among period were shown in Table 4.10. Highest carbon in litter of the beginning period was found in natural site next to 11, 2-year-old, control and 7-year-old were 38.72, 35.50, 34.74, 33.29 and 32.97 g/100g, respectively. After 286 days, highest carbon was also found in the natural site compared with 7, 2-year-old, control and 11-year-old site were 30.79, 29.54, 26.25, 25.70 and 25.37 g/100g, respectively.

Table 4.10 Carbon content (%) in litter in different periods

Period / Site	1	2	3	4
	0 day Early rainy (May.11)	103 days Rainy (Aug.11)	187 days Cool (Nov.11)	286 days Cool dry (Feb.12)
control	A 33.29±1.95 **b**	AB 31.79±4.90 **a**	AB 25.89±1.98 **ab**	B 25.37±1.16 **c**
2-year-old	A 34.74±2.13 **ab**	A 32.92±4.18 **a**	B 25.55±1.93 **ab**	B 25.70±0.82 **c**
7-year-old	A 32.97±2.74 **b**	AB 25.52±3.95 **a**	B 22.39±4.02 **b**	AB 29.54±3.27 **ab**
11-year-old	A 35.50±1.50 **ab**	AB 29.97±3.71 **a**	B 26.33±2.16 **ab**	B 26.25±0.38 **bc**
natural	A 38.72±0.39 **a**	AB 35.21±2.92 **a**	B 31.72±3.89 **a**	B 30.79±0.90 **a**

Note: Value are means± SD (n= 12). Means followed by different letters on the same column on the right indicate significant differences at $p < 0.05$ among study sites and different capital letters on the same row on the left indicate significant differences at $P < 0.05$ among periods.

4.10 Carbon remaining (%) in different period

Carbon remaining (%) from period by period was calculated using equation below.

$$\text{Carbon remaining (\%)} = (X_t/X_0) \times (C_t/C_0) \times 100$$

X_0 = initial dry mass of litter
X_t = remaining litter mass after time t
C_0 = initial carbon in litter
C_t = remaining carbon in litter after time t

Percentage of carbon remaining dropped from beginning period around 30 %. In restored forest and control site were not different among period of times ($p < 0.05$) but carbon remaining in natural site was quit fluctuated. After 103 days, carbon remaining was not different among study sites. After 187 days, carbon remaining in natural site was significantly higher than other sites. Highest carbon remaining in 2-year-old site next to control, 11-year-old, natural and 7-year-old site were 68.15, 66.08, 61.66, 51.48 and 40.36 %, respectively after 286 days (Table 4.11). Carbon remaining in different period and trend line was shown in Fig.4.10 and predicted mass remaining in 1 year of control, 2, 7, 11-year-old and natural site using regression equation were 63.46, 43.55, 31.17, 41.26 and 46.22 % , respectively (Table 4.12).

Table 4.11 Carbon remaining (%) in different period

Site \ Period	1	2	3	4
	0 day Early rainy (May.11)	103 days Rainy (Aug.11)	187 days Cool (Nov.11)	286 days Cool dry (Feb.12)
control	100	A 71.19±14.11 **a**	A 64.06±9.88 **b**	A 66.08±22.13 **ab**
2-year-old	100	A 71.24±13.06 **a**	A 55.58±14.72 **b**	A 68.15±21.69 **a**
7-year-old	100	A 61.21±11.10 **a**	A 50.62±16.28 **b**	A 40.36±25.22 **b**
11-year-old	100	A 58.07±17.36 **a**	A 62.93±15.20 **b**	A 61.66±18.46 **ab**
natural	100	B 68.57±11.89 **a**	A 91.29±2.03 **a**	B 51.48±10.78 **ab**

Note: Value are means± SD (n= 12). Means followed by different letters on the same column on the right indicate significant differences at $p < 0.05$ among study sites and different capital letters on the same row on the left indicate significant differences at $p < 0.05$ among periods.

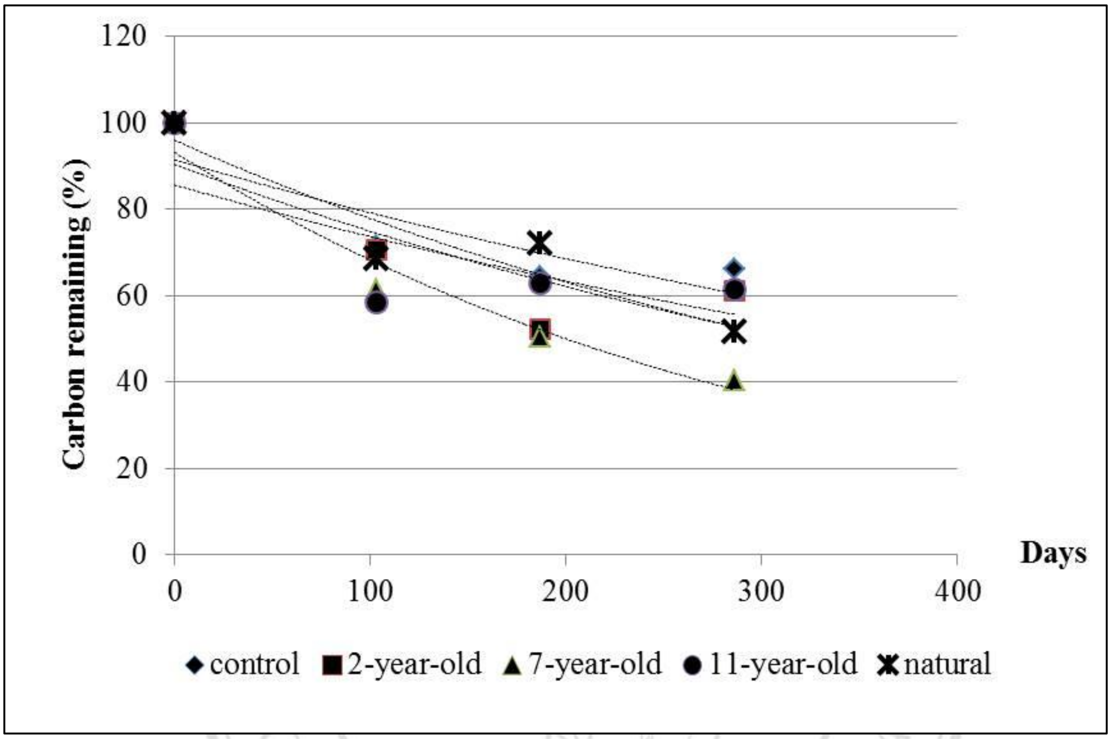


Figure 4.9 Carbon remaining with trend line in different periods

Table 4.12 Regression equation and R^2 of all study sites

site	Equation	R^2	Predicted carbon remaining (%) in 1 year
Control	$y = 91.421e^{-0.001x}$	0.75	63.46
2-year-old	$y = 90.368e^{-0.002x}$	0.68	43.55
7-year-old	$y = 93.18e^{-0.003x}$	0.96	31.17
11-year-old	$y = 85.615e^{-0.002x}$	0.54	41.26
natural	$y = 95.919e^{-0.002x}$	0.86	46.22

4.11 Nitrogen

Nitrogen of mixed litter mass at the different times was determined. At the beginning time, highest of nitrogen was found in 7-year-old next to natural, 11, 2-year-old and control site were 1.67, 1.66, 1.62, 1.30 and 1.24 (g/100g), respectively (Table 4.13). Among period of times, after 103 days nitrogen was decreased from beginning period in 11 and 7-year-old sites. In 2-year-old, control and natural sites nitrogen was not different among periods.

After 103 days, nitrogen in litter was not different among study sites. The negative relationship between nitrogen and duration times (R^2 = 0.90) was found and shown in Fig. 4.10.

Table 4.13 Nitrogen (g/100 g) in litter in different periods

Period	1	2	3	4
Site	0 day Early rainy (May.11)	103 days Rainy (Aug.11)	187 days Cool (Nov.11)	286 days Cool dry (Feb.12)
control	A 1.24±0.11 **c**	A 1.14±0.17 **a**	A 1.03±0.03 **b**	A 1.01±0.03 a
2-year-old	A 1.30±0.14 **bc**	A 1.28±0.32 **a**	A 1.06±0.12 **b**	A 1.05±0.05 a
7-year-old	A 1.67±0.09 **a**	B 1.15±0.19 **a**	B 0.95±0.18 b	B 1.02±0.21 a
11-year-old	A 1.62±0.16 **ab**	B 1.22±0.11 **a**	B 1.03±0.11 b	B 1.04±0.01 a
natural	A 1.66±0.22 **ab**	A1.48±0.23 **a**	A 1.54±0.36 a	A 1.33±0.27 a

Note: Value are means± SD (n= 12). Means followed by different letters on the same column on the right indicate significant differences at *P*<0.05 among study sites and different letters on the same row on the left indicate significant differences at *P*<0.05 among periods.

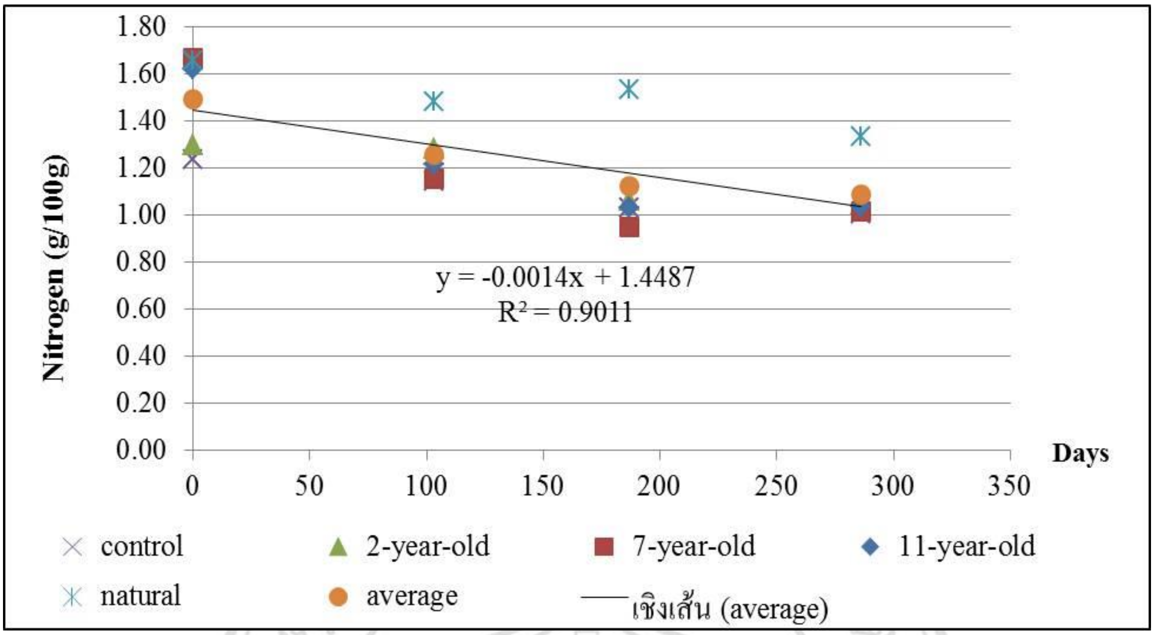


Figure 4.10 Relationship between nitrogen in litter and duration times

4.12 Carbon:Nitrogen

Carbon:nitrogen was determined during period of times. The positive relationship between carbon:nitrogen and duration times ($R^2 = 0.43$). Carbon:nitrogen from the first to the last period ranged from 19.79 – 26.90, 22.10 – 27.80, 20.65 – 25.51 and 23.11 – 29.03, respectively (Table 4.14 and Fig. 4.11).

Table 4.14 Carbon nitrogen ratio in different periods

Period / Site	1	2	3	4
	0 day Early rainy (May.11)	103 days Rainy (Aug.11)	187 days Cool (Nov.11)	286 days Cool dry (Feb.12)
control	26.90	27.80	25.04	25.24
2-year-old	26.72	25.67	24.04	24.50
7-year-old	19.79	22.10	23.55	29.03
11-year-old	21.91	24.64	25.51	25.24
natural	23.35	23.74	20.65	23.11

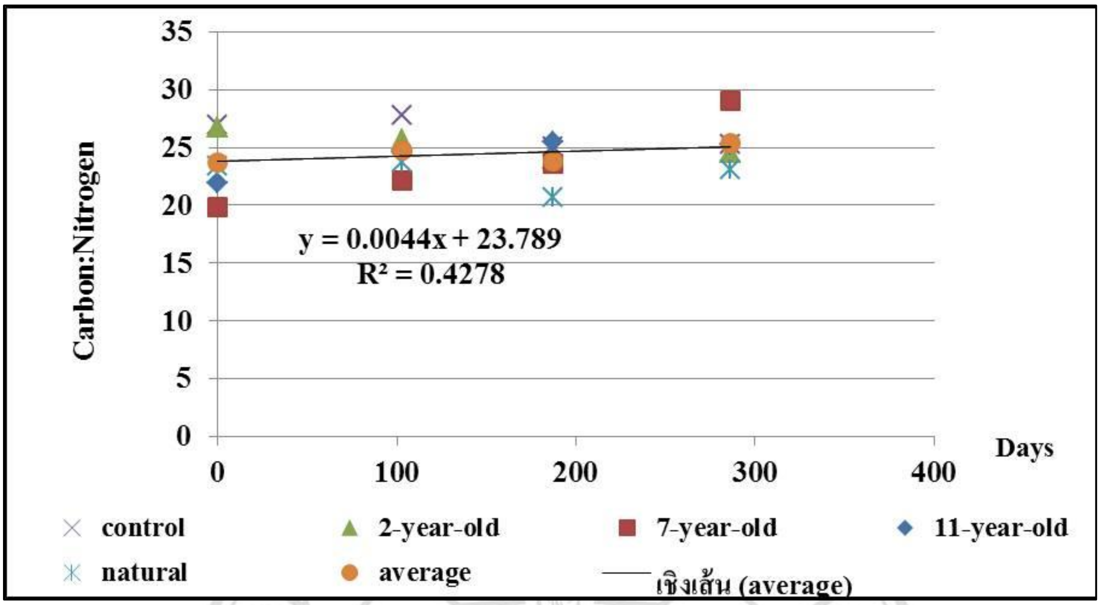


Figure 4.11 The relationship between carbon nitrogen ratio in litter and duration times

4.13 *K* value

K value was calculated. Over 286 days *k* value ranged from 1.08 – 2.85. *K* value in 7-year-old was higher significantly from other sites (Table 4.13).

Table 4.15 *K* value

Site	*k*
control	1.20 ± 0.88 b
2-year-old	1.08 ± 0.78 b
7-year-old	2.85 ± 1.10 a
11-year-old	1.27 ± 0.40 b
natural	1.12 ± 0.29 b

Note: Value are means± SD (n= 12). Means followed by different letters on the same column on the right indicate significant differences at $P<0.05$ among study sites.

4.14 Soil profiles

Soil profile of each study site was dig from top soil down to 200 cm in depth. Topography of study site was recorded (Table 4.16). Each layer of soil was collected and analyzed (Fig. 4.12). Then the results from laboratory comprised with observed data using for described soil profile descriptions. Soil classification of each soil profile was determined using soil taxonomy USDA 11th edition, 2010 and also shown in Table 4.17.

Table 4.16 Summary of study site topography

Pedon	site	Elevation (m.asl.)	Slope (%)	Slope aspect	GPS
1	control	1,332	10	ESE 99^0	N18^0 51’ 410” E098^0 50’ 881”
2	2-year-old	1,311	16	ENE 60^0	N18^0 51’ 410” E098^0 50’ 931”
3	7-year-old	1,228	22	ENE 86^0	N18^0 51’ 569” E098^0 50’ 968”
4	11-year-old	1,332	9	NNW 352^0	N18^0 51’ 410” E098^0 50’ 881”
5	natural	1,288	14	WSW 266^0	N18^0 51’ 893” E098^0 51’ 717”

Table 4.17 Soil classification

Pedon	Site	Order	Suborder	Great group	Sub group	Soil family
1	control	Ultisols	Ustults	Haplustults	Typic Haplustults	Fine loamy
2	2-year-old	Ultisols	Ustults	Haplustults	Typic Haplustults	Fine
3	7-year-old	Ultisols	Ustults	Haplustults	Typic Haplustults	Fine loamy
4	11-year-old	Ultisols	Ustults	Haplustults	Typic Haplustults	Fine loamy
5	natural	Ultisols	Ustults	Haplustults	Typic Haplustults	Fine

Control **2-year-old** **7-year-old** **11-year-old** **Natural**

Figure 4.12 Soil profiles of each study site

4.14.1 Soil physical properties

4.14.1.1 Bulk density

Soil bulk density increased with depth but not significantly different among study sites. Soil bulk density from 0 – 200 cm. in depth in pedon 1 - 5 (control, 2, 7. 11-year-old and natural sites) were 0.78 – 1.12, 0.68 – 1.07, 0.75 – 1.14, 0.78 – 1.12 and 0.62 – 1.06 g/cm^3, respectively. According to appendix C, soil bulk density among study sites were low (< 1.2 g/cm^3) (Tables 4.18a-b).

4.14.1.2 Soil texture

In all study sites, the pattern of percentage of sand, silt and sand seem to be similar. Percentage of sand tended to be decreased followed by soil depth in pedon 1 – 5. Percentage of silt was quite constantly. In pedon 1 – 4, percentage of silt was around 20 % but in pedon 5 (natural site) was around 15 %. Clay percentage of pedon 1 (control site) was quit constant around 25 % (Tables 4.18a-b and Fig. 4.13).

Table 4 .18a Soil physical properties

Soil depth (cm)	Bulk density (g/cm^3)	Sand (%)	Silt (%)	Clay (%)	Texture	Texture class
Pedon 1 (control site)						
0-5	0.78	53.6	23.9	22.5	Sandy clay loam	Moderately fine-textured
5--10	0.85	51.8	22.3	25.9	Sandy clay loam	
10--20	0.90	49.2	24	26.8	Sandy clay loam	
20-30	0.90	46.7	26.5	26.8	Sandy clay loam	
30-40	0.95	44.1	26.6	29.3	Clay loam	
40-60	0.92	46.7	25.7	27.6	Sandy clay loam	
60-80	0.91	43.4	27.3	29.3	Clay loam	
80-100	1.15	39	28.2	32.8	Clay loam	
100-150	1.12	39	30.8	30.2	Clay loam	
150-200	1.12	46.7	29.1	24.2	Loam	Medium-textured
Pedon 2 (2-year-old site)						
0-5	0.68	51.8	19.8	28.4	Sandy clay loam	Moderately fine-textured
5-10	0.79	39	21.5	39.5	Clay loam	
10-20	0.76	39	21.5	39.5	Clay loam	
20-30	0.82	33.9	23.1	43	Clay	Fine-textured
30-40	0.92	31.4	24	44.6	Clay	
40-60	1.12	31.4	24	44.6	Clay	
60-80	1.14	33.9	23.1	43	Clay	
80-100	1.12	31.4	28.1	40.5	Clay	
100-150	1.21	31.4	28.1	40.5	Clay	
150-200	1.07	28.8	32.4	38.8	Clay loam	Moderately fine-textured

Table 4.18b Soil physical properties

Soil depth (cm)	Bulk density (g/cm^3)	Sand (%)	Silt (%)	Clay (%)	Texture	Texture class
			Pedon 3 (7-year-old site)			
0-5	0.75	56.9	30	13.1	Sandy loam	Moderately coarse-textured
5-10	0.81	56.2	30.7	13.1	Sandy loam	
10-20	0.82	58.8	28.9	12.3	Sandy loam	
20-30	0.89	64	26.2	9.8	Sandy loam	
30-40	0.85	44.1	27.5	28.4	Clay loam	Moderately fine-textured
40-60	0.94	55.7	13.4	30.9	Sandy clay loam	
60-80	0.98	43.2	24.2	32.6	Clay loam	
80-100	0.96	41.6	23.3	35.1	Clay loam	
100-150	0.92	39	23.3	37.7	Clay loam	
150-200	1.14	40.6	21.7	37.7	Clay loam	
			Pedon 4 (11-year-old site)			
0-5	0.78	64.4	23.2	12.4	Sandy loam	Moderately coarse-textured
5-10	0.83	69	18.6	12.4	Sandy loam	
10-20	0.81	69	18.6	12.4	Sandy loam	
20-30	0.85	64.4	20.7	14.9	Sandy loam	
30-40	0.82	49.1	24.1	26.8	Sandy clay loam	Moderately fine-textured
40-60	0.93	46.6	23.3	30.1	Sandy clay loam	
60-80	1.02	44	23.3	32.7	Clay loam	
80-100	1.04	44	23.3	32.7	Clay loam	
100-150	1.09	44	23.3	32.7	Clay loam	
150-200	1.12	41.6	18.2	40.2	Clay	Fine-textured
			Pedon 5 (natural site)			
0-5	0.62	56.9	20.6	22.5	Sandy clay loam	Moderately fine-textured
5--10	0.63	56.9	19.7	23.4	Sandy clay loam	
10--20	0.80	51.8	15.6	32.6	Sandy clay loam	
20-30	0.90	51.8	15.6	32.6	Sandy clay loam	
30-40	0.85	46.7	15.6	37.7	Sandy clay	Fine-textured
40-60	0.90	44.1	13.2	42.7	Clay	
60-80	0.98	41.6	14.1	44.3	Clay	
80-100	0.93	44.1	10.6	45.3	Clay	
100-150	0.97	44.1	13.2	42.7	Clay	
150-200	1.06	41.6	13.1	45.3	Clay	

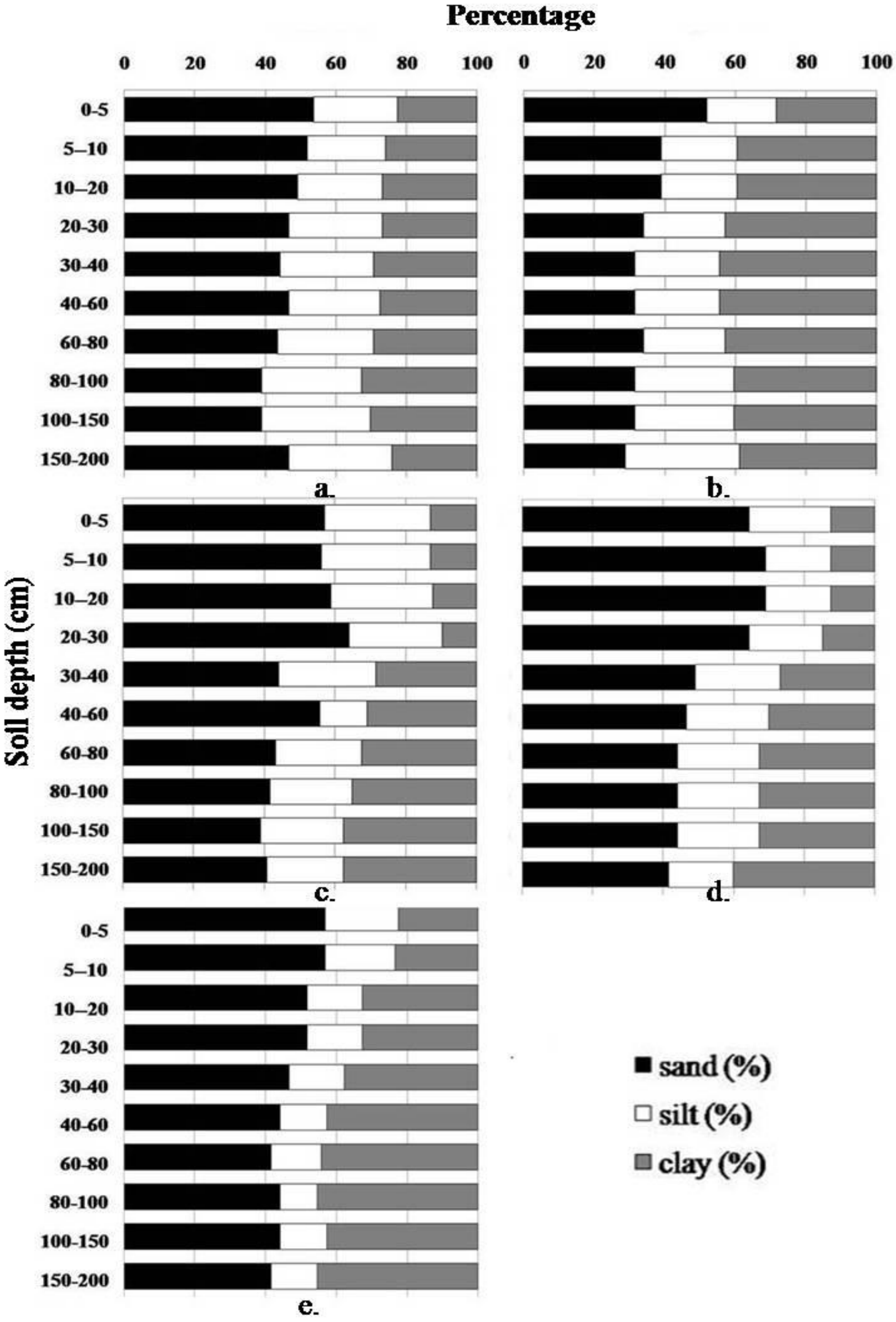


Figure 4.13 Soil texture

4.14.2 Soil chemical properties

4.14.2.1 Soil pH

According to appendix C, soil in pedon 1 (control site) and pedon 2 (2-year-old site) were very strongly acid (4.5 – 5.0). Upper soil in pedon 3 (7 – year-old site) (0- 30 cm.) was strongly acid (5.4 – 5.7) while lower than 30 cm. was very strongly acid (5.4 – 5.7). Soil pH in pedon 4 (11- year-old site) was very extremely acid (4.8 - 5.3) whereas in pedon 5 (natural site) was ranged from extremely acid to very strongly acid (Tables 4.19a –b).

4.14.2.2 OM, N, P and K

OM, N, P and K decreased with depth. According appendix C, OM of top soil (first 5cm. in depth) in all study sites was low, but in pedon 5 (natural site) was moderately low. Nitrogen in 0 – 30 cm. soil depth in old-restored plot: pedon 3 and pedon 4 (7 and 11 year-old) and pedon 5 (natural forest) were medium rate (2.0 – 5.0 g/kg). Phosphorus in first 5 cm. was indicate high in pedon 4 (32.33 g/kg), moderately high in pedon 3 (21.81 g/kg), medium in pedon 2 (13.84 g/kg), moderately low in pedon 1 (9.99 g/kg) and low in pedon 5 (4.82 g/kg) (Tables 4.19a-b).

.

Table 4.19a Soil chemical properties

Soil depth (cm)	pH 1:1	OM g/100g	OC g/100g	TotalN g/100g	P (mg/kg)	K (mg/kg)
Pedon 1 (control site)						
0-5	5.01	10.08	5.85	0.39	9.99	180.81
5-10	4.79	7.16	4.15	0.26	6.31	114.19
10-20	4.44	5.03	2.92	0.19	1.23	75.34
20-30	4.39	4.39	2.55	0.16	0.88	64.23
30-40	4.38	2.76	1.60	0.11	0.53	64.23
40-60	4.61	2.76	1.60	0.11	0.26	47.58
60-80	4.89	1.88	1.09	0.09	0.45	58.68
80-100	4.82	0.74	0.43	0.03	0.18	25.38
100-150	4.78	0.6	0.35	0.02	0.27	19.83
150-200	4.81	0.47	0.27	0.02	0.36	5.13
Pedon 2 (2-year-old site)						
0-5	4.76	6.86	3.98	0.28	13.84	286.28
5-10	4.7	5.83	3.38	0.24	3.68	164.15
10-20	4.79	5.26	3.05	0.21	2.28	103.09
20-30	4.56	3.58	2.08	0.14	0.26	47.58
30-40	4.53	2.53	1.47	0.10	0.26	42.03
40-60	4.53	1.86	1.08	0.07	0.26	19.83
60-80	4.58	1.41	0.82	0.05	0.09	13.96
80-100	4.6	0.93	0.54	0.03	0.91	3.17
100-150	4.52	0.87	0.50	0.02	0.27	8.72
150-200	4.8	0.7	0.41	0.02	0.55	3.17
Pedon 3 (7-year-old site)						
0-5	5.75	7.71	4.47	0.38	21.81	397.3
5-10	5.41	6.75	3.92	0.34	15.59	291.83
10-20	5.44	6.18	3.58	0.31	17.61	208.56
20-30	5.49	5.51	3.20	0.27	8.59	108.64
30-40	5.3	3.47	2.01	0.16	1.93	80.89
40-60	5.01	3.09	1.79	0.14	1.58	108.64
60-80	4.85	2.5	1.45	0.11	0.96	108.64
80-100	4.88	1.99	1.15	0.08	0.79	103.09
100-150	4.97	1.56	0.90	0.10	1.18	136.40
150-200	4.96	1.4	0.81	0.01	0.55	30.93

Table 4.19b Soil chemical properties

Soil depth (cm)	pH 1:1	OM g/100g	OC g/100g	TotalN g/100g	P (mg/kg)	K (mg/kg)
			Pedon 4 (11-year-old site)			
0-5	4.65	8.97	5.20	0.37	32.33	180.81
5-10	5.12	7.71	4.47	0.31	47.83	97.54
10-20	4.42	7.12	4.13	0.28	24.18	80.89
20-30	5.4	5.62	3.26	0.24	5.61	91.99
30-40	4.45	4.69	2.72	0.17	2.98	42.03
40-60	4.31	3.12	1.81	0.08	1.4	30.93
60-80	4.31	2.35	1.36	0.08	1.14	36.48
80-100	4.41	1.16	0.67	0.05	0.09	36.48
100-150	4.95	0.86	0.50	0.04	0.7	8.72
150-200	5.24	0.69	0.40	0.02	0.55	8.72
			Pedon 5 (natural site)			
0-5	4.52	11.59	6.72	0.42	4.82	158.6
5-10	4.52	9.91	5.75	0.39	4.12	75.34
10-20	4.46	6.99	4.05	0.27	1.84	42.03
20-30	6.79	5.55	3.22	0.36	15.68	119.74
30-40	4.49	3.27	1.90	0.11	0.79	42.03
40-60	4.38	2.13	1.24	0.10	0.26	14.27
60-80	4.36	1.48	0.86	0.06	0.82	14.27
80-100	4.64	1.09	0.63	0.04	0.55	19.83
100-150	4.56	0.78	0.45	0.04	0.45	3.17
150-200	4.67	0.73	0.42	0.02	0.36	3.17

4.14.2.3 CEC and percentage base saturation

According to Appendix C, CEC of first 5 cm. depth of soil in pedon 1, 2, 4 and 5 were moderately high (15 – 20 cmol+/kg) while in pedon 3 was high. Base saturation (%) in the same depth of pedon 1, 4 and 5 were low (< 35 %) but in pedon 2 and 3 were medium (35 – 75%) (Tables 4.20a – b).

Table 4.20a CEC and percentage base saturation

Soil depth (cm)	K (cmol+/kg)	Ca (cmol+/kg)	Mg (cmol+/kg)	Na (cmol+/kg)	Sum of base (cmol+/kg)	CEC (cmol+/kg)	Base saturation (%)
				Pedon 1 (control site)			
0-5	0.46	3.00	0.93	0.06	4.45	15.49	28.70
5-10	0.29	0.52	0.24	0.06	1.11	12.73	8.72
10-20	0.19	0.00	0.05	0.09	0.34	9.87	3.42
20-30	0.16	0.03	0.02	0.11	0.32	8.81	3.69
30-40	0.16	0.07	0.02	0.08	0.33	7.22	4.57
40-60	0.12	0.18	0.10	0.14	0.54	6.79	7.96
60-80	0.15	0.58	0.23	0.07	1.02	5.09	20.12
80-100	0.07	0.08	0.08	0.08	0.30	2.97	10.10
100-150	0.05	0.20	0.07	0.04	0.36	2.23	16.30
150-200	0.01	0.11	0.15	0.17	0.45	2.55	17.69
				Pedon 2 (2-year-old site)			
0-5	0.73	3.63	1.12	0.06	5.55	15.49	35.81
5-10	0.42	0.43	0.14	0.24	1.22	13.27	9.21
10-20	0.26	2.57	0.11	0.07	3.02	12.84	23.51
20-30	0.12	0.49	0.04	0.08	0.73	11.35	6.46
30-40	0.11	0.19	0.02	0.05	0.36	5.94	6.12
40-60	0.05	0.25	0.02	0.11	0.43	6.05	7.06
60-80	0.04	0.09	0.03	0.10	0.25	4.88	5.20
80-100	0.01	0.12	0.07	0.06	0.26	3.93	6.50
100-150	0.02	0.14	0.10	0.08	0.34	3.93	8.71
150-200	0.01	0.09	0.09	0.06	0.24	5.09	4.67
				Pedon 3 (7-year-old site)			
0-5	1.02	9.74	3.32	0.08	14.16	20.59	68.76
5-10	0.75	6.28	1.97	0.07	9.07	18.78	48.30
10-20	0.53	5.19	0.73	0.07	6.52	17.40	37.48
20-30	0.28	4.62	0.85	0.08	5.84	16.34	35.74
30-40	0.21	2.06	0.68	0.03	2.98	11.57	25.73
40-60	0.28	0.97	0.51	0.07	1.83	10.40	17.62
60-80	0.28	0.63	0.48	0.05	1.44	9.02	15.96
80-100	0.26	0.68	0.64	0.07	1.65	8.17	20.18
100-150	0.35	0.40	0.50	0.10	1.34	6.15	21.78
150-200	0.08	0.21	0.41	0.15	0.84	4.56	18.40

Table 4.20b CEC and percentage base saturation

Soil depth (cm)	K (cmol+/kg)	Ca (cmol+/kg)	Mg (cmol+/kg)	Na cmol+/kg	Sum of base (cmol+/kg)	CEC cmol+/kg	Base saturation (%)
Pedon 4 (11-year-old site)							
0-5	0.46	2.58	0.62	0.08	3.75	19.74	19.00
5-10	0.25	0.49	0.15	0.09	0.98	16.13	6.06
10-20	0.21	0.20	0.06	0.09	0.56	14.33	3.90
20-30	0.24	0.06	0.04	0.02	0.36	13.80	2.58
30-40	0.11	0.04	0.02	0.09	0.26	13.80	1.89
40-60	0.08	0.00	0.01	0.12	0.21	11.57	1.82
60-80	0.09	0.15	0.02	0.07	0.34	8.70	3.85
80-100	0.09	0.22	0.01	0.07	0.40	7.43	5.38
100-150	0.02	0.28	0.06	0.08	0.43	4.88	8.86
150-200	0.02	0.06	0.05	0.07	0.21	3.29	6.28
Pedon 5 (natural site)							
0-5	0.41	0.89	0.45	0.07	1.82	16.77	10.83
5-10	0.19	0.04	0.07	0.10	0.41	14.64	2.78
10-20	0.11	0.06	0.04	0.09	0.30	10.82	2.76
20-30	0.31	0.04	0.07	0.29	0.70	9.34	7.45
30-40	0.11	0.03	0.01	0.06	0.21	7.22	2.92
40-60	0.04	0.01	0.03	0.11	0.18	5.52	3.35
60-80	0.04	0.01	0.02	0.06	0.12	4.03	3.06
80-100	0.05	0.01	0.01	0.11	0.18	3.82	4.69
100-150	0.01	0.00	0.01	0.07	0.09	2.55	3.48
150-200	0.01	0.01	0.01	0.07	0.10	1.91	5.33

14.14.3 Soil fertility

Score of each parameter were defined and sum of them were used for estimating soil fertility level according to Appendix C. The first 30 cm in depth of soil in pedon 1, 2 and 5 were indicated as medium fertility and lower than 30 cm in depth was indicated as low fertility. In pedon 3, first 5 cm in depth was high, while 5 – 100 cm in depth was medium and lower than that was low (Tables 4.21a-b).

Table 4.21a Soil fertility

Soil depth (cm)	O.M. (g/kg)	P (mg/kg)	K (mg/kg)	CEC (cmol+/kg)	Base saturation (%)	Score	Fertility level
Pedon 1 (control site)							
0-5	100.80 (3)	9.99 (1)	180.81 (3)	15.49 (2)	28.70 (1)	10	medium
5-10	71.60(3)	6.31 (1)	114.19 (3)	12.73(2)	8.72(1)	10	medium
10-20	50.30(3)	1.23 (1)	75.34 (2)	9.87(1)	3.42(1)	8	medium
20-30	43.90(3)	0.88 (1)	64.23 (2)	8.81(1)	3.69(1)	8	medium
30-40	27.60 (2)	0.53 (1)	64.23 (2)	7.22(1)	4.57(1)	7	low
40-60	27.60 (2)	0.26 (1)	47.58 (1)	6.79(1)	7.96(1)	6	low
60-80	18.80 (2)	0.45 (1)	58.68 (1)	5.09(1)	20.12(1)	6	low
80-100	7.40 (1)	0.18 (1)	25.38 (1)	2.97(1)	10.10(1)	5	low
100-150	6.00 (1)	0.27 (1)	19.83 (1)	2.23(1)	16.30(1)	5	low
150-200	4.70 (1)	0.36 (1)	5.13 (1)	2.55(1)	17.69(1)	5	low
Pedon 2 (2-year-old site)							
0-5	68.60 (3)	13.84 (2)	286.28 (3)	15.49 (2)	35.81 (2)	12	medium
5-10	58.30 (3)	3.68 (1)	164.15(3)	13.27(2)	9.21(1)	10	medium
10-20	52.60 (3)	2.28 (1)	103.09(3)	12.84(2)	23.51(1)	10	medium
20-30	35.80 (3)	0.26 (1)	47.58 (2)	11.35(2)	6.46(1)	9	medium
30-40	25.30 (2)	0.26 (1)	42.03(2)	5.94 (1)	6.12(1)	7	low
40-60	18.60 (2)	0.26 (1)	19.83 (1)	6.05(1)	7.06(1)	6	low
60-80	14.10 (1)	0.09 (1)	13.96(1)	4.88(1)	5.20(1)	5	low
80-100	9.30 (1)	0.91 (1)	3.17(1)	3.93(1)	6.50(1)	5	low
100-150	8.70 (1)	0.27 (1)	8.72(1)	3.93(1)	8.71(1)	5	low
150-200	7.00 (1)	0.55 (1)	3.17(1)	5.09(1)	4.67(1)	5	low
Pedon 3 (7-year-old site)							
0-5	77.10 (3)	21.81 (2)	397.30 (3)	20.59 (3)	68.76 (2)	13	high
5-10	67.50 (3)	15.59 (2)	291.83 (3)	18.78(2)	48.30(2)	12	medium
10--20	61.80 (3)	17.61 (2)	208.56 (3)	17.40(2)	37.48(2)	12	medium
20-30	55.10 (3)	8.59 (1)	108.64 (3)	16.34(2)	35.74(2)	11	medium
30-40	34.70 (2)	1.93 (1)	80.89 (2)	11.57(2)	25.73(1)	8	medium
40-60	30.90 (2)	1.58 (1)	108.64 (3)	10.40(2)	17.62(1)	9	medium
60-80	25.00 (2)	0.96 (1)	108.64 (3)	9.02 (1)	15.96(1)	8	medium
80-100	19.90 (2)	0.79 (1)	103.09 (3)	8.17(1)	20.18(1)	8	medium
100-150	15.60 (2)	1.18 (1)	136.40 (3)	6.15 (1)	21.78(1)	8	medium
150-200	14.00 (1)	0.55 (1)	30.93 (1)	4.56(1)	18.40(1)	5	low

Table 4.21b Soil fertility

Soil depth (cm)	O.M. (g/kg)	P (mg/kg)	K (mg/kg)	CEC (cmol+/kg)	Base saturation (%)	Score	Fertility level
Pedon 4 (11-year-old site)							
0-5	89.70 (3)	32.33 (3)	180.81 (3)	19.74 (2)	19.00(1)	12	medium
5-10	77.10 (3)	47.83(3)	97.54 (3)	16.13(2)	6.06(1)	12	medium
10-20	71.20 (3)	24.18 (2)	80.89 (2)	14.33(2)	3.90(1)	10	medium
20-30	56.20 (3)	5.61 (1)	91.99 (3)	13.80(2)	2.58(1)	10	medium
30-40	46.90 (3)	2.98 (1)	42.03 (1)	13.80(2)	1.89(1)	8	medium
40-60	31.20 (2)	1.40 (1)	30.93 (1)	11.57(2)	1.82(1)	7	low
60-80	23.50 (2)	1.14 (1)	36.48 (1)	8.70 (1)	3.85(1)	7	low
80-100	11.60 (1)	0.09 (1)	36.48 (1)	7.43(1)	5.38(1)	5	low
100-150	8.60 (1)	0.70 (1)	8.72 (1)	4.88(1)	8.86(1)	5	low
150-200	6.90 (1)	0.55 (1)	8.72 (1)	3.29(1)	6.28(1)	5	low
Pedon 5 (natural site)							
0-5	115.9 (3)	4.82 (1)	158.6 (3)	16.77 (2)	10.83 (1)	10	medium
5-10	99.1 (3)	4.12 (1)	75.34 (2)	14.64 (2)	2.78 (1)	9	medium
10-20	69.9 (3)	1.84 (1)	42.03 (1)	10.82 (2)	2.76 (1)	8	medium
20-30	55.5 (3)	15.68 (2)	119.74 (3)	9.34 (1)	7.45 (1)	10	medium
30-40	32.7 (2)	0.79 (1)	42.03 (1)	7.22 (1)	2.92 (1)	6	low
40-60	21.3 (2)	0.26 (1)	14.27 (1)	5.52 (1)	3.35 (1)	6	low
60-80	14.8 (1)	0.82 (1)	14.27 (1)	4.03 (1)	3.06 (1)	5	low
80-100	10.9 (1)	0.55 (1)	19.83 (1)	3.82 (1)	4.69 (1)	5	low
100-150	7.8 (1)	0.45 (1)	3.17 (1)	2.55 (1)	3.48 (1)	5	low
150-200	7.3 (1)	0.36 (1)	3.17 (1)	1.91 (1)	5.33 (1)	5	low

4.15 Soil sampling using soil auger

4 soil pits from each study site was conducted in July 2012. Each soil layer: 0-5, 5-10, 10-20, 20-30, 30-40, 40-60, 60-80, 80-100, 100-150 and 150 -200 cm in depth were collected soil auger. Soil samples from 4 points were mixed and sub-sampled into 3 replicates. Soil chemical parameters: pH, N, P, K, CEC and organic matter were analyzed.

4.15.1 Soil pH

Soil pH in each site from different soil depths (0 -200 cm) were determined. The differences among study sites in the same depth was investigated and shown in Table 4.22. Soil pH of 11-year-old site from 0 – 100 cm in depth tended to be lower than other sites and pH ranged from 3.97 – 4.93. In contrast, 0- 20 cm in depth pH in 7-year-old was higher than other sites significantly. Below 60 cm, pH in control site was significantly higher other sites (Table 4.22).

Table 4.22 Soil pH in different soil depth from 0 – 200 cm in all study sites

Soil depth (cm)	control	2-year-old	7-year-old	11-year-old	natural
0-5	4.79±0.02 **c**	4.96±0.03 **b**	5.16 ±0.03 **a**	4.53 ±0.03 **d**	4.50±0.06 **d**
5-10	4.55±0.15 **b**	4.68±0.03 **b**	4.99±0.02 **a**	4.03±0.02 **c**	4.53±0.03 **b**
10-20	4.57±0.03 **b**	4.54±0.01 **b**	4.74±0.03 **a**	4.17±0.10 **c**	4.31±0.05 **c**
20-30	4.43±0.01 **ab**	4.49±0.01 **a**	4.48±0.02 **a**	4.14±0.05 **c**	4.37±0.03 **b**
30-40	4.43±0.05 **a**	4.41±0.02 **a**	4.35±0.01 **a**	4.04±0.04 **b**	4.41±0.00 **a**
40-60	4.38±0.02 **b**	4.44±0.02 **ab**	4.44±0.02 **a**	3.97±0.03 **c**	4.41±0.02 **ab**
60-80	4.62±0.03 **a**	4.48±0.02 **c**	4.55±0.02 **b**	3.97±0.01 **d**	4.54±0.03 **b**
80-100	4.91±0.06 **a**	4.51±0.03 **c**	4.61±0.02 **b**	4.07±0.02 **d**	4.61±0.01 **b**
100-150	5.03±0.07 **a**	4.47±0.05 **d**	4.63±0.04 **bc**	4.52±0.06 **cd**	4.67±0.03 **b**
150-200	5.17±0.16 **a**	4.63±0.01 **a**	4.74±0.03 **a**	4.68±0.03 **a**	5.72±1.74 **a**

Note: Value are means± SD (n= 3). Means followed by different letters on the same row on the right indicate significant differences at *P*<0.05 among study sites.

4.15.2 Soil nitrogen (N)

In natural forest site, soil nitrogen (N) in 0 – 10 cm in depth was higher than other sites significantly (Table 4.23). Below 20 until 200 cm in depth, in 7-year-old site was highly significant than other sites. In all study sites, nitrogen was decreased with soil depth.

Table 4.23 Soil N (g/100g) in different soil depth from 0 – 200 cm in all study sites

Soil depth (cm)	control	2-year-old	7-year-old	11-year-old	natural
0-5	0.358±0.073 **b**	0.281±0.003 **b**	0.309±0.019 **b**	0.347 ±0.018 **b**	0.499±0.031 **a**
5-10	0.222±0.005 **c**	0.225±0.005 **c**	0.263±0.006 **b**	0.217±0.008 **c**	0.382±0.011 **a**
10-20	0.182±0.011 **b**	0.165±0.009 **b**	0.230±0.010 **a**	0.175±0.012 **b**	0.240±0.018 **a**
20-30	0.128±0.003 **b**	0.132±0.006 **b**	0.176±0.012 **a**	0.116±0.010 **b**	0.159±0.015 **a**
30-40	0.118±0.005 **bc**	0.084±0.006 **d**	0.148±0.006 **a**	0.104±0.007 **c**	0.127±0.015 **b**
40-60	0.073±0.010 **bc**	0.056±0.010 **c**	0.124±0.007 **a**	0.073±0.003 **bc**	0.082±0.003 **b**
60-80	0.042±0.005 **c**	0.029±0.003 **d**	0.108±0.008 **a**	0.053±0.003 **bc**	0.055±0.003 **b**
80-100	0.019±0.008 **c**	0.023±0.002 **bc**	0.100±0.022 **a**	0.030±0.002 **bc**	0.048±0.002 **b**
100-150	0.023±0.004 **c**	0.010±0.002 **c**	0.076±0.009 **a**	0.022±0.002 **c**	0.036±0.006 **b**
150-200	0.018±0.002 **c**	0.011±0.001 **d**	0.060±0.001 **a**	0.018±0.002 **c**	0.030±0.001 **b**

Note: Value are means± SD (n= 3). Means followed by different letters on the same row on the right indicate significant differences at *P*<0.05 among study sites.

4.15.3 Soil phosphorus (P)

Soil phosphorus was tended to decrease with soil depth. The first 10 cm in depth, soil phosphorus in 11-year-old site was higher than others. Below 80 cm in depth, soil phosphorus in 7 year-old site was higher than other sites significantly (Table 4.24).

Table 4.24 Soil phosphorus (mg/kg) in 0 – 200 cm in all study sites

Soil depth (cm)	control	2-year-old	7-year-old	11-year-old	natural
0-5	8.03±0.18 **bc**	13.32±0.61 **b**	32.25±7.86 **a**	31.60±2.64 **a**	4.92±0.46 **c**
5-10	4.15±0.60 **c**	7.74±0.91 **c**	26.99±2.24 **b**	40.57±5.29 **a**	2.60±0.00 **c**
10-20	1.61±0.48 **c**	3.91±1.13 **c**	16.88±2.74 **a**	10.23±2.54 **b**	1.30±0.20 **c**
20-30	1.23±0.38 **c**	2.04±0.56 **bc**	6.46±0.34 **a**	3.13±1.28 **b**	0.87±0.06 **c**
30-40	1.06±0.06 **a**	0.91±0.13 **a**	5.71±4.28 **a**	1.71±0.39 **a**	0.73±0.21 **a**
40-60	0.87±0.15 **b**	0.73±0.27 **b**	2.84±0.31 **a**	2.32±0.42 **a**	0.47±0.15 **b**
60-80	0.67±0.06 **b**	0.58±0.18 **b**	2.47±0.49 **a**	1.26±0.19 **b**	0.63±0.06 **b**
80-100	0.67±0.35 **bc**	0.41±0.18 **c**	1.90±0.31 **a**	1.13±0.15 **b**	0.47±0.06 **c**
100-150	0.13±0.06 **b**	0.41±0.13 **ab**	0.82±0.35 **a**	0.61±0.15 **ab**	0.47±0.15 **ab**
150-200	0.10±0.00 **c**	0.53±0.15 **ab**	0.58±0.10 **a**	0.26±0.20 **bc**	0.43±0.06 **ab**

Note: Value are means± SD (n= 3). Means followed by different letters on the same row on the right indicate significant differences at *P*<0.05 among study sites

4.15.4 Potassium (K)

Soil potassium of all sites was tended to decrease with soil depth. In the first 10 cm was high in 7-year-old and 2-year-old sites. Below 10 cm, soil potassium in 7-year-old site was higher than other sites significantly (Table 4.25).

Table 4.25 Soil potassium (mg/kg) in 0 – 200 cm in all study sites

Soil depth (cm)	control	2-year-old	7-year-old	11-year-old	natural
0-5	170.10±11.63 **b**	247.27±10.37 **a**	245.80±4.45 **a**	159.46±0.97 **bc**	140.97±7.41 **c**
5-10	110.69±9.79 **b**	158.93±24.29 **a**	175.16±11.03 **a**	82.09±8.63 **b**	98.61±10.09 **b**
10-20	96.53±5.83 **b**	91.90±7.51 **b**	139.12±10.14 **a**	77.05±15.26 **b**	67.23±13.06 **b**
20-30	55.34±0.88 **c**	90.89±10.14 **b**	115.77±9.99 **a**	42.29±6.73 **c**	48.41±11.13 **c**
30-40	56.93±8.30 **ab**	54.33±6.87 **b**	103.07±7.51 **a**	33.81±1.79 **b**	66.71±36.77 **ab**
40-60	72.99±13.06 **b**	41.13±6.64 **c**	106.63±18.72 **a**	23.36±1.76 **c**	34.29±3.27 **c**
60-80	24.88±9.19 **b**	34.53±32.33 **b**	96.47±14.07 **a**	22.56±5.03 **b**	28.54±1.57 **b**
80-100	32.20±8.92 **b**	14.22±4.65 **c**	76.67±4.90 **a**	13.70±1.68 **c**	25.92±2.40 **bc**
100-150	11.86±0.88 **b**	12.19±5.49 **b**	39.60±4.03 **a**	17.62±1.94 **b**	12.85±4.15 **b**
150-200	6.29±0.00 **c**	11.74±3.85 **bc**	21.33±4.03 **a**	16.50±0.97 **ab**	11.28±3.14 **bc**

Note: Value are means± SD (n= 3). Means followed by different letters on the same row on the right indicate significant differences at *P*<0.05 among study sites.

4.15.5 Cation exchange capacity (CEC)

CEC in soil was decreased with soil depth. In the first 20 cm in depth, CEC from soil in natural site was significantly higher than other sites. Below 60 cm in depth, in 7-year-old site was higher than other sites. The amount of CEC in different soil depths (0 -200 cm) ranged from 1.90 – 24.23 cmol(+)/kg (Table 4.26).

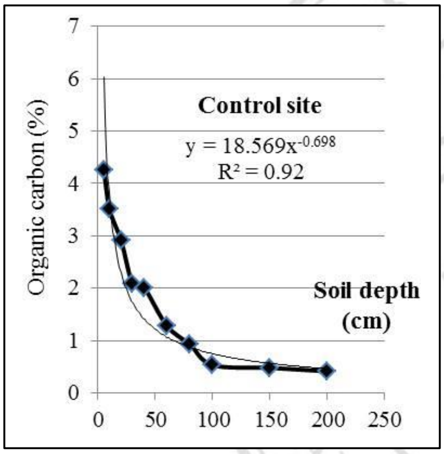
Table 4.26 Cation exchange capacity cmol(+)/kg in different sites

Site	CEC cmol(+)/kg				
	control	2-year-old	7-year-old	11-year-old	natural
0-5	17.03±0.44 **b**	16.45±0.69 **b**	17.83±0.35 **b**	18.11±0.83 **b**	24.23±0.73 **a**
5-10	14.27±0.24 **b**	14.25±0.25 **b**	15.65±0.35 **b**	11.99±0.52 **c**	18.77±0.95 **a**
10-20	10.88±2.68 **b**	11.93±0.26 **ab**	13.81±0.35 **ab**	10.51±0.64 **b**	14.50±0.70 **a**
20-30	9.78±0.18 **ab**	10.92±0.89 **a**	11.49±0.35 **a**	7.94±0.10 **b**	11.31±1.42 **a**
30-40	9.96±0.51 **ab**	7.66±1.46 **bc**	10.48±0.93 **a**	6.43±0.05 **c**	9.80±0.72 **ab**
40-60	8.03±0.40 **ab**	5.55±1.66 **bc**	9.98±0.87 **a**	5.37±0.38 **c**	7.25±0.44 **bc**
60-80	4.89±0.42 **b**	5.39±1.63 **b**	8.73±0.42 **a**	3.91±0.24 **b**	5.25±0.46 **b**
80-100	3.33±0.38 **b**	4.43±1.43 **b**	8.28±0.78 **a**	2.43±0.60 **b**	4.57±0.11 **b**
100-150	3.30±0.18 **b**	4.06±0.52 **b**	6.45±0.62 **a**	1.70±0.05 **c**	3.81±0.34 **b**
150-200	2.89±0.14 **b**	4.13±0.24 **a**	4.75±0.45 **a**	1.90±0.19 **c**	2.82±0.32 **b**

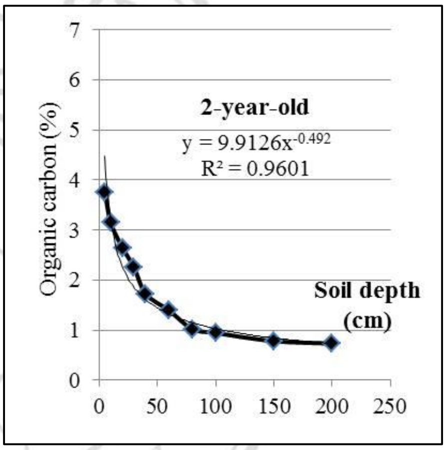
Note: Value are means± SD (n= 3). Means followed by different letters on the same row on the right indicate significant differences at *P*<0.05 among study sites.

4.15.6 Organic carbon (OC)

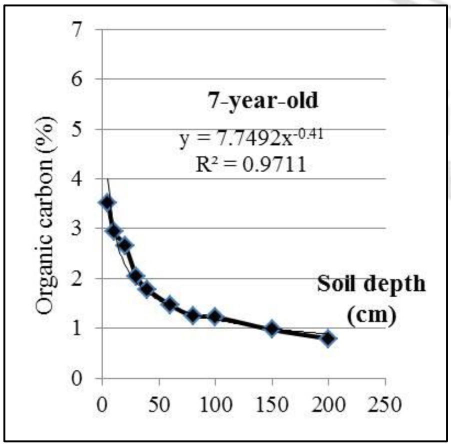
Organic carbon calculated from organic matter using 0.58. In the first 0-5 cm on top soil, natural and 11-year-old sites were higher than other sites significantly. In the top soil layer (0 – 40 cm) high amounts of organic carbon were found in the natural site, but below 40 cm in depth, high amount of carbon were found in 7-year-old site. The negative regression correlation between soil depth and organic carbon is shown in Figs 4.14 a- e.



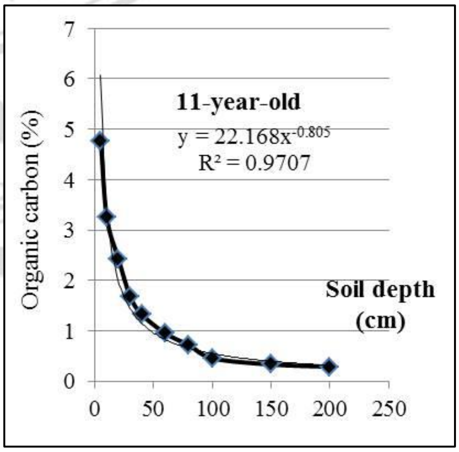
a.



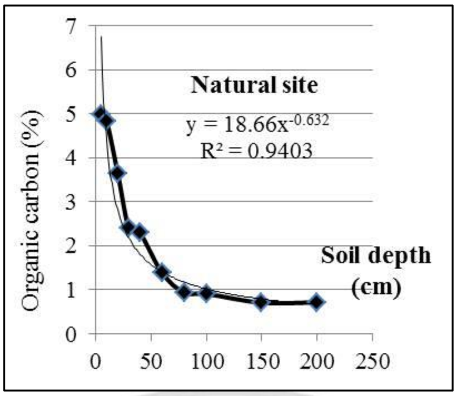
b.



c.



d.



e.

Figures 4.14 a-e. Organic carbon (%)

4.15.7 Soil organic carbon

Highest soil organic carbon in total 200 cm in depth was found in 2-year-old but it was not higher significantly than 7–year-old and natural site. Soil carbon stock in 200 cm of depth were 205.88, 254.40, 251.14, 161.82 and 244.96 tC/ha. Whereas, in 100 cm of depth were 156.10, 168.12, 160.16, 127.41 and 172.99 tC/ha., respectively (Table 4.27).

Table 4.27 Soil carbon stock in 0 – 100, 100 -200 and total 200 cm. in depth

Soil depth (cm)	Soil organic carbon (tC/ha)				
	control	2-year-old	7-year-old	11-year-old	natural
0 – 100	156.10 **c**	168.12 **ab**	160.16 **bc**	127.41**d**	172.99 **a**
100 -200	49.78 **c**	86.28 **a**	90.98 **a**	34.41**d**	71.97 **b**
0 – 200	205.88 **b**	254.40 **a**	251.14 **a**	161.82 **c**	244.96 **a**

Note: Value are means±SD (n= 3). Means followed by different letters on the same row on the right indicate significant differences at P<0.05 among study sites.

4.16 Model

Simulated soil carbon mass using fullCAM started from 2010 to 2020. Simulated soil carbon in control (non-planted site), restored forest site and natural forest site were increasing yearly. The high rate of carbon mass was found in natural forest next to 7, 11 year-old site and control site. The difference of C mass was quite high in the several years after starting simulation, after that it was gradually increased and then constant (Table 4.28 and Figs.4.15).

Table 4.28 Simulated C mass of soil (tC/ha) from 2010 – 2020

Year	control		7-year-old		11-year-old		natural	
	C	df	C	df	C	df	C	df
2010	0.90		1.72		1.93		3.13	
2011	1.57	0.67	3.08	1.36	2.47	0.54	5.10	1.97
2012	1.86	0.29	3.61	0.53	2.72	0.25	6.05	0.95
2013	2.07	0.21	4.01	0.4	2.98	0.26	6.75	0.7
2014	2.24	0.17	4.33	0.32	3.22	0.24	7.30	0.55
2015	2.38	0.14	4.59	0.26	3.45	0.23	7.76	0.46
2016	2.5	0.12	4.83	0.24	3.67	0.22	8.18	0.42
2017	2.62	0.12	5.04	0.21	3.88	0.21	8.56	0.38
2018	2.72	0.1	5.24	0.2	4.09	0.21	8.91	0.35
2019	2.82	0.1	5.43	0.19	4.30	0.21	9.25	0.34
2020	2.92	0.1	5.62	0.19	4.49	0.19	9.57	0.32
Min.	0.06		0.14		0.16		0.23	
Max.	2.92		5.62		4.49		9.57	

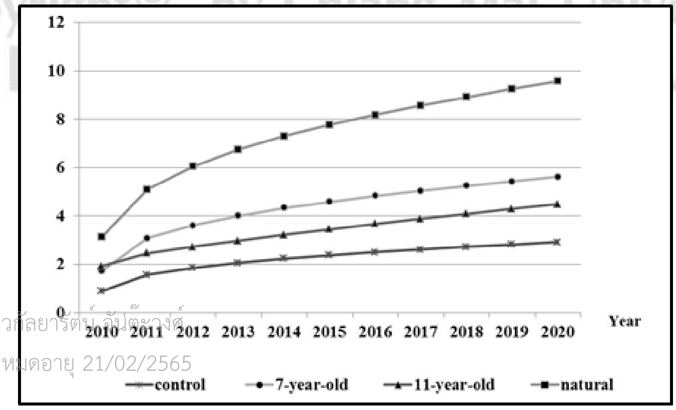


Figure 4.15 Simulated soil carbon mass (tC/ha) in all study sites

CHAPTER 5

Discussion

5.1 Litterfall

Litterfall in restored forest in different ages depended on the age of restored forest except for the 2-year-site. Although, the 11-year-site was quite young, litterfall over two years was high (5.13 and 5.09 t/ha) compared with natural forest (7.01 and 7.26 t/ha/yr). The mean of annual litter in natural forest was 6.43 t/ha/yr which is around 25-year-old (personal communication). The relationship between annual litter and age was represented by the equation was y = 2.3402ln(x) – 0.5052, (R^2 =0.9189). Extrapolation of which estimates that 19.30 years would be required for restored forest to achieve litterfall rates similar to natural. So, it meant that the period of time that the amount of litter in restored forest site will be equal to the natural forest but spending less time (Fig. 5.1).

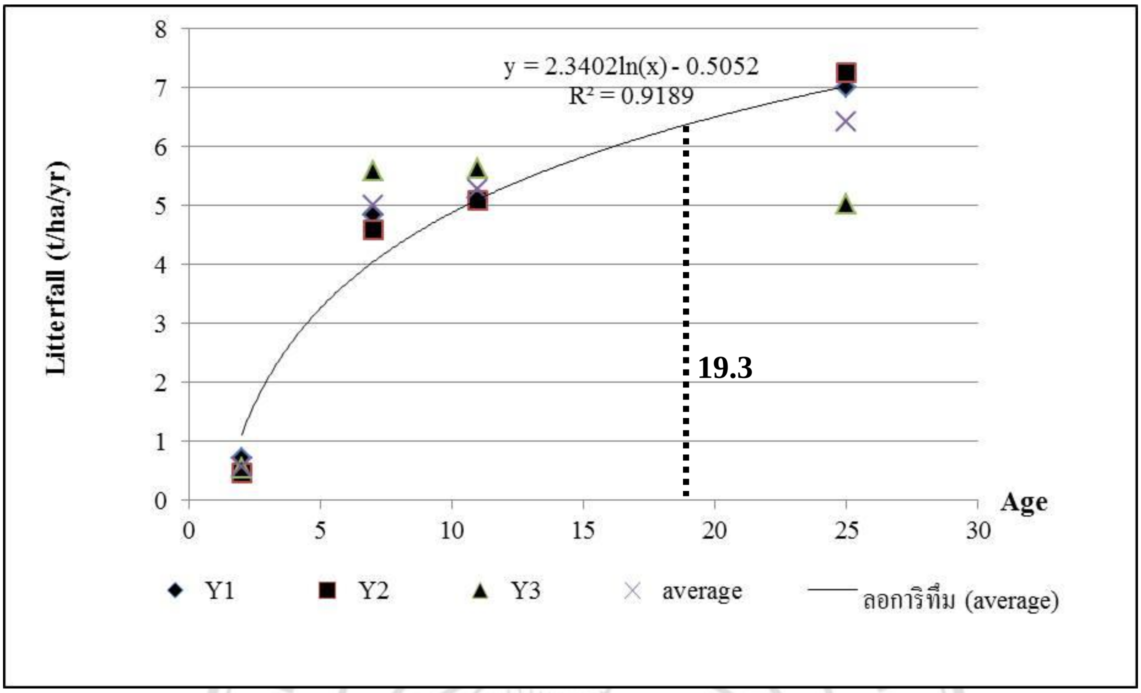


Figure 5.1 Relationship between total litterfall (t/ha/yr) and age since planted

Litter production in the present study is compared with that in other plantations in Table 5.1. Litterfall in my restored plots was similar to that of old un-thinned teak plantations in western Thailand (Sumantakul and Viriyabuncha, 2007). Nevertheless, the results of this study were lower than the results of Tanavat *et al*. (2011) who studied fast-growing tree species: *Eucalyptus camaldulensis, Acacia* hybrid (*mangium xauriculaemis*), *Leucaena leucecephala* and the study of Sumantakul and Viriyabuncha (2007) studies in *E. camaldulensis and A. mangium* of different ages.

And lower than that of fast-growing species e.g. *Acacia mangium* and *A. auriculiformis* which were similar ages to my sites. The results of this study were lower than the study of Lee and Woo (2012), Sale and Agbidye, (2011), Yang *et al*. (2004) and Celentano *et al*. (2011) due to many factors, such as old age of plantations, fast-growing plant species and also high annual precipitation. Those factors or combination of them can produced high amount of litter production (Table 5.2).

In natural forest was included in this study were hill evergreen forest dominated by Fagacece. The result of natural forest site of this study the amount of litter in adjacent natural forest ranged from 7.01 in the first year, 7.26 t/ha/yr in the second year and estimated litterfall in the third year was 5.02 t/ha/yr. Litterfall in my natural site was lower than the result of Glumphabutr and Kaitpraneet (2007) who studied in hill evergreen forest at Khao Khitchakut National Park, Chanthaburi province (Table 5.3).

Annual pattern of litterfall was similar to that reported by others. High amounts of litter were recorded during the dry season (December – April). Whereas, the study of Visaratana and Chernkhuntod (2005) in dry evergreen forest at Sakaerat environmental Research Station, Nakhon Ratchasima Province, North Eastern Thailand was 7.66 t/ha/yr. The amount of litter was very similar to my natural forest site but the highest peak was found in June.

Table 5.1 Comparison of the present study and other plantation studies in Thailand

Location	Plantation	Litter production (t/ha/yr)	Mean Annual rainfall (mm)	References
Western Thailand (Prachinburi province)	Plantation (3-year-old)			
	-*Eucalyptus camaldulensis*	11.43		Tanavat *et al*., 2011
	-*Acacia* hybrid (mangium x auriculaemis)	13.67	1,540	
	-*Leucaena leucecephala*	10.56		
Western Thailand (Kanchanaburi province)	Unthinned teak plantation			
	-6-year-old	4.45		
	-14-year-old	5.65		Sumantakul and Viriyabuncha, 2007
Eastern Thailand (Cha Choeng Sao province)	-27-year-old	6.69	1,655	
	Acacia mangium			
	-6-year-old	10.37		
	Eucalyptus camadulensis			
	-6-year-old	8.29		
	-14-year-old	8.97		
FORRU, Doi Suthep–Pui National park, northern Thailand	**Forest restoration plot**			
	-11-year-old)	**5.09 – 5.13**	**1,154**	**Present study**
	-7-year-old)	**4.60 – 4.85**		
	-2-year-old)	**0.46 – 0.71**		
	-Control plot	**2.27 – 2.46**		
Huey Bong Silvicutural Research Station, Chiang Mai Province	*Pinus caribaea* plantation - 29-year-old	4.68	1,100	Sangsathien *et al*., 2012
Mae Klong Watershed Research Station),Lintin, Thong Pha Phum, Kanchanaburi Province, western Thailand	Teak-gmelina stand planted in 1977	2.22	1,650	Takahashi *et al*., 2012
Huai Lam Kradon subwatershed in the Wang Thong watershed, lower northern Thailand	Para rubber tree plantation	1.37	1,300 -1,700	Podong and Poolsiri, 2012

Table 5.2 Comparison of the present study and other plantation studies

Location	Forest type	Litter production (t/ha/yr)	Mean annual rainfall (mm)	References
Mount Makiling Forest Reserve is located in South Central Luzon,Philippines	*Acacia mangium* and *A. auriculiformis* were planted between 1993 and 1997	11.44 8.72	2,397	Lee and Woo, 2012
Shasha Forest Reserve, Nigeria	Teak plantations planted since 1965,	6.7		
	1970	7.4		
	1975	10		Sale and Agbidye, 2011
	1980	8.3		
	1985	6.8		
Xinkou Experimental Forestry Centre of Fujian Agricultural and Forestry University, Sanming, Fujian, China	33-year-old plantations of two coniferous trees, Chinese fir (*Cunninghamia*			Yang *et al*., 2004
	lanceolata, CF)	5.47		
	Fokienia hodginsii (FH	7.29	1,749	
	Ormosia xylocarpa (OX)	5.69		
	Castanopsis kawakamii (CK)	9.54		
Las Cruces Biological Station Coto Brus county, southern Costa Rica	Planted species included two native timber-producing hardwoods (*Terminalia amazonia* and *Vochysia guatemalensis*) interplanted with two N-fixing species (*Inga edulis* and *Erythrina poeppigiana*)	6.3	3,500	Celentano *et al*., 2011
FORRU, Doi Suthep –Pui National park, northern Thailand	**Forest restoration plot**			
	-11-year-old	**5.09 – 5.13**		
	-7-year-old	**4.60 – 4.85**	**1,154**	**Present study**
	-2-year-old	**0.46 – 0.71**		
	-Control plot	**2.27 – 2.46**		
Huitong Experim ental Station of Forest Eco logy, Hunan Province, China	Plantation of *C. lanceolata* and *Alnus cremastogyne* (MCA),	4.97	1,200	Wang *et al*., 2009
	mixed plantation of *C. lanceolata* and *Kalopana* x *septemlobus* (MCK) 1990	3.98		
Manipur, north eastern India	Plantation site with *Quercus serrata*	4.20	1,384	Pandey *et al*., 2007

Table 5.3 Litter production in different forest type in Thailand

Location	Forest type	Litter production (t/ha/yr)	Mean Annual rainfall (mm)	References
Sakaerat environmental Research station, Nakhon Ratchasima	Dry evergreen forest (DEF)	7.67	1,000 – 1,500	Visaratana and Chernkhuntod, 2005
Khao Khitchakut National Park and Khao Soi Dao Wildlife Sanctuary, Chanthaburi province	Moist evergreen forest (MEF) Hill evergreen forest (HEF) Dry evergreen forest (DEF)	7.85 8.83 4.88	-	Glumphabutr and Kaitpraneet, 2007
Doi Suthep–Pui National park, northern Thailand	**Hill evergreen forest**	**5.02 - 7.26**	**1,154**	**Present study**
Mae Nam Phachi Wildlife Sanctuary, Ratchaburi province	Dry Dipterocarpus Forest (DDF) Mixed Deciduous Forest (MDF)	7.89 3.29 4.96	959 – 1,285	Chaiyo *et al.*, 2011
The Huai Lam Kradon subwatershed in the Wang Thong watershed, in lower northern Thailand	Secondary mixed deciduous forest	4.16	1,300 -1,700	Podong and Poolsiri, 2012
The Mae Klong Watershed Research Station), Lintin, Thong Pha Phum, Kanchanaburi Province, western Thailand	Mixed DeciduousForest (MDF)	2.38	1,650	Takahashi *et al.*, 2012

5.2 The effect of species composition and density

The 2007 or 2-year-old site was accidentally on fire in March, 2010. The burnt site was vegetation for surveyed using circular plots in May, 2011. The survey revealed an average of 267 saplings/rai (FORRU, 2012). Some framework species could survive after the fire such as *Erythrina subumbrans*, *Melia toosendan*, *Prunus cerasoides* and *Spondias axillaris* (FORRU, 2012).

Jinto (2009) found that tree density in 2002, 1998 and natural site were 224, 288 and 192 tree/rai, respectively. Tree density in restored sites were similar to the result of Anusarnsunthorn and Elliott (2004). Since the planting density used for the framework species method is quite high (500 trees per rai), even with slightly higher than 50% mortality, average tree density was maintained at 224.7 trees per rai, which is equivalent to an average spacing of 2.7 m between trees. From a summary of the performance of the trees planted in 1998 that studied by the end of 2002 (4th years after planting), sixteen species (55%) maintained a survival rate of higher than 50%.

Sinhaseni (2008) reported that recruited species in 1998 and 2002 were 33 and 27 species, respectively. Most seedlings grew from seeds that dispersed into the planted plots by animals (rather than by wind). Half of the species of the surveyed seedlings were pioneers and one fourth of the species were climax tree species. However, once the forest canopy is closed, no more seedlings of pioneer species can grow to maturity. While, climax tree species grow for many years in shaded conditions. Therefore, climax tree species can regenerate beneath their own shade.

The proportion of climax and pioneer species in restored forests changed naturally. The proportion of climax species increased with age of planted plots. When the plots were older, the proportion of climax species increased (Sinhaseni, 2008). In the 1998 plots, the number of the climax was more than the pioneer species. Whist in the 2002 site, climax: pioneer species was 50: 50.

Litterfall can vary depending on various factors e.g. soil type, weather and age of plant community (Martius *et al*., 2004). In case of plantations or restored forest sites, planting density (Dickens *et al*., 2004) combined with other factors, such as growth rate (fast-growing species), survival rate after planted, proportion of pioneer and climax species, site preparation, management and precipitation also affects to litter production. In our restored plot, planting density was 3000 trees/ha, whilst Tanavat *et al.* (2011) used 10,000 trees/ha in fast-growing tree plantations, eastern Thailand. Moreover, high primary productivity related to high precipitation (Grosso *et al*., 2008). Therefore, high annual rainfall in eastern and western Thailand can promote the production of litterfall comparing with northern Thailand. Lawrence (2005) reported that annual litter production increased significantly with forest age. Moreover, Kohler (2008) stated that most studies on litterfall in tropical forests refer to old-growth forests and the few available data for young successional forests indicate that litterfall in early- to mid-successional stages may be higher than in mature forests (Ong *et al*., 1981).

5.3 Carbon return through litterfall

Most researchers normally use a conversion factor of 0.50 to provide estimate carbon pools (Lewis, 2009). But carbon concentration of litter in our study was ranged from 32.97 – 38.72% (Table 4.3) which was lower than typical values. And some studies for example in southern China, carbon concentration in litter averaged 45 % in natural *Castanopsis kawakamii* forest and monoculture plantations of *C. kawakamii* and Chinese fir (Guo *et al*., 2004) and ranged from 39.4 to 45.8 % in *Cunninghamia lanceolata* and *Michelia macclurei* plantations (Niu *et al*., 2009).

Jain *et al*. (2010) stated that carbon concentration varies, depending on tree species, substrate, and location and the variability in carbon content as a function of forest type. So, high carbon content found in natural forest site higher than restored and control site. High carbon content was found in natural forest site followed restored forest (11, 7 and 2-year-old) and control plot were 38.72, 34.40 and 33.29%, respectively (Table 4.3). It showed that high carbon content was found in natural forest. It indicated that litter quality in terms of carbon content varied with tree species (Chandrashekar, 2011).

When calculated in terms of carbon content through litterfall, it ranged from carbon of 0.25 – 2.71 tC/ha in year1 and 0.75 – 2.81 tC/ha in year2. High input of carbon content was found in natural forest site next to 11 and 7-year-old site. However, restored forest site especially in 1998 and 2002 were young regenerated plot but can contribute the high amount of carbon input via litterfall.

5.4 Forest fire and the effect of forest fire

In this study forest fire occurred accidentally in March, 2010 and destroyed litter, ground flora and small planted tree in young study site (planted since 2007). After that some weeds and also ground flora recovered in the following rainy season. Some of the survival planted tree re-sprouted. Therefore, litterfall in 2-year-old site was not high, but in the other restored forest tended to increase with age. However, in May, 2011 burnt site was surveyed using circular sample and the survey revealed that average of 267 saplings/rai still survived in that site (FORRU, 2012). It showed that tree density decreased around 50%.

Fire has different effects on soil organic carbon in forest ecosystems. Wang *et al.* (2012) reported that fire decreased soil organic C by 20.3%, consistent with some other studies (Antunes *et al*., 2009). And also some studies demonstrated that fire significantly decreased soil organic C (Zhang *et al*., 2005), but some studies noted an increase (Boerner *et al*., 2004), and some other studies indicated the no effect or little effect of fire (Knoepp *et al*., 2004).

Fire resulted in disturbance of many forest lands depending on its severity and forest composition (Lecomte *et al*., 2005). The impact of fire on forest soil depends on various factors such as intensity of fire, fuel load and soil moisture (Verma and Jayakumar, 2012). Variations in fire intensity are related to many factors, including forest floor biomass/depth, slope position, aspect, and angle, and fire weather (Boerner *et al*., 2000b). Fire leads to burning of organic matter and this affects the nutrient status of soil for sometime (Lecomte *et al*., 2005). Moreover, the effect of fire on SOM is highly variable from total destruction of SOM to partially scorching depending on fire severity, dryness of the surface OM and fire type (Gonzalez-Perez *et al*., 2004). So in this study, forest floor was full of plenty of leaf litter that dropped during dry season and soil moisture content was quite low so it was quite severe when fire occurred. After fire occurred, it was spending long period for forest recovery process.

5.5 Litter decomposition of mixed three species
(*Ficus subincisa*, *Erythrina subumbrans* and *Castanopsis diversifolia*)

Percentage of dry mass loss rapidly in first weeks varied from 10 to 60% among species. Percentage of *Ficus subincisa* decreased from 100% to 40 – 60 % compared to *Erythrina subumbrans* decreased around 25-45% but in *Castanopsis diversifolia* was decreased only 10-15 % among study sites. Decay rate varied among species but not among sites ($P<0.05$). Decay rates of *E. subumbrans* ranged from 1.05 - 2.12, while decay rate of *C. diversifolia* ranged from 0.41 - 0.87 and in *F. subincisa* ranged from 1.21 - 4.15.

Rapid initial rates of decomposition may reflect leaching of soluble compounds and the decay of easily degradable compounds and tissues (Loranger *et al*., 2002). After the initial rapid phase, *F. subincisa* and *E. subumbrans* decomposed slowly but dry mass of *C. diversifolia* was contant until the late phase dry mass was lost again. *C. diversifolia* was presented low *k* value and dry mass loss may be due to physical features of leaves (Cornelissen and Thompson, 1997) such as its hardness and thickness. A rapid mass loss observed during late rainy season in October could be due to the favorable conditions for fast decomposing litter and soil moisture contents, high relative humidity and congenial atmospheric temperature, all indirectly favoring the soil biological activity (Isaac and Nair, 2005). The higher decay rate in the wet months according to the results of Isaac and Nair (2005) and is attributed to rapid microbial activity and accentuated leaching due to rainfall. And the subsequent decline in the decomposition rate during the dry period may be due to the associated lowering of soil moisture and temperature which can decrease the activity of decomposing organisms (Seneviratne *et al*., 2006).

K value of *C. diversifolia* was less than 1 but the other two species were more than one. From the study of Melvin *et al.* (2011) suggested that if the litter decomposition constant or *k* values of the study sites were less than one, indicating that the turnover time for leaf litter is more than one year. Variations were observed in the decay rate within the different species. Substrate quality, climate and quantity and quality of decomposer organisms are the primary determinants of litter decay rates (Swift *et al*., 1979). In the present study, since the environmental conditions remained the same for all the three species, the variations in the decay rates may be attributed to the litter quality. Initial litter quality such as C/N ratio considered in the present study was found to be negatively correlated to litter decomposition rate whereas initial N and C was found to be the best predictors of the decomposition rate. According to Lavelle *et al*. (1993) model, it can be expected that under constant climate and a similar community of soil organisms, litter quality is the most important factor regulating decomposition. Therefore, they expected that high litter quality (low C/N) in secondary forest and broad-leaf forest would lead to accelerated decomposition. Compared to the present study, high N and low C/N was found in *Erythrina subumbrans* and *Ficus subincisa* but not in *Castanopsis diversifolia*. So in this study decomposition rates of *Erythrina subumbrans* and *Ficus subincisa* were, higher than *Castanopsis diversifolia*, probably because of litter quality.

Ostertag *et al*. (2008) suggested that site effects may be more important than litter quality in determining decomposition rates. Similarly, litter mass loss was faster in young secondary forest (25 years) than in bush fallow (4 years) or 12-year-old secondary forest in Cameroon (Hauser *et al*., 2005), also suggesting the importance of site effects. In contrast, in a comparison between a mid-successional forest (ca. 50 years) and an adjacent mature tabonuco forest in Puerto Rico, decomposition rate was slightly higher in the secondary forest, and this difference was related to litter quality, but not site quality (Zou *et al.*, 1995). Similar to the present study which decompositions rates were not significantly different among study sites, but differed among species indicating that litter decomposition is related to litter quality more than site. Different species have different decomposition rates and nutrient release patterns, which are related to litter quality and environmental factors (Sundarapandian and Swamy, 1999). Nitrogen, the most common factor limiting litter decomposition, determines the growth and turnover of microbial biomass mineralizing organic carbon (Heal *et al*., 1997). In the present study, nitrogen in different species were not significantly different ranging from 1.15-2.09 in the initial phase. High N in *E. subumbrans*, overall, compared to other species may have been due to the fact that it is a nitrogen-fixing species.

In this study, I focused on litter decomposition in restored forest, using framework species which established variety of plant species and also plant litter. Altered decomposition rate and litter quality were determined in different litter materials. From the present study, litter quality of each species was important in affecting to decomposition rates and also need more information for further studies in any other framework species. Rapid decomposition rate and high litter quality (low C/N, high initial N) were also found in plant litter of framework species that we selected (*F. subincisa* and *E. subumbrans*). Moreover, decay rates (*k* values) of those two species were more than one and can be indicated that turnover rate of leaf litter less than one year. Therefore, not only do *F. subincisa* and *E. subumbrans* posses all the essential characteristics of framework species, but they also supply high-quality litter, in terms of transferring from litter to organic matter and returned to soil during decomposition process.

5.6 Litter decomposition of mixed species using big bag

Carbon content of litter in natural forest was significant higher than that of other sites, whilst nitrogen content in 7-year-old site was higher than at the other sites. After 286 days carbon and nitrogen content (%) in natural were still higher than at other sites. Martinez-Yrizar *et al.* (2007) proposed that decomposition rates vary among litter types differing in structural or nutritional quality. The litter types used in their experiment significantly differed in initial quality and annual decomposition rates. Faster decomposition rates were found for high quality litter (i.e., low lignin content and lignin:nutrient ratios in *Encelia farinosa*) and lower for poor quality litter (i.e., high lignin content and lignin:nutrient ratios in *Olneya tesota*). Many studies have reported a direct influence of litter chemistry and physical properties of the leaves on litter decomposition rates. So in this study, the effect of site and litter quality were combined and dominated decomposition rates. However, initial mixed litter in older restored sites were not different in terms of plant species. So decomposition rate was dominated by other factors and may be microclimate which is the primary influence on understory composition many biogeochemical processes e.g. humid and warm weather (Heal *et al.*, 1997) due to different aspect was the main reason for high decomposition in 7-year-old site.

Such differences in nitrogen release pattern from the leaf litter might be associated to the litter quality and the dependent decomposer communities. Net release or net immobilization can be predicted from the organic material's C/N ratio or N concentration. Carbon and nitrogen during period of times gradually decreased. But the relationship between C/N and duration times (R^2 = 0.43) was very week. The line was quite stable (C/N = 23 – 25). Carbon content (%) in litter in different periods were determined and found that after 286 days carbon content among study sites were raged 25 – 30 % which was significant highly in natural site. While nitrogen content were ranged 1.01 - 1.33% which was not different among study sites. Available studies suggest that plant materials with N >1.7%, C/N ratio < 25 generally mineralize, whilst those with N<1.7%, C/N ratio>25 lead initially to immobilization of mineral N (Seneviratne, 2000) likely because of greater N demand by microbes decomposing litter with relatively lower N content (Hobbie *et al.*, 2006), until respiration and decomposition lower the C/N ratio (Heal *et al.*

1997). It is clear that nitrogen concentration and C/N ratio are major determinants of the ability of plant residues to supply N (Seneviratne, 2000).

After 286 days, *k* values ranged from 1.08 – 2.85. *K* value in 7-year-old was significantly higher than other sites (*k* = 2.85). *K* values from previous studies in different types of forest in Thailand were quite varied (Table 5.4). Moreover, decay rate of this study was compared with other studies especially in tropical forest (Table 5.5). In lowland tropical forest in Sarawak *k* values were ranged from 0.38 – 2.36 and mean rate of decomposition was 1.10 (Hirobe *et al*., 2004). Whereas, Melvin *et al*. (2011) studied in standing forest plot in different ages compared with secondary forest in Sarawak, Malaysia found that *k* values in 1991, 1993, 1999 plot and secondary forest were 0.224, 0.216, 0.216 and 0.208, respectively. In upper montane rainforest of Sri Lanka, *k* value was 0.76 (Weerakkody and Parinson, 2006). But the study of Barbbuiya *et al*. (2008) in wet evergreen forest of northeast India ranged from 1.042 – 5.374. Moreover, Yang *et al*. (2004) studied in four plantation of coniferous and broad leaved trees compared with natural forest in subtropical China and *k* values ranged from 1.157 – 4.619. While the study of Yang and Chen (2009) in southwestern China, Xishuangbanna, using mixed species of litter in each forest type. *K* values in secondary forest, broad-leaved forest and rainforest were 1.075, 1.989 and 2.123, respectively. Compared with the previous studies, *k* values in the present study were quite moderate. If the litter decomposition constant or *k* values of the study sites were less than one, it indicates that the turnover time for leaf litter is longer than one year (Melvin *et al.*, 2011) and it also indicates that litter turnover in all study sites is shorter than 1 year.

Table 5.4 Decay rates of variety plant species in different forest type of Thailand

Location	Forest type	Dominated species	*k*	Annual rainfall (mm)	References
Doi Suthep pui National park, Chiang Mai province	Forest restoration site				Gavinjan, 2005
	Planted 1997		2.07		
	1999	Mixed of two species	2.40		
	2001	*Prunus cerasoides* and *Ficus altissima*	3.14	1, 500	
	control		2.69		
Kabin buri, Prachinburi province	Plantation	*Eucalyptus camaldulensis*	1.36	1,000	Tanavat *et al*., 2012
		Acacia hybrid (*mangium x auriculaeformis*)	0.53		
		Leucaena leucocephala	2.5		
Meaklong Watershed Research station, Kanchanaburi Province	Mixed deciduous forest	*Pterocarpus macrocarpus*	1.83	800	Ladpala and Phanuthai, 2006
		Xylia xylocarpa	1.83		
		Schleichena oleosa	1.28		
		Holarrhena pubescens	2.09		
		Berrya cordifolia	1.99		
		Bambusa tulda	1.83		
		Gigantachloa albociliata	1.34		
Sakaerat Environmental Research Station, Nakornratchasrima province	Dry evergreen forest	*Hopea ferrea*	1.62	1,240	Boonriam, 2010
Doi Suthep pui National park, Chiang Mai province	**Forest restoration site**	***Erythrina subumbrans***	**1.05 - 2.12**	**1,154**	**Present study**
		Castanopsis diversifolia	**0.41 - 0.87**		
		Ficus subincisa	**1.21 – 4.15**		
		Mixed of three species	**1.46 – 1.87**		
	Control site	**Grass**	**1.20**		
	2-year-old site	**Grass + mixed framework species**	**1.08**		
	7- year-old site	**Mixed framework species**	**2.85**		
	11-year-old site	**Mixed framework species**	**1.27**		
	Natural	**Mixed species dominated by *Castanopsis diversifolia***	**1.12**		
Kog-ma watershed reseaech area, Doi Suthep –pui National park	Hill evergreen forest	*Castanopsis accumunatissima*	0.99 – 1.05	2,784	Torreta and Takeda, 1999
		Schima wallichii	0.55 – 0.61		
Huai Lam Kradon subwatershed in the Wang Thong watershed in lower northern Thailand	Secondary mixed deciduous forest		0.06 – 0.51	1,300 - 1,700	Podong and Poolsiri, 2012
	Para rubber plantation		0.02 – 0.59		
Kaeng krachan National park, Petchaburi and Prachuab Kiri Khan provinces	Mixed deciduous forest	*Alchornea tiliifolia*	0.07 – 0.11	967.9	Jampanin, 2004
	Dry evergreen forest	*Blachia siamensis*	0.03 – 0.07		
		Bhesa robusta			
	Hill evergreen forest	*Castanopsis diversifolia*	0.04		
		Quercus lamellosa			

Table 5.5 Decay rates of variety plant species in different forest types

Location	GPS	Forest type	Dominated species	*k*	Annual rainfall	References
Changlang district of Arunachal Pradesh, northeast India.	27^{0} 23'30'' N to 27^{0} 39' 40'' N to 96^{0} 15'2'' E to 96^{0} 58' 33'' E	Tropical wet evergreen forest	*Ailanthus grandis*	1.89	2,000 – 3,400	Barbbuiya *et al.* , 2008
			Altingia excelsa	2.47		
			Castanopsis indica	1.76		
			Duabanga sonneratioides Dysoxylum binectariferum	3.89 5.37		
			Mesua ferrea	1.04		
			Shorea assamica	3.12		
			Talauma hodgsonii	2.30		
			Terminalia myriocarpa	2.78		
			Vatica lancefolia	2.05		
Doi Suthep pui National park, Chiang Mai province		**Forest restoration site**	***Erythrina subumbrans***	**1.05 -2.12**	**1,154**	**Present study**
			Castanopsis diversifolia	**0.41 - 0.87**		
			Ficus subincisa	**1.21 – 4.15**		
			Mixed of three species	**1.46 – 1.87**		
		Control site	**Grass**	**1.20**		
		2-year-old site	**Grass + mixed framework species**	**1.08**		
		7- year-old site	**Mixed framework species**	**2.85**		
		11-year-old site	**Mixed framework species**	**1.27**		
		Natural	**Mixed species dominated by *Castanopsis diversifolia***	**1.12**		
The main research sites of the Chinese Ecological Research Network (CERN) in Xishuangbanna tropical area , SW China	101^{0} 46'E, 21^{0} 54'N	Secondary forest	*Litsea monopetala* *Millettia laptobotrya*	1.08	1,500 – 1,600	Yang and Chen, 2009
		Broad-leaf forest	*Lithocarpus truncates Castanopsis mekongensis Pometia tomentosa*	1.11		
		Rain forest	*Amoora tetrapetala*	2.12		
Hakgala strict natural reserve, Sri Lanka	6^{0} 55'N, 80^{0} 49'E	Montane rainforest	*Allophylus varians*, *Cinnamonum ovalifolium* etc.	0.76	2,013	Weerakkody and Parkinson, 2006
Riau, Indonesia	101^{0}47'32.1''E 00^{0} 20' 48.2''	*Acacia mangium* industrial forest	*Acacia mangium*	0.7	2,000	Samingan and Sudirman, 2009
Semengoh Forest Reserve, Sarawak Malaysia	1^{0}23'N, 110^{0}19'E	Lowland tropical rain forest	15 species e.g. *Shorea*, *Hopea*, *Cotylelobium* etc.	0.38 – 2.36	3,850	Hirobe *et al.*, 2004
Universit Putra Malaysia Bintulu Sarawak Campus, MalaysiaSarawak Malaysia	03^{0} 12 N , 113^{0} 02 E	Rehabilitation of Tropical Rainforest Ecosystems	Standing forest plot in 1991	0.224	2, 933	Melvin *et al.*, 2011
			1993	0.216		
			1999	0.216		
			Secondary forest	0.208		

5.7 Organic carbon

Litter on the forest floor was the major input of carbon into the soil and accumulated in the top soil. Highly significant amounts of carbon content were found in the top soil (0 – 5 cm) in the natural and 11-year-old sites, due to high loading of the litter accumulation. Organic carbon (%) (derived by multiplying organic matter content by 0.58) declined sharply with increasing soil depth, through the upper soil layers, and less steeply lower down, closely following a power law relationship:

$$OC\% = A \times Depth^{K}$$

… where depth is measured in cm and A and K are constants for each site. Constant A varied from 7.75 (2-year-old site) to 22.17 (11-year-old site), whereas constant K varied from -0.410 (7-year-old site) to -0.805 (11-year-old site). The coefficients of determination (R^2) for these relationships were very high (0.92 – 0.97) (Figs 4.14 a-e.), indicating that for future studies, once A and K have been determined from upper soil layers (0-1 m), OC% in lower soil layers (1-2 m) can be reliably predicted.

5.8 Comparing organic matter and organic carbon data after restoration

Soil data (1998 site or 11-year-old site) before planting (since 1997) at the same soil depth (0 -10 cm in depth) are compared with the present study and shown in Table 5.6. Organic matter had increased from 5.37 % to 6.93 %. Thus over 11 years following restoration work, by the framework species method, soil organic matter content increased from 73% to 94% of the level typically recorded in undisturbed evergreen forest soil at a similar elevation (Elliott *et al.*, 2000). Moreover, the restored plot (R11) result was compared with adjacent natural hill evergreen forest (elevation 1,300 m), the result showed that it takes around 20 % (from 63% to 82%) to reach the value of OM in natural forest. Mean organic carbon increased in both control plots and those subjected planted with framework tree species. However the increase in carbon in the control plots was not significant, whilst in the 11-year restoration plot was increased significantly ($P<0.05$). Organic carbon increased significantly from 3.10 % to 4.02%.

Table 5.6 % OM and % OC before restoration and during this study in the C, 11-year-old site and natural forest site.

Soil properties	Site			
	Pre-restoration study 1997 (N = 16)	C (this study) (N = 6)	11-year-old site (this study) (N = 6)	Natural forest site (this study) (N = 6)
% OM	5.35 ± 1.00 **c**	6.69 ± 0.73 **bc**	6.93 ± 1.45 **b**	8.45 ± 0.21 **a**
% OC	3.10 ± 0.58 **c**	3.88 ± 0.42 **bc**	4.02 ± 0.84 **b**	4.90 ± 0.12 **a**

Note: Means±SD and significant differences at $P<0.05$ among sites.

5.9 Soil organic carbon stock

Routine soil surveys usually measure carbon stock data down to a depth of only 1 m Batjes (1996) estimates that if this was increased to 2 m depth, global estimates of soil organic carbon (SOC) storage would increase by 60%. In this study, soil organic carbon was investigated down deep to 2 m. High amounts of soil organic carbon stock in total 2 m in young study site (2 and 7-year-old) were 254.40 and 251.14 tC/ha, respectively. And assumed that high soil organic carbon in young study site due to less utilization by young tree. Young forests have initially high carbon sequestration rates, these decline in ageing forests. While, mature forests eventually reach equilibrium, in which no or little further sequestration takes place (SFC ad hoc WG climate change and forestry, 2010).

Nevertheless, soil organic carbon in control site in total 2 m (205.88 tC/ha) was which was higher than 11-year-old site (161.82 tC/ha). The control plots had been continually covered in grasses and other herbaceous weeds, restoration plot establishment. The control site was not planted area with trees and retained covered with grass e.g. *Imperata cylindrical*. Soil carbon in control site was also high especially on topsoil (0 – 10 cm), due to the high root density under grass (van der Kamp *et al*., 2009) and the fact that the Imperata roots penetrate into the subsoil, inputting organic matter directly into lower soil layers (Billings, 2006).

One explanation for this apparent contradiction is that the larger rooting system of these C4 species (in this control site of this study mostly C4 grass) may release greater quantities of labile material to the microbial community (e.g., fine root turnover and exudation), stimulating carbon mineralization in the rooting zone (Baer *et al.*, 2002).

Although routine soil surveys collect carbon stock data down to a depth of 1 m, Batjes (1996) estimates a 60% increase in the global soil organic carbon (SOC) storage with depth extended to 2.0 m. Therefore, soil profile and collection below 1 m. in this study site should be might interesting. Nevertheless, when we compared with other studies we might compared in the same level of soil sampling.

Generally in Thailand, soil carbon stock normally investigated to 100 cm depth. In present study, soil carbon stock in 100 cm of depth among study sites ranged from 127.41 – 172.99 tC/ha. The highest amount of soil carbon was found in natural forest site comparing to 2, 7, control and 11-year-old site which were quite higher than other plantations in Thailand. The result of Pibumrung *et al.* (2008) which conducted in reforestation plot with native and exotic species was 146.83 tC/ha. Their results were quite similar to my study plot, especially the 7 and 2-year-old sites, which ranged from 160.16 – 168.12 tC/ha (Table 5.7a).

It is interesting that soil carbon in teak plantations of Pumijumnong (2007) especially in old plots (61.72 -105.67 tC/ha) is lower than the result of this study (Table 5.6a). This might have been the soil texture, which strongly affects soil carbon dynamics (Parton *et* *al.*, 1994). In general terms, fine-textured soils have a higher soil carbon content than coarse-textured soils (Hassink, 1994). At the study site of Pumijumnong (2007), the soil was loamy sand and sandy loam texture, the coarse-textured with low aggregating, and low water absorption, nutrients and organic carbon. The accumulation of soil organic carbon was less than in clay-textured soil. In contrast, the soil in this study site contained a high clay percentage and also higher soil organic carbon than has been reported for reddish brown lateric soils (Tangsinmankong, 2007) (Table 5.7a).

Moreover, Saengruksawong *et al.* (2012) studied soil carbon stock in different ages of rubber plantation in northeastern Thailand which changed from dipterocarpus forest by farmers. The soil group was very shallow, red yellow podzolic with high soil erosion and low level of water absorption during the rainy season and low fertility. Consequently, soil carbon stocks in plantation plots were lower than at other sites (13.37–18.52 tC/ha) (Table 5.7b).

Soil carbon stock of natural forest in the present study was moderate rate which was higher than dry dipterocarp forest and mixed deciduous forest of many previous researches. But lower than upper montane of Doi Inthanon National park (Tables 5.8a-b).

A comparison between this study and a forest restoration experiment at University Putra Malaysia, Bintulu Sarawak Campus (Ch'ng *et al*., 2011) is shown in Table 5.9, since the forest restoration concept there (i.e. restoration of a near-natural forest ecosystem) matches the objective of the plots in the present study. The Bintulu study measured carbon down to 40 cm depth only, so the comparison is with 40 cm depth from the present study. SOC values in our restored plots were much higher than in the Bintulu plots, overall.

Soil organic matter and soil organic carbon in younger restored site considered higher than in the Bintulu rehabilitated forest. Moreover, Ch'ng *et al*. (2011) also found no significant difference in the quantity of stable carbon for the different ages of rehabilitated forest similar to this study that soil organic carbon that found in different restored site was not higher with forest stand ages (Table 5.9). This was similar to the result of Pumijumnong (2007), who estimated soil carbon in different ages of teak plantation in 10, 14, 18, 27 and 28 year-old in central region of Thailand were 157.03, 61.72, 78.78, 105.67 and 66.83 tC/ha, respectively. The quantity of soil carbon stock did not increase with age (Table 5.7a).

Even though their research conducted in tropical rain forest but different kind of method and plant species (planting indigenous timber species from the family Dipterocarpaceae and Non-Dipterocarpaceae) which established since 1991 after shifting cultivation in restored plot accompanied with other factors such as previous land use can build different level of carbon stock (Ch'ng *et al*., 2011). Moreover, as reported by other authors, the number of years under the previous land use, the stage of the succession, distance from seed sources and intervention or management, among others (Mesquita, 2000) may all be factors, that individually or in a combination, determine the amount of carbon found at the soil.

Table 5.7a Soil carbon studies in different plantation and other land use type in Thailand

Study site	Land histories	Vegetation type	soil organic carbon (t C ha^{-1})	Soil depth (cm)	Soil group	Parent material	References
Num Yao sub-watershed, Nan province	Protected from logging for over half a century Planted since 1979 Cleared prior to 1957	Reforestation planted since 1979 (exotic+ native species) :*Gmelina aborea,Eucalyptus camaldulensis, Tectona grandis,Pterocarpus macrocarpus ,Afzelia xylocarpa,Pterocarpus macrocarpus, Acacia catechu*	146.83±7.22	0 - 100	Red yellow podzolic soils, Red brown lateritic soils	Sandstone, shal stone and limestone	Pibumrung *et al*., 2008
FORRU,northern Thailand	**Degraded hill evergreen forest and agriculture before restoration**	**Forest restoration plot**		**0 – 100**	**Red brown lateritic soils**	**Granite**	**Present study**
		- 1998 (14-year-old)	**127.41**				
		- 2002(10-year-old)	**160.16**				
		- 2007(5 year-old)	**168.12**				
		Natural forest	**172.99**				
Huay Kha Khaeng Wildlife Sanctuary and teak plantation of Thai Plywood Co., Ltd. Lansak, Uthaithani Province		Teak plantation		0-100			Tangsinmankong, *et al*., 2007
		- 24-year-old	105.67				
		- 15-year-old	78.78				
		- 6-year-old	157.03				
Central Thailand	Mixed deciduous forest before Planted since 1989	Teak plantation		0 – 100	Non calcic Brown soils	Limestone	Pumijumnong *et al*., 2007
		- 28-year-old	66.83				
		- 27-year-old	105.67				
		- 18-year-old	78.78				
		- 14-year-old	61.72				
		- 10-year-old	157.03				
Sakaerat environmental research station, Nakornratchasrima Province	Forner land-use of agricultural land was changed from forest 40 years ago	Reforest *Acacia mangium* (16 –year-old)	66	0-50			Chidthaisong and Lichaikul, 2005
		Agriculture maize	60				

Table 5.7b Soil carbon studies in different plantation and other land use type in Thailand

Study site	Land histories	Vegetation type	Soil organic carbon (tCha^{-1})	Soil depth (cm)	Soil group	Parent material	References
Prachuap Khiri Khan Silvicultural Research Station, Southern Thailand		Native and exotic species plantation (14-15-year-old)		0-50			Meungpong *et al*., 2010
		- *Acacia crassicarpa*	58.63				
		- *Azadirachta indica*	44.49				
		- *Pterocarpus*	46.78				
		macrocarpus	62.64				
		- *Shorea roxbyrghii*	56.77				
		- *Tectona grandis*	49.00				
		- *Xylia xylocarpa*	49.90				
North – east (Nongkhai province)	Dipterocarpus forest	Rubber plantation		0-100	Red yellow podzolic soils	Siltstone and sandy stone	Saengruksawong *et al.*, 2012
		- 1-year-old	14.26				
		- 5-year-old	16.83				
		- 10-year-old	18.52				
		- 15-year-old	16.05				
		- 20-year-old	13.37				

Table 5.8a Soil carbon studies in different forest type in Thailand

Study site	Vegetation type	Soil organic carbon (t C ha^{-1})	Soil depth (cm)	References
Doi Inthanon National park (Keaw Mae Pan area)	Upper montane forest	262.47 – 288.80	0 -100	Timpan, 2008
Num Yao sub-watershed, Nan province	Hill evergreen and Mixed deciduous forest	196.24±22.81	0-100	Pibumrung *et al*., 2008
FORRU, northern Thailand	**Forest restoration plot** **- 1998 (14-year-old)** **- 2002(10-year-old)** **- 2007(5 year-old)** **Natural forest**	 **127.41** **160.16** **168.12** **172.99**	**0 – 100**	**Present study**
Doi Suthep-Pui national park, Chiang Mai province	Dry dipterocarp forest (DDF)	67.99	0 -100	Khamyong, 2009
	Mixed deciduous forest (MDF)	136.57	0-100	
	Dry evergreen forest (DEF)	139.01	0-160	
	Pine forest (PF)	123.20	0-160	
	Montane forest (MF)	133.03	0-120	
Boakaew watershed station, Chiang Mai province	Fragmented Montane forest Dominated by		0 -100	Satienpirakul, 2013
	- *Pinus kesiya*	84.33		
	- *Castanopsis accuminattissima*	93.07 – 150.78		
	- *Castanopsis diversifolia*	107.99		
	- *Shima wallichii*	263.87		
Sakaerat environmental research station, Nakornratchasrima Province	Dry evergreen forest (DEF)	118	0-50	Chidthaisong and Lichaikul, 2005
Huay Kha Khaeng Wildlife Sanctuary and teak plantation of Thai Plywood Co., Ltd. Lansak, Uthaithani Province	Mixed deciduous forest	70.96	0-100	Tangsinmankong, *et al*., 2007
Ban Sai Thong Community forest, Lamphun Province	DDF old conservation area	42.95	0- 80	Phonchaluen, 2009
	DDF new conservation area	16.16	0 – 20	
	MDF old conservation area	40.49	0 – 110	
	MDF new conservation area	86.11	0 - 100	

Table 5.8b Soil carbon studies in different forest type in Thailand

Study site	Vegetation type	Soil organic carbon (t C ha^{-1})	Soil depth (cm)	References
Huai Hong Khrai Royal Development Study Center (HHK), Chiang Mai Province, Northern Thailand	Dry dipterocarp forest (DDF) Mixed deciduous forest (MDF)	29.57 39.88	0 -100 0 - 160	Chaiwong et al., 2013
Petrified wood forest park, Tak province	Dry dipterocarp forest (DDF)	31.22	0 -100	Wongin, 2011

Table 5.9 Comparison SOM and SOC the UPM Mitsubishi Forest Restoration Project, Sarawak, Malaysia and the present study

Location	Land histories	Forest type	SOM at 40 cm (Mgha^{-1})	SOC at 40 cm (MgCha-1)	Reference
FORRU, Doi Suthep – Pui National park, northern Thailand	Degraded hill evergreen forest and agriculture before restoration	Restored forest plot			Present study
		-2-year-old	128.34	74.61	
		-7-year-old	129.53	75.32	
		-11-year-old	123.97	72.08	
UPM-Mitsubishi rehabilitated forest at University Putra Malaysia, Bintulu Sarawak Campus	Previously abandoned after shifting cultivation and rehabilitated since 1991 by planting indigenous forest tree species at very high density.	Rehabilitated forest			Ch'ng *et al.*, 2011
		-1-year-old	64.31	37.30	
		-2-year-old	95.96	55.66	
		-3-year-old	68.21	39.56	
		-4-year-old	61.77	35.83	
		-5-year-old	43.59	25.28	
		-6-year-old	59.12	34.29	
		-7-year-old	67.45	39.12	

5.10 Comparing some soil properties the study of Schuler (2008) and present study

Schuler studied soil characteristic and soil profile in Mae Sa Mai area in various vegetation types including evergreen forest, deciduous forest, pine forest, fruit tree orchards and also under cultivation of agronomy. Soil in the Mae Sa Mai area were mostly Acrisols, covering about 70% of the area according to World References Base for Soil Resources (WRB). In present study the soil type classed as a Ultisol. Soil color, structure, fraction and texture of both studies were similar, bulk density from my study was lower than that reported by Schuler (2008) (Table 5.10).

Table 5.10 Comparison soil study of Schuler and present study

Soil	Schuler (2008)	Present study
Type	Acrisol	Ultisol
Color	Reddish color	Reddish color
Structure		
Topsoil (0 -20 cm)	Granular	Granular
Subsoil (below 20 cm)	Subangular blocky	Subangular blocky
Soil fraction	Sand dominated	Sand domainated
Texture		
Topsoil	Clay loam	Sandy loam, Sandy clay loam, Clay loam
Subsoil	Clay	Clay loam, Clay
Bulk density (g/cm^3)	1.1 - 1.3	0.6 – 1.14

5.11 Comparing some soil properties of the study of Laorpansakul (2000) and present study

The study of Laorpansakul (2000) determined soil characteristic in the Queen Sirikit Botanic Garden (QSBG) where closed to Ban Mae Sa Mai. He conducted soil in different type of forest. In this case, soil in hill evergreen forest was compared to this study and shown in Table 5.11a-b. Soil type, structure and soil texture in both studies were similar. Bulk density in QSBG was quite higher than present study. Soil pH in QSBG was quite higher than this study. Organic matter (%) of upper and middle slope in hill evergreen forest of QSBG were similar to organic matter (%) in natural forest of this study. Therefore, SOC of QSBG natural forest was similar to this study.

Table 5.11a Comparison soil study of QSBG and present study

Soil	QSBG			Present study				
	Upper	Middle	Lower	control	2-year-old	7-year-old	11-year-old	Natural forest
Type	Ultisol			Ultisol				
Structure								
Topsoil (0–20 cm)	Granular			Granular				
Subsoil (below 20 cm)	Subangular blocky			Subangular blocky				
Texture								
Topsoil (0–20 cm)	Sandy loam			Sandy clay loam, Sandy clay, clay loam				
Subsoil (below 20 cm)	Clay loam to clay			Sandy clay loam, clay loam, clay				
Bulk density (g/cm^3)	0.79 – 1.31	0.72 - 1.23	1.13 – 1.46	0.78 – 1.12	0.68 – 1.07	0.75 – 1.14	0.78 - 1.12	0.62 – 1.06

Table 5.11b Comparison soil study of QSBG and present study

Soil	QSBG				Present study			
	Upper	Middle	Lower	Control	2-year-old	7-year-old	11-year-old	Natural forest
pH (0 – 5 cm)	5.28	6.09	5.11	5.01	4.76	5.75	4.65	4.52
OM (%) (0 -5 cm)	10.31	12.50	5.49	10.08	6.86	7.71	8.97	11.59
OC (%) (0 – 5 cm)	5.98	7.25	3.19	5.85	3.98	4.47	5.20	6.72
Base saturation (%) (0 – 5 cm)	23.45	43.63	21.33	28.70	35.81	68.76	19.00	10.83
CEC (0 – 5 cm)	24.80	43.53	19.07	15.49	15.49	20.59	19.74	16.77
SOM 0-1 m (t/ha)	262.90	307.37	226.60	268.49	289.17	275.48	219.15	297.54
SOC 0-1 m (tC/ha)	152.48	178.27	131.43	156.10	168.12	160.16	127.41	172.99

According to the study of Fonseca *et al.* (2011) which investigated carbon accumulation in the biomass and soil of different aged secondary forests in the humid tropics of Costa Rica. They found a positive but low correlation between the amount of soil carbon and the age of the forest, in contrast high correlation was found between biomass and forest age. The low correlation between soil carbon and forest age can be attributed partly to the slow incorporation of carbon into the soil (Gamboa *et al*., 2008) together with the young age of the studied forests. However, as reported by other authors, previous land use, the number of years under the previous land use, the stage of the succession, distance from seed sources and intervention or management, among others (Mesquita, 2000) may all be factors, that individually or in a combination, determine the amount of carbon found at the soil. However, this assumption still needs to be proven.

Recent works suggested that increase of organic matter storage in subsoils may not be as straight forward, because subsoil carbon may become available to microbial decomposition, following carbon input (Fontaine *et al*., 2007) and/or mechanical disruption (Xiang *et al*., 2008). It also has been found that subsoil C may respond to land-use and/ or management change (Follett *et al*., 2009). Main C sources of subsoil OM are dissolved organic matter, root biomass and physically or biologically transported particulate organic matter. Organic matter input into subsoil horizons occurs as root litter and root exudates, dissolved organic matter and/or bioturbation. The relative importance of these sources is dependent on climatic parameters, soil inherent processes as well as land-use. For example, high input of dissolved organic matter can be expected under humid climate conditions (Michalzik *et al*., 2001).

Another important source of subsoil OM is plant roots. These affect the placement of carbon in soil. In a global review of root distribution, grasses had the shallowest root profiles, trees were intermediate and shrubs had the deepest profiles (Jackson *et al*., 1996). Specific allocation patterns through vegetation types were also found to govern vertical SOC distribution (Jobbagy and Jackson, 2000). The importance of roots for soil C sequestration was underlined by the fact that they have a high potential to be stabilized in soil (Rasse *et al*., 2006). So, below 40 cm in depth we still determined much more soil organic carbon especially in young restored site (2002 and 2007 site).

Several factors affect SOC stock change including previous land-use (Stevens and van Wesemael, 2008), precipitation (Jackson *et al*., 2002) and the type of forest established (Guo and Gifford, 2002). Given such variation in the direction of soil C stock change and the period required for recovery to initial soil C stock levels, elucidating the mechanisms related to SOC accumulation after afforestation and also in forest restoration program in more detail are still essential because the SOC dynamics vary among forests due in part to soil type (Hagedorn *et al*., 2003).

5.11 Model

The simulated soil carbon in 11, 7, control and natural site increased yearly and ranged from 1.93 – 4.49, 1.72 – 5.62, 0.05 – 0.46, and 3.13 – 9.57 tC/ha, respectively. From starting year (2010), soil carbon mass was highest in natural next to 11, 7, control and 2-year-old site. Since 2011, soil carbon mass in natural site was to higher than 7, 11, control site. Initial litter input per year and clay percentage were the important data that input for model simulation. So that, trend line of natural, 11, 7-year-old site were more increased rapidly than others due to litterC input. However, simulated soil carbon mass was quite different from current measured soil organic carbon in the study sites. And may be probably under-estimated than the real situation. Soil carbon mass in study sites may be more or less than present due to many relevant factors with unpredictable changes such as forest fire, termites and tree fall or harvesting problems. Moreover, several factors affecting SOC stock change including the previous land-use type (Stevens and van Wesemael, 2008) and the type of forest established (Guo and Gifford, 2002) were not included in this model. Nevertheless, data that input in model just two year (2010-2011) need more information in long-term for validation and comparing data between measurement and simulation.

CHAPTER 6

CONCLUSIONS

6.1 Overall conclusions

1. Litterfall in the restored forest site will equal to that of natural forest within 20 years of restoration work.
2. Litterfall was the major input and to the top soil.
3. High soil organic carbon in the younger study site was due to less utilization by young trees.

6.2 Schematic carbon diagram

Overall output was put in the box as following diagrams:

Control site

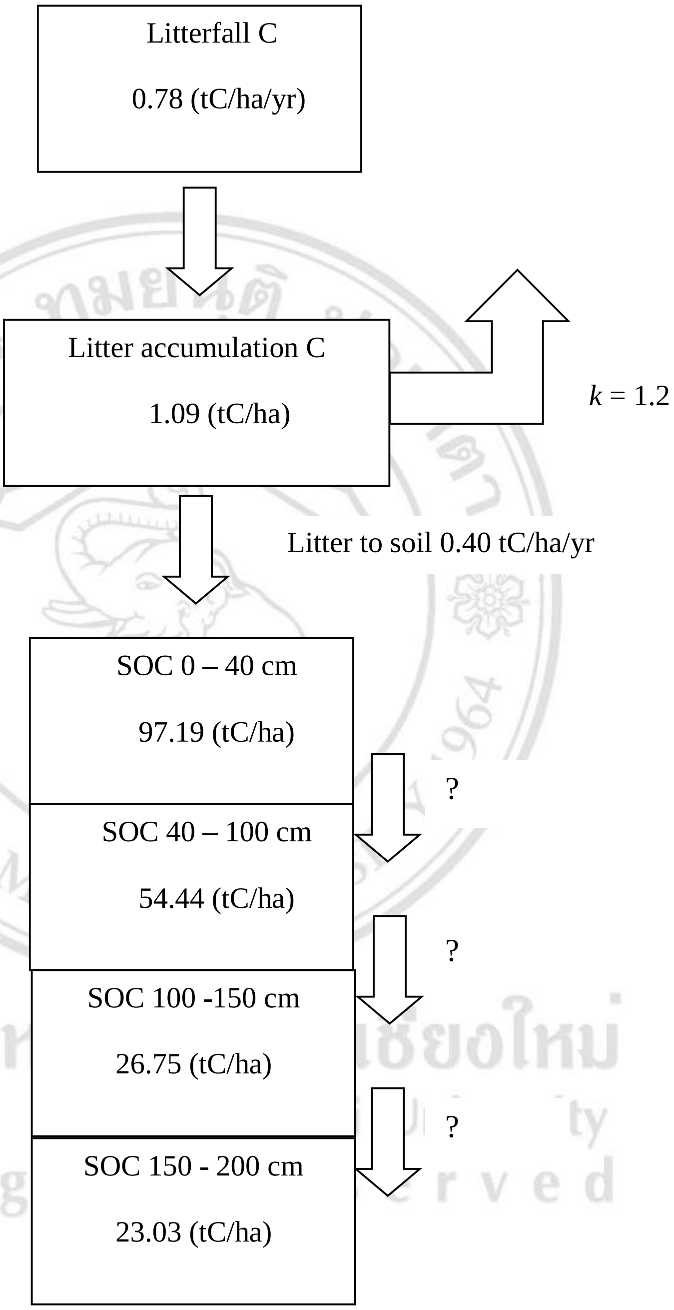


Figure 6.1 Diagram of control site

2-year-old site

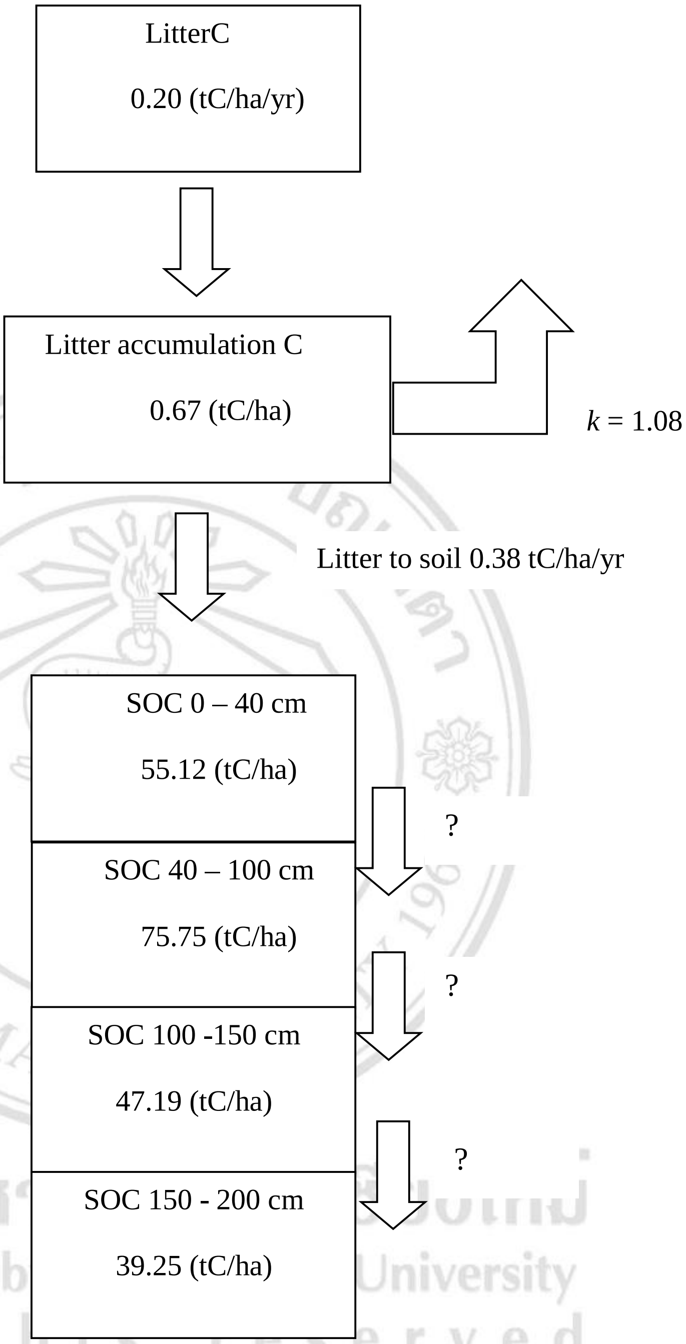


Figure 6.2 Diagram of 2-year-old site

7-year-old site

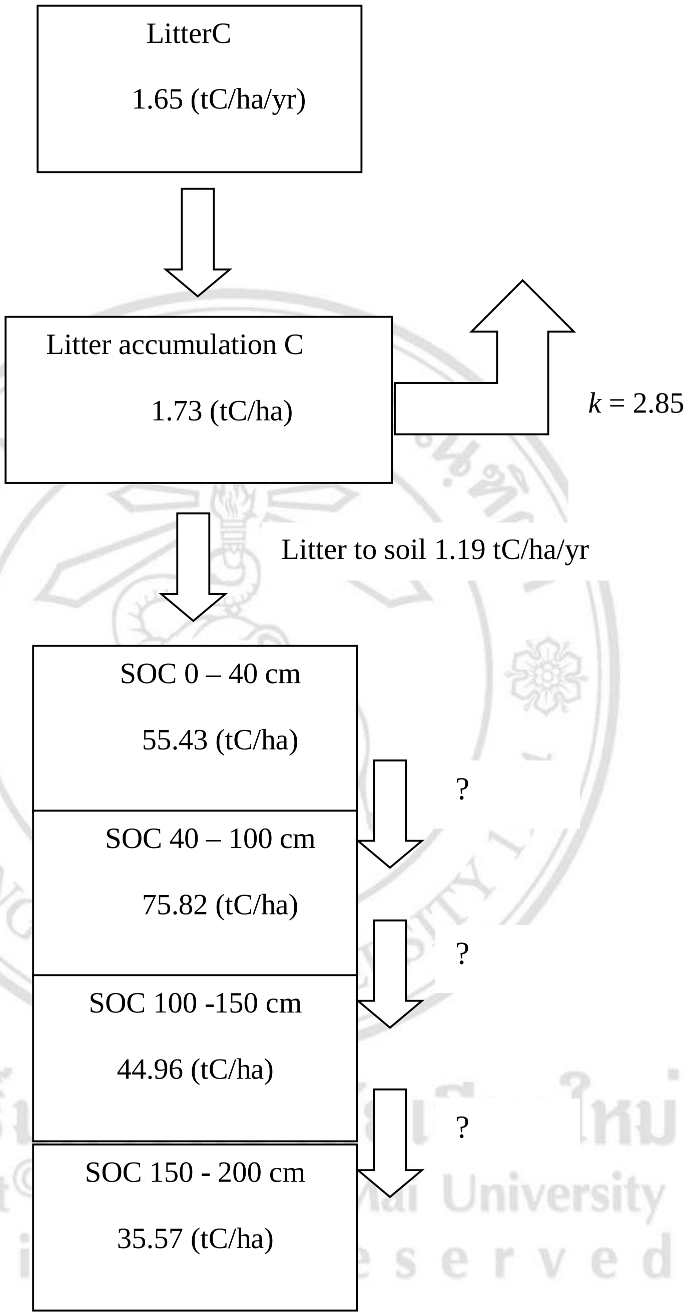


Figure 6.3 Diagram of 7-year-old site

11-year-old site

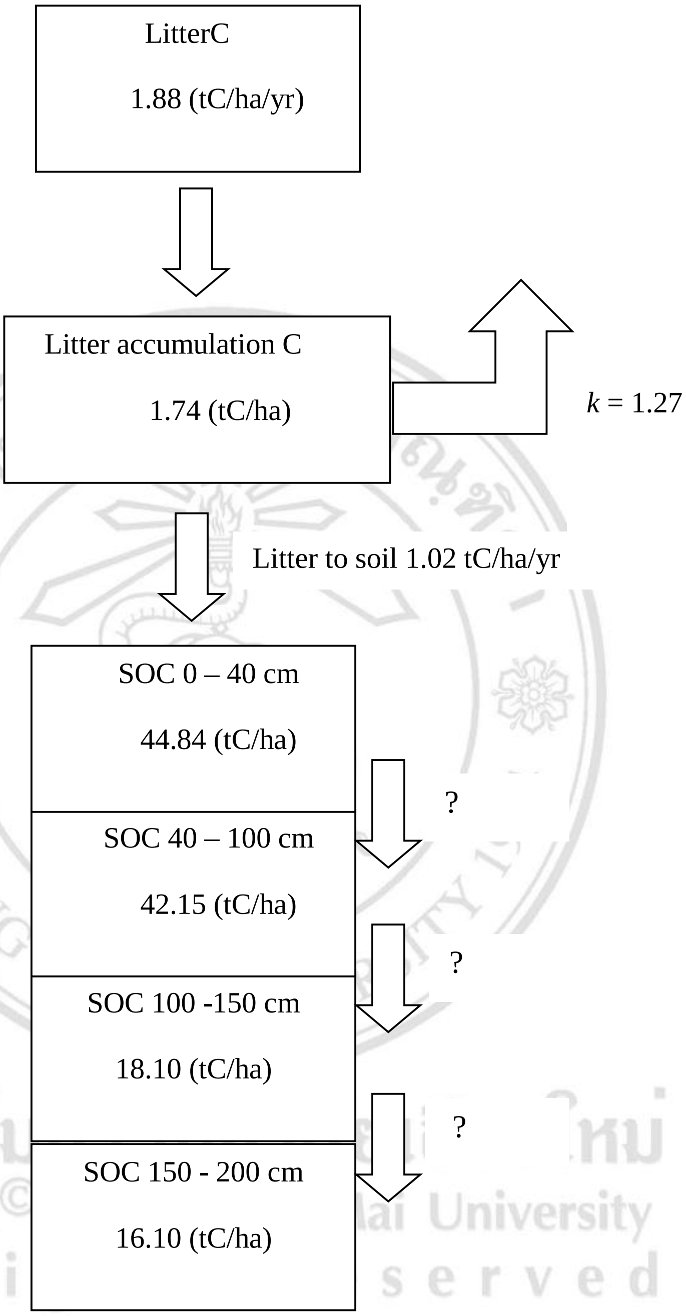


Figure 6.4 Diagram of 11-year-old site

Natural forest site

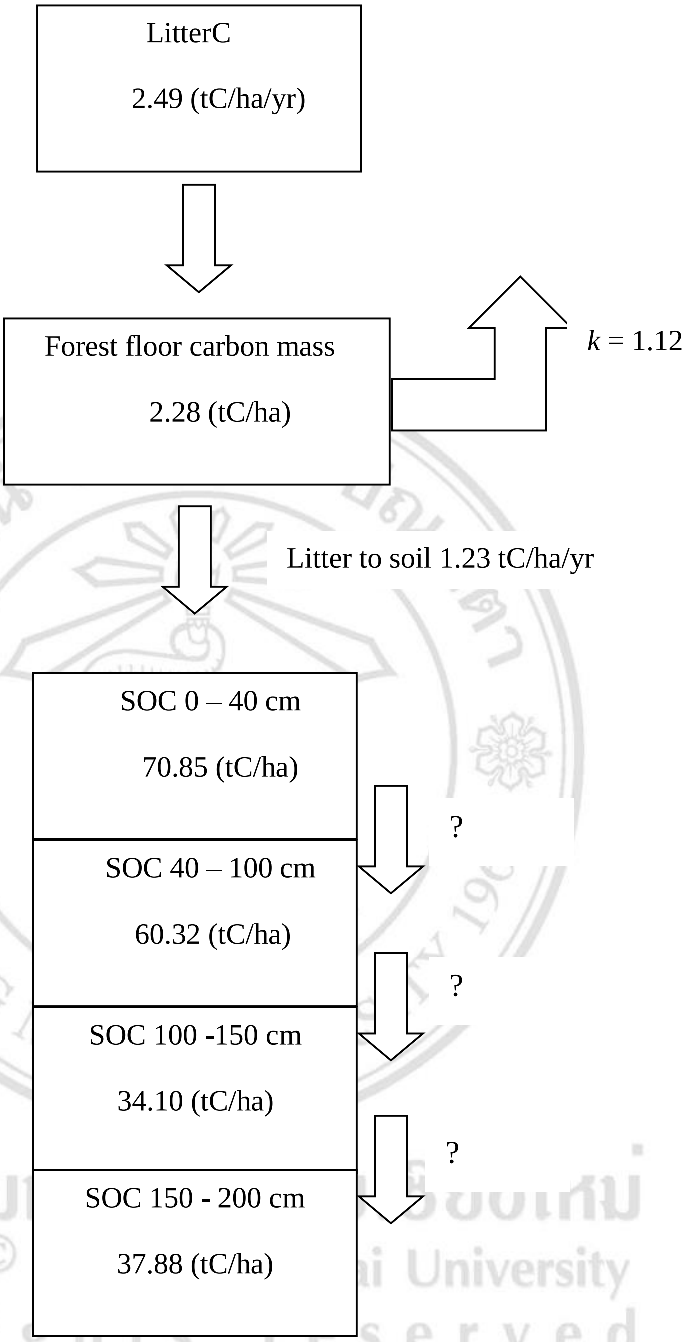


Figure 6.5 Diagram of natural forest site

6.3 Recommendations for further study

For SOC, long-term monitoring in the different plots is needed, and using radiocarbon for monitoring old and new carbon which in the study sites in the future would be interesting to investigate carbon dynamic in restored forest system. However, numerical model using field data was tried but lack of following data:

- soil respiration rate in different soil depths from top soil to deeper soil
- soil organic carbon accumulation rate
- organic carbon depletion rate per year
- transfer rate of organic carbon from top soil to deeper soil

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APPENDIX A

Species of trees planted in 1998, 2002 and 2007

No.	Species	1998	2002	2007
1	*Acrocarpus fraxinifolius*	-	/	/
2	*Adinandra integerrima*	-	-	/
3	*Aglaia lawii*	-	-	/
4	*Alangium kurzii*	-	-	/
5	*Albizia odoratissima*	-	-	/
6	*Alseodaphine andersonii*	-	-	/
7	*Aphanamixis polystachya*	/	-	/
8	*Apodytes dimidiata*	-	-	/
9	*Aquilaria crassna*	-	/	/
10	*Archidendron clypearia*	-	-	/
11	*Artocarpus gomezianus*	-	-	/
12	*Artocarpus lakoocha*	-	-	/
13	*Baccaurea ramiflora*	-	-	/
14	*Balakata baccata*	-	-	/
15	*Bauhinia variegata*	-	-	/
16	*Betula alnoides*	-	-	/
17	*Bischofia javanica*	/	/	/
18	*Bridelia glauca*	-	-	/
19	*Canarium subulatum*	-	-	/
20	*Carallia brachiata*	-	-	/
21	*Careya arborea*	-	-	/
22	*Castanopsis armata*	-	-	/
23	*Castanopsis calathiformis*	/	-	/
24	*Castanopsis diversifolia*	-	/	/
25	*Castanopsis tribuloides*	-	/	/
26	*Cephalotaxus griffithii*	-	-	/
27	*Cinnamomum caudatum*	-	-	/
28	*Cinnamomum iners*	/	-	-
29	*Cryptocarya amygdalina*	-	-	/
30	*Dalbergia oliveri*	-	-	/
31	*Debregeasia longifolia*	-	-	/
32	*Diospyros glandulosa*	/	-	/

No.	Species	1998	2002	2007
33	*Dipterocarpus costatus*	-	-	/
34	*Elaeocarpus lanceifolius*	-	/	/
35	*Erythina stricta*	-	/	-
36	*Erythrina subumbrans*	/	/	/
37	*Eugenia albiflora*	/	/	-
38	*Eugenia cinerea*	-	-	/
39	*Eugenia formosa*	-	-	/
40	*Eugenia tetragona*	-	-	/
41	*Euodia meliifolia*	-	-	/
42	*Eurya acumminata*	/	-	-
43	*Ficus altissima*	/	-	-
44	*Ficus auriculata*	-	-	/
45	*Ficus benghalensis*	-	-	/
46	*Ficus benjamina*	-	-	/
47	*Ficus benjamina* var. *benjamina*	-	/	-
48	*Ficus callosa*	-	/	-
49	*Ficus capillipes*	-	/	-
50	*Ficus fistulosa*	-	-	/
51	*Ficus fistulosa* var. *fistulosa*	-	/	-
52	*Ficus hispida*	-	-	/
53	*Ficus microcarpa*	-	-	/
54	*Ficus racemosa*	-	-	/
55	*Ficus subincisa*	-	/	-
56	*Garcinia mackeaniana*	/	-	-
57	*Gmelina arborea*	/	/	/
58	*Helicia nilagirica*	/	-	-
59	*Heynea trijuca*	-	/	/
60	*Horsfieldia amygdalina*	/	-	-
61	*Horsfieldia thorelii*	/	-	-
62	*Hovenia dulcis*	/	/	/
63	*Lithocarpus elegans*	-	-	/
64	*Litocarpus sootepensis*	-	-	/
65	*Macaranga denticulata*	-	/	/
66	*Machilus boombycina*	-	/	-
67	*Magnolia liliifera*	-	-	/
68	*Mahonia nepalensis*	-	-	/
69	*Manglietia garrettii*	/	-	/
70	*Markhamia stipulata*	-	-	/

No.	Species	1998	2002	2007
71	*Melia toosendan*	/	/	/
72	*Michelia baillonii*	-	-	/
73	*Michelia champaca*	-	-	/
74	*Michelia floribunda*	-	-	/
75	*Morus macroura*	-	-	/
76	*Nyssa javanica*	/	/	/
77	*Oroxylum indicum*	-	-	/
78	*Ostodes paniculata*	-	/	/
79	*Phoebe lanceolata*	/	-	-
80	*Phoebe* sp.	/	-	-
81	*Phyllanthus emblica*	-	-	/
82	*Podocarpus neriifolius*	-	/	/
83	*Polyalthia viridis*	-	-	/
84	*Prunus cerasoides*	/	/	/
85	*Quercus brandisiana*	-	-	/
86	*Quercus kingiana*	-	-	/
87	*Quercus semiserrata*	/	/	/
88	*Quercus vestita*	/	-	-
89	*Rhus rhetsoides*	-	/	/
90	*Sapindus rarak*	/	/	/
91	*Sarcosperma arboreum*	/	/	/
92	*Spondias axillaris*	/	/	/
93	*Styrax benzoides*	-	-	/
94	*Trichilla connaroides*	/	-	-
	Total species	27	24	46

APPENDIX B

Soil profile description

Pedon 1 control or non-planted site

Location: Ban Mae Sa Mai, Mae Rim District, Chiang Mai Province

N18^0 51’ 410’’, E098^0 50’ 881’’

Elevation: 1,332 m.asl.

Slope: 10 %

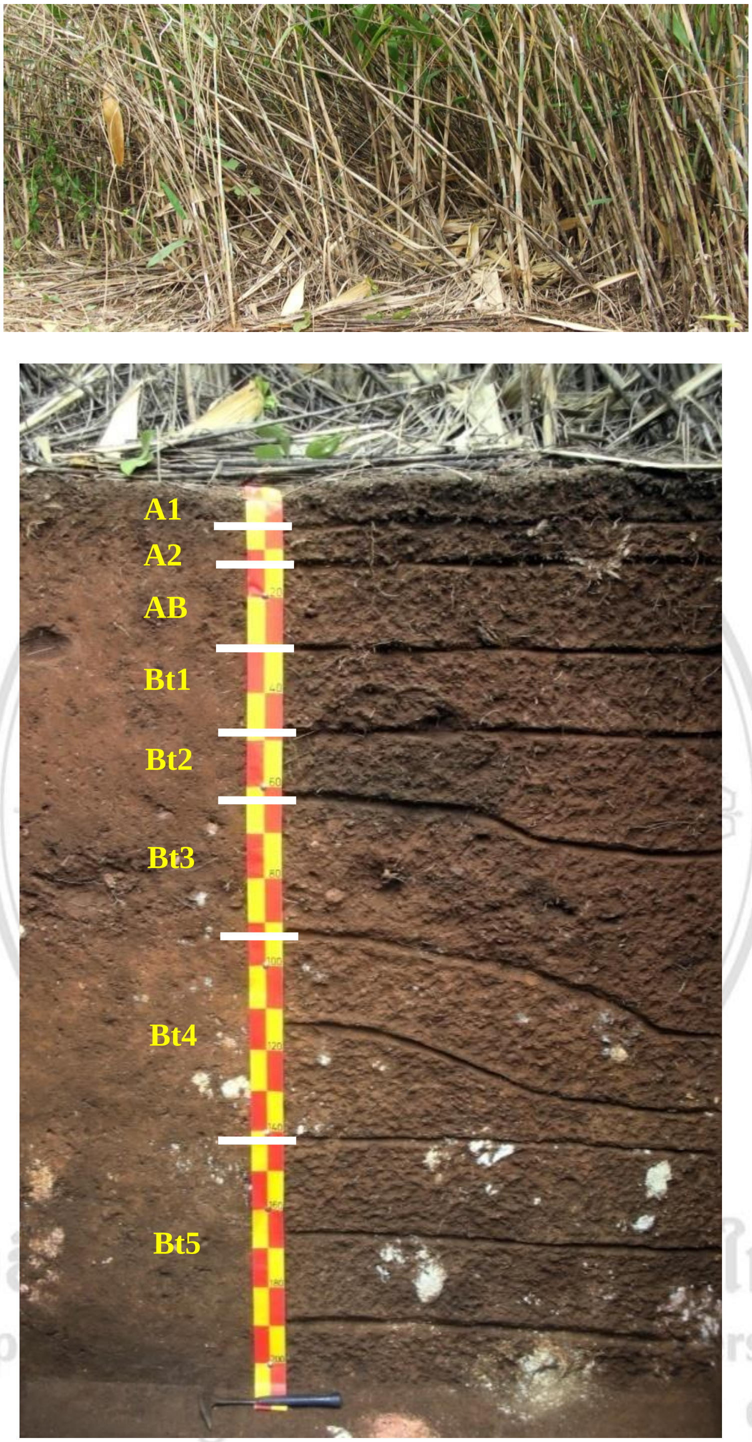
Aspect: ESE 99^0

Vegetation type: Non-planted area dominated by the grasses *Thysanolaena latifolia, Phragmites vallatoria* and *Imperata cylindrical*

Horizon	**Depth (cm)**	**Description**
A1	0-5	Very dark grey (5YR 3/1) moist and dark reddish gray (5YR 4/2) dry; sandy clay loam; very fine subangular blocky; many ($\geq$ 10 dm^3) very coarse (diameter $\geq$10 mm) root, coarse (diameter $\geq$10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 5.0)
A2	5-14	Dark reddish brown (5YR 3/2) moist and dark brown (7.5 YR 4/4) dry; sandy clay loam; very fine subangular blocky; ; many ($\geq$ 10 dm^3) very coarse (diameter $\geq$10 mm) root, coarse (diameter $\geq$10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.7); gradual and smooth boundary

AB	14-30	Dark reddish brown (5YR 3/3) moist and strong brown (7.5 YR 4/6) dry; sandy clay loam; very fine subangular blocky; many ($\geq$ 10 dm^3) very coarse (diameter $\geq$10 mm) root, coarse (diameter $\geq$10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; extremely acid (pH = 4.4); gradual and smooth boundary
Bt1	30-48	Dark reddish brown (5YR 3/4) moist and strong brown (7.5 YR 4/6) dry; clay loam; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter $\geq$10 mm), coarse (diameter $\geq$10 mm) , medium (diameter 2 -5 mm) , fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; extremely acid (pH = 4.3) ; gradual and smooth boundary
Bt2	48-62/72	Dark reddish brown and dark red (5YR 2/2) moist and brown (7.5 YR 4/2) dry; sandy clay loam; very fine angular blocky; common (1 -5 root/dm^3) very coarse (diameter $\geq$10 mm), coarse (diameter $\geq$10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.6); gradual and smooth boundary
Bt3	62/72-93/115	Reddish brown (5YR 4/4) moist and yellowish red (5YR 5/8) dry; clay loam; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter $\geq$10 mm), coarse (diameter $\geq$10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.8); gradual and smooth boundary

Bt4	93/115-142	Reddish brown (5YR.4/4) moist and yellowish red (5YR 5/8) dry; clay loam; very fine subangular blocky; few (< 1 root/dm^3) very coarse (diameter ≥10 mm), coarse (diameter ≥10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.8); gradual and smooth boundary
Bt5	$142\text{-}200^+$	Dark reddish brown (5YR 3/3) moist and strong brown (7.5 YR 5/6); loam; very fine subangular blocky; very strongly acid (pH = 4.8); few (< 1 root/dm^3) very coarse (diameter ≥10 mm), coarse (diameter ≥10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.8); gradual and smooth boundary



Pedon 1 Control site

Pedon 2 2-year-old (2007 site)

Location: Ban Mae Sa Mai, Mae Rim District, Chiang Mai Province

N18^{0} 51’ 410’’, E098^{0} 50’ 931’’

Elevation: 1,311 m.asl.

Slope: 16 %

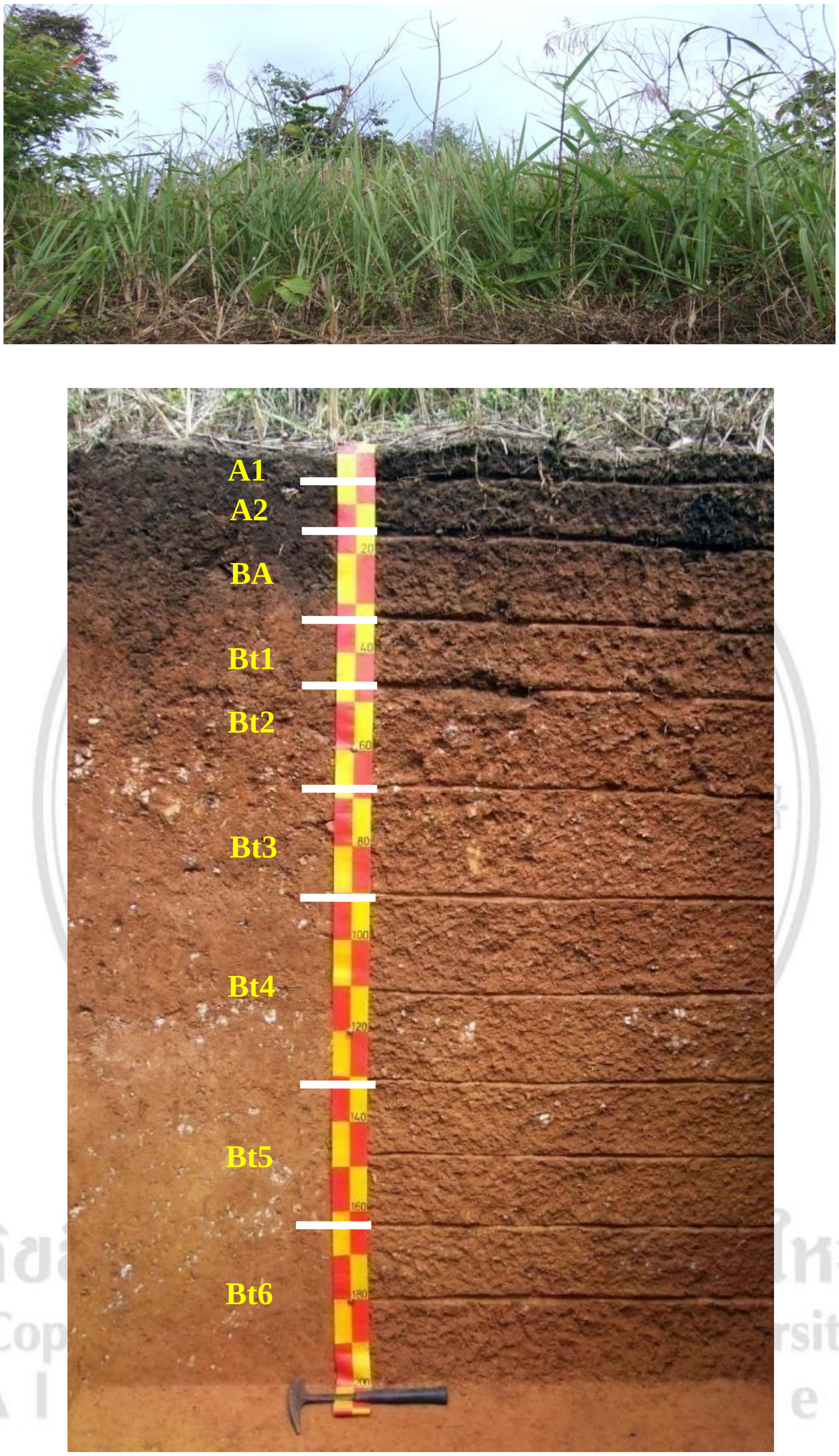
Aspect: ENE 60^{0}

Vegetation type: Restored forest with framework species since 2007

Horizon	**Depth (cm)**	**Description**
A1	0-5	Dark reddish brown (5YR 3/2) moist and strong brown (7.5 YR 4/6) dry; sandy clay loam; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm) root, coarse (diameter 5 – 10 mm) and medium (diameter 2 -5 mm), many (≥ 10 root/dm^3) fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.7)
A2	5-18	Dark reddish brown (5YR 3/2) moist and strong brown (7.5 YR 4/6) dry; clay loam; very fine sub angular blocky; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm) root, coarse (diameter 5 – 10 mm) and medium (diameter 2 -5 mm), many (≥ 10 root/dm^3) fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.7); gradual and smooth boundary
BA	18-32	Dark reddish brown (5YR 3/4) moist and strong brown (7.5 YR 5/6); clay; very fine subangular blocky; gravel content 6.18 % ; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm), coarse (diameter 5 – 10 mm) and medium (diameter 2 -5 mm), many (≥ 10 root/dm^3) fine (diameter 1 -2 mm)

		and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.5); gradual and smooth boundary
Bt1	32-46	Yellowish red (5YR 4/6) moist and reddish yellow (7.5 YR 6/6) dry; clay; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm), coarse (diameter 5 – 10 mm) and medium (diameter 2 -5 mm), many (≥ 10 root/dm^3) fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.5); gradual and smooth boundary
Bt2	46-67	Yellowish red (5YR 5/6) moist and reddish yellow (5YR 6/6); clay; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm), coarse (diameter 5 – 10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.5); gradual and smooth boundary
Bt3	67-90	Yellowish red (5YR 5/6) moist and reddish yellow (5YR 6/6) dry; clay; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm), coarse (diameter 5 – 10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.5); gradual and smooth boundary
Bt4	90-130	Yellowish red (5YR 5/6) moist and reddish yellow (5YR 6/8) dry; clay; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm), coarse (diameter 5 – 10 mm), medium (diameter 2 -5 mm) root; very strongly acid (pH = 4.6); gradual and smooth boundary

Bt5	130-163	Yellowish red (5YR 5/8) moist and reddish yellow (5YR 7/6) dry; clay; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter $\geq$10 mm), coarse (diameter 5 – 10 mm), medium (diameter 2 -5 mm) root; very strongly acid (pH = 4.5); gradual and smooth boundary
Bt6	$163\text{-}200^+$	Yellowish red (5YR 5/8) moist and pink (5YR 7/4) dry; clay loam; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter $\geq$10 mm), coarse (diameter 5 – 10 mm), medium (diameter 2 -5 mm) root; very strongly acid (pH = 4.8); gradual and smooth boundary



Pedon2 2-year-old (2007 site)

Pedon3 7-year-old (2002 site)

Location: Ban Mae Sa Mai, Mae Rim District, Chiang Mai Province

N18^0 51’ 569’’, E098^0 50’ 968’’

Elevation: 1,228 m.asl.

Slope: 22 %

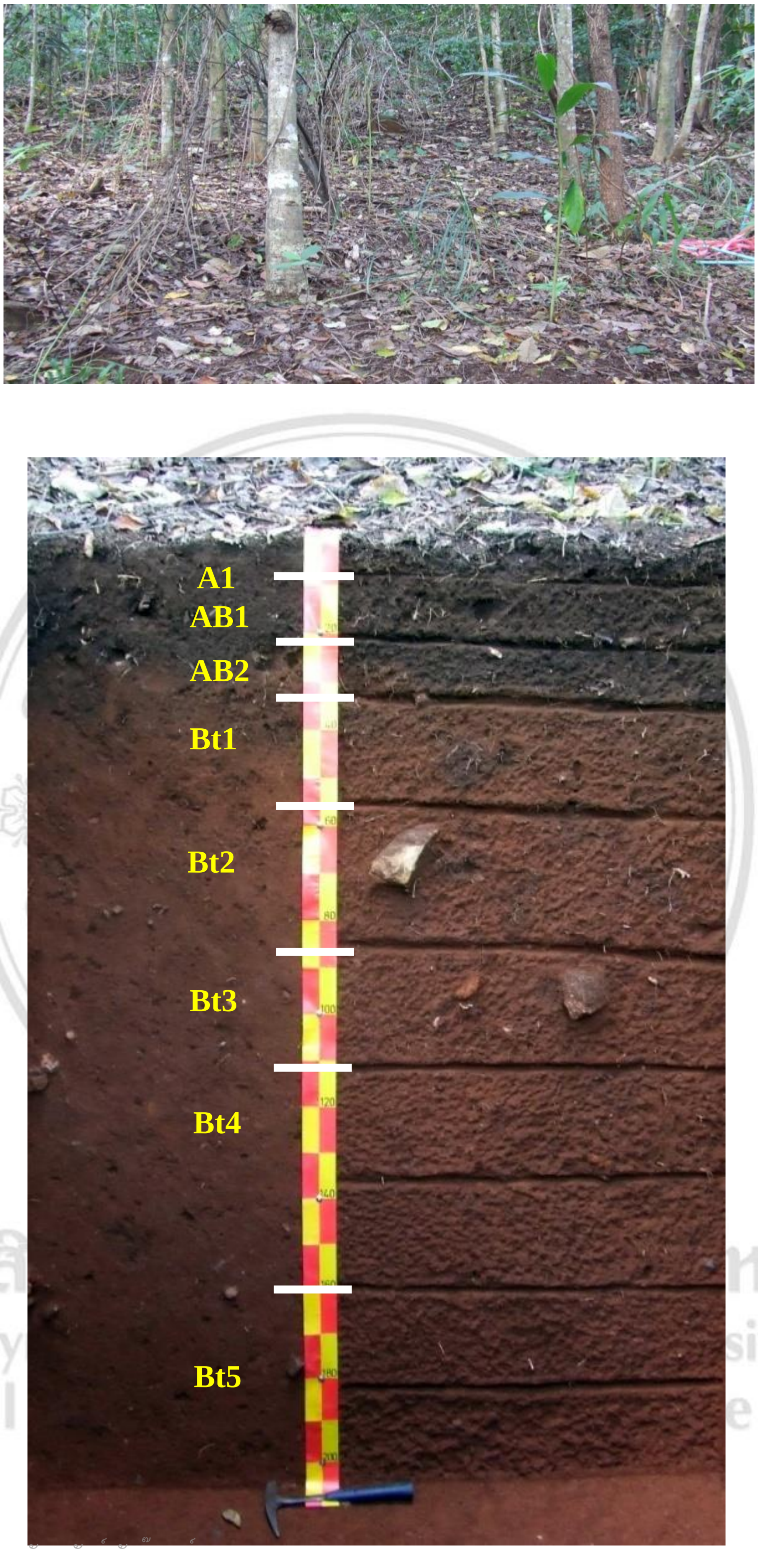
Aspect: ENE 86^0

Vegetation type: Restored forest with framework species since 2002

Horizon	**Depth (cm)**	**Description**
A1	0-6	Dark reddish brown (5YR 3/2) moist and brown (7.5 YR 4/4) dry; sandy loam; very fine granular; common (diameter 5 – 10 mm) very coarse (diameter ≥10 mm) root, few (< 1 root/ dm^3) coarse (diameter 5 – 10 mm), common (1 -5 root/dm^3) medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and many (≥ 10 dm3) very fine (diameter < 1 mm) roots; moderately acid (pH = 5.7)
AB1	6-21	Dark reddish brown (5YR 3/2) moist and brown (7.5 YR 4/4) dry; sandy loam; very fine subangular blocky; common (diameter 5 – 10 mm) very coarse (diameter ≥10 mm) root, common (1 -5 root/dm^3) coarse (diameter 5 – 10 mm), many (≥ 10 dm3) medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; moderately acid (pH = 5.7); gradual and smooth boundary

AB2	21-32	:Dark reddish brown (5YR 3/3) moist and brown (7.5 YR 4/4) dry; sandy loam; very fine subangular blocky; few (< 1 root/ dm^3) very coarse (diameter ≥10 mm) root, common (1 -5 root/dm^3) coarse (diameter 5 – 10 mm), many (≥ 10 dm3) medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; strongly acid (pH = 5.4); gradual and smooth boundary
Bt1	32-55	Dark reddish brown (2.5YR 2.5/4) moist and reddish brown (5 YR 4/4) dry; clay Loam; very fine subangular blocky; strongly acid (pH = 5.1); common (1 -5 root/dm^3) very coarse (diameter ≥10 mm) root, coarse (diameter 5 – 10 mm), many (≥ 10 root/dm^3) medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; strongly acid (pH = 5.1); gradual and smooth boundary
Bt2	55-85	Dark reddish brown (2.5YR 3/4) moist and red (2.5 YR 4/6) dry; sandy clay loam; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm), coarse (diameter 5 – 10 mm), many (≥ 10 dm^3) medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.8); gradual and smooth boundary
Bt3	85-110	Dark reddish brown (2.5YR 3/4) moist and red (2.5 YR 4/6) dry; clay loam; very fine subangular blocky; common (1 -5 root/dm^3) coarse (diameter 5 – 10 mm) root and medium (diameter 2 -5 mm), many (≥ 10 dm^3) fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.8); gradual and smooth boundary

Bt4	110-160	Dark red (2.5YR 3/6) moist and red (2.5 YR 4/6) dry; clay loam; very fine sub angular blocky; few (< 1 root/ dm^3) very coarse (diameter $\geq$10 mm), common (1 -5 root/dm^3) coarse (diameter 5 – 10 mm), medium (diameter 2 -5 mm) , fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.9); gradual and smooth boundary
Bt5	$160\text{-}200^+$	Dark red (2.5YR.3/6) moist and red (2.5 YR 5/6) dry; clay loam; very fine subangular blocky; common (1 -5 root/dm^3) fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.9); gradual and smooth boundary



Pedon3 7-year-old (2002 site)

Pedon 4 11-year-old (1998 site)

Location: Ban Mae Sa Mai, Mae Rim District, Chiang Mai Province

N18^0 51’ 410’’, E098^0 50’ 881’’

Elevation: 1,332 m.asl.

Slope: 9 %

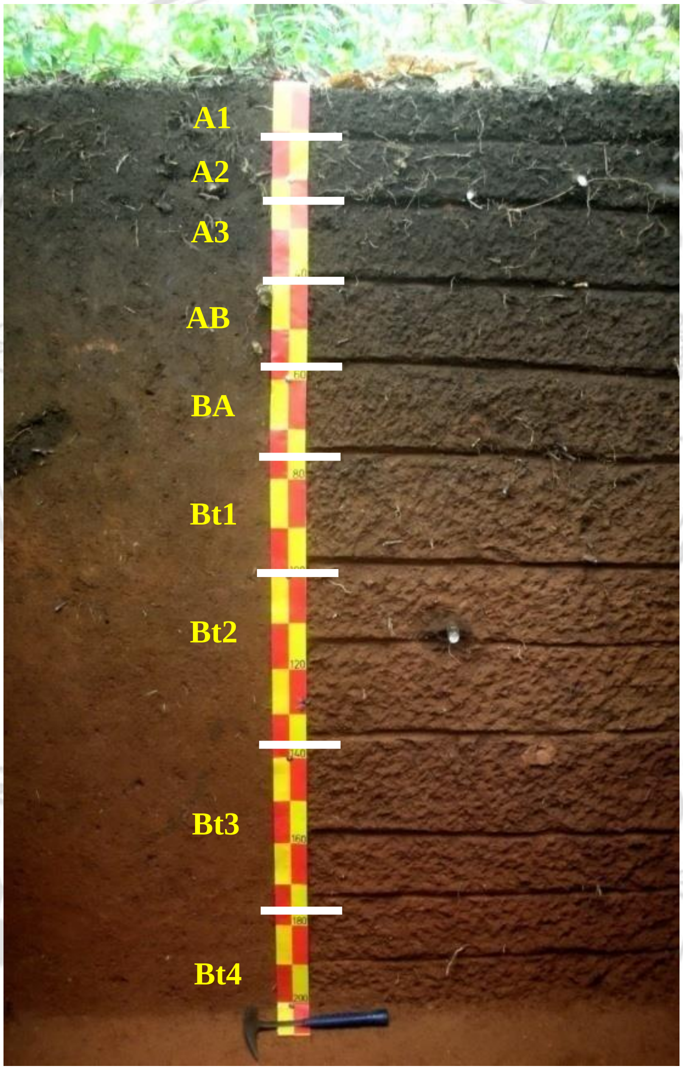
Aspect: NNW 352^0

Vegetation type: Restored forest with framework species since 1998

Horizon	**Depth (cm)**	**Description**
A1	0-10	Black (5YR 2.5/1) moist and dark reddish grey (5YR 4/2) dry; sandy loam; very fine subangular blocky; many (≥ 10 dm^3) very coarse root (diameter ≥10 mm), coarse (diameter 5 – 10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine roots (diameter < 1 mm); very strongly acid (pH = 4.8); charcoal presented
A2	10-23	Black (5YR 2.5/1) moist and dark reddish grey (5YR 4/2) dry; sandy loam; very fine subangular blocky; many (≥ 10 dm^3) very coarse root (diameter ≥10 mm), coarse (diameter 5 – 10 mm) , medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine roots (diameter < 1 mm); extremely acid (pH = 4.4); gradual and smooth boundary; charcoal presented
A3	23-39	Black (5YR 2.5/1) moist and reddish grey (5YR 5/2) dry; sandy loam; very fine subangular blocky; common (1 -5 dm^3) very coarse root (diameter ≥10 mm), coarse (diameter 5 – 10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine roots (diameter < 1 mm); strongly acid

		(pH = 5.4); gradual and smooth boundary; charcoal presented
AB	39-55	Dark reddish brown (5YR 3/2) moist and reddish brown (5YR 5/4) dry; sandy clay loam; very fine subangular blocky; common (1-5 root / dm^3) , very coarse root (diameter ≥10 mm), coarse (diameter 5 – 10 mm), many (≥ 10 dm^3) medium, fine and very fine roots; extremely acid (4.4); gradual and smooth boundary; charcoal presented
BA	55-74	Dark reddish brown (5YR.3/2) moist and reddish yellow (5YR 6/6) dry; sandy clay loam; very fine subangular blocky; few (< 1 root/dm^3) very coarse root (diameter ≥10 mm), coarse (diameter 5 – 10 mm), common medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine roots(diameter < 1 mm); extremely acid (pH = 4.31); gradual and smooth boundary; charcoal presented; weathered root pore presented
Bt1	74-97	Dark reddish brown (5YR 3/4) moist and reddish yellow (5YR 6/6) dry; sandy clay loam; very fine subangular blocky; few (< 1 root/ dm^3) very coarse root (diameter ≥10 mm), coarse (diameter 5 – 10 mm), common (1 -5 root/dm^3) medium (diameter 2 -5 mm) , fine (diameter 1 -2 mm) and very fine roots (diameter < 1 mm); extremely acid (pH = 4.31); gradual and smooth boundary; charcoal presented
Bt2	97-132	Dark red (2.5 YR 3/6) moist and reddish yellow (5YR 6/8) dry; clay loam; very fine subangular blocky; few (<1 root/dm^3) very coarse (diameter ≥10 mm) , coarse (diameter 5 – 10 mm), medium (diameter 5 – 10 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; extremely acid (4.41); gradual and smooth boundary; charcoal presented

Bt3	132-171	Dark red (2.5 YR 3/6) moist and reddish yellow (5YR 6/8) dry; clay loam; very fine subangular blocky few (< 1 root/ dm^3) very coarse (diameter ≥10 mm) root, coarse (diameter 5 – 10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.95); gradual and smooth boundary
Bt4	$171\text{-}200^+$	Dark red to red (2.5 YR.3/6) moist and reddish yellow (5YR 7/8) dry; clay; very fine subangular blocky; few(< 1 root/ dm^3) very coarse (diameter ≥10 mm), coarse (diameter 5 – 10 mm), medium (diameter 2 -5 mm) , fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; strongly acid (pH = 5.24); gradual and smooth boundary



Pedon 4 11-year-old (1998 site)

Pedon5 Natural site

Location: Ban Mae Sa Mai, Mae Rim District, Chiang Mai Province

N18^0 51’ 893’’, E098^0 51’ 717’’

Elevation: 1,288 m.asl.

Slope: 14 %

Aspect: WSW 266^0

Vegetation type: Natural hill evergreen forest

Horizon	**Depth (cm)**	**Description**
A1	0-6	Black (5YR 2.5) moist and dark brown (7.5YR 3/4) dry; sandy clay loam; very fine subangular blocky; many ($\geq$ 10 dm^3) very coarse (diameter $\geq$10 mm), coarse (diameter $\geq$10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.5)
A2	6-11	Very dark grey (5YR 3/1) moist and dark reddish brown (5YR 3/3) dry; sandy clay loam; very fine subangular blocky; many ($\geq$ 10 dm^3) very coarse (diameter $\geq$10 mm), coarse (diameter $\geq$10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.5); gradual and smooth boundary

AB	11-26	Dark reddish brown (2.4YR 2.5/4) moist and yellowish red (5YR 4.5/6) dry ; sandy clay loam; very fine subangular blocky; many (≥ 10 dm^3) very coarse (diameter ≥10 mm) root, coarse (diameter ≥10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; extremely acid (pH = 4.4); gradual and smooth boundary
Bt1	26-48	Dark reddish brown (2.5YR 3/4) moist and red (2.5YR 4/6) dry; sandy loam; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm), and coarse (diameter ≥10 mm), many (≥ 10 dm^3) medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; moderately acid (pH = 5.6); gradual and smooth boundary
Bt2	48-70	:Dark reddish brown (2.5YR 3/4) moist and red (2.5YR 4/6) dry; clay; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm), coarse (diameter ≥10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; extremely acid (pH = 4.3); gradual and smooth boundary
Bt3	70-91	Dark reddish brown (2.5YR 3/4) moist and red (2.5YR 4/6) dry; clay; very fine subangular blocky; common (1 -5 root/dm^3) very coarse (diameter ≥10 mm), coarse (diameter ≥10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; extremely acid (pH = 4.3); gradual and smooth boundary

Bt4	91-131	Dark red (2.5YR 3.5/6) moist and red (2.5YR 4.5/8) dry; clay; very fine subangular blocky; few (< 1 root/dm^3) very coarse (diameter $\geq$10 mm), coarse (diameter $\geq$10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.6); gradual and smooth boundary
Bt5	131-200$^+$	Dark red (2.5YR 3.4/6) moist and red (2.5Yr 5.5/8) dry ; clay; very fine sub angular blocky; few (< 1 root/dm^3) very coarse (diameter $\geq$10 mm), coarse (diameter $\geq$10 mm), medium (diameter 2 -5 mm), fine (diameter 1 -2 mm) and very fine (diameter < 1 mm) roots; very strongly acid (pH = 4.6); gradual and smooth boundary

Figure 4. Natural site

Soil horizon designations

Master horizons and layers

Master, or major, horizons in this study are designated by the following capital letters.

A Mineral horizons at the soil surface: A horizons have humified organic matter mixed with mineral material and result from the decomposition of rootsnor from cultivation that has physically disturbed the horizon.

B Mineral horizons formed below A horizons in which parent material has been significantly altered by concentrations of silicate clay, iron, aluminum,carbonates, gypsum, or humus or by removal of the more soluble components: There are many kinds of B horizons, but the main consideration in identifying a B horizon is that it formed as subsoil, below one or more horizons, and is significantly different from the material in which it was formed as a result of pedogenic processes.

Transitional and combination horizons

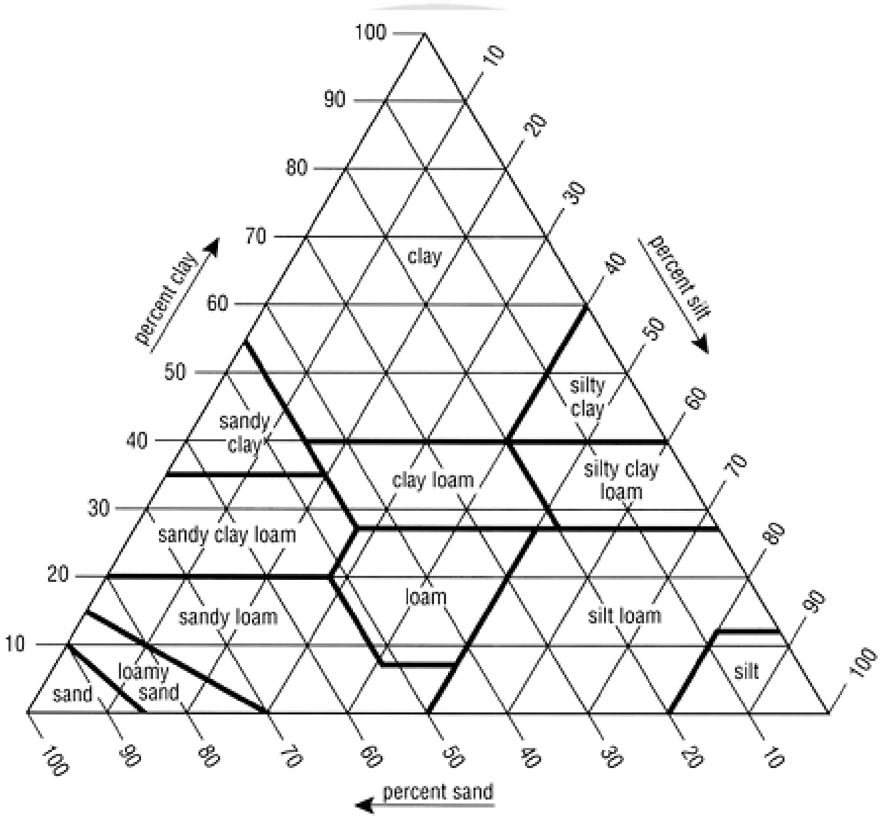
Where a substantial thickness is present between two master horizons, a transitional or combination horizon may be described. Transitional horizons, which are dominated by propertied of one master horizon while having subordinate properties of an adjacent master horizon capital letters. The first letter indicates the dominant master horizon characteristics. In this study found transitional horizon as an AB horizon and a BA horizon. An AB horizon is transitional horizon between the A and B horizons that is more like the A horizon than the B horizon. While BA horizon is more like the B than the A horizon.

Subordinate distinctions within master horizons and layers

Lowercase letters are used to designate specific features within master horizons. In this study, B horizon followed by t indicates that this horizon is the horizon with accumulation of silicate clay coating on ped faces, in pores, or as bridges between sand-size mineral grains: The clay coats may be formed by either clay illuviation or migration within the horizon.

APPENDIX C

Soil texture



Percentage of sand, silt and clay in the basic textural classes

1. Groupings of soil texture classes

General terms	Texture classes
Sandy soil materials:	
Coarse-textured	Sands (coarse sand, sand, fine sand, very fine sand), Loamy sands (loamy coarse sand, loamy sand, loamy fine sand, loamy very fine sand)
Loamy soil materials:	
Moderately coarse-textured	Coarse sandy loam, sandy loam, fine sandy loam
Medium-textured	Very fine sandy loam, loam, silt loam, silt
Moderately fine-textured	Clay loam, sandy clay loam, silty clay loam
Clayey soils:	
Fine-textured	Sandy clay, silty clay, clay

2. **Root quantity and size (**Soil Survey Division Staff, 1993)

Quantity of roots	Numbers of each size per unit area
Few	< 1 per unit area
Very few	< 0.2 per unit area
Moderately	0.2 – 1 per unit area
Common	1 – 5 per unit area
Many	>5 per unit area

Size class	Diameter size (mm)
Very fine	< 1
Fine	1 – 2
Medium	2 – 5
Coarse	5 – 10
Very coarse	>10

3. Bulk density

Rating	Bulk density (Mg m^{-3})
Low	<1.2
Moderately Low	1.2–1.4
Medium	1.4–1.6
Moderately High	1.6-1.8
High	1.8-2.0
Very High	>2.0

4. pH (Soil Survey Division Staff, 1993)

Rating	Range
Ultra acid	< 3.5
Extremely acid	3.5-4.4
Very strongly acid	4.5-5.0
Strongly acid	5.1-5.5
Moderately acid	5.6-6.0
Slightly acid	6.1-6.5
Neutral	6.6-7.3
Slightly alkaline	7.4-7.8
Moderately alkaline	7.9-8.4
Strongly alkaline	8.5-9.0
Very strongly alkaline	> 9.0

5. **Organic matter** (% organic carbon x 1.724)

Rating	Range (g.kg^{-1})
Very low	< 5
Low	5– 10
Moderately low	10 – 15
Medium	15 – 25
Moderately high	25 – 35
High	35 – 45
Very high	>45

6. **Total nitrogen** (Land use planning division, 1993)

Rating	Range (g.kg^{-1})
Very low	< 1.0
Low	1.0 – 2.0
Medium	2.0 -5.0
High	5.0 – 7.5
Very high	> 7.5

7. **Available P** (Bray II)

Rating	Range (g.kg^{-1})
Very low	< 3
Low	3 - 6
Moderately low	6 – 10
Medium	10 -15
Moderately high	15 - 25
High	25 – 45
Very high	>45

8. Available K (NH_4OAc)

Rating	Range ($mg.kg^{-1}$)
Very low	<30
Low	30 – 60
Medium	60 – 90
High	90 – 120
Very high	>120

9. Extractable bases (NH_4OAc)

Rating	Range ($cmol\ kg^{-1}$)				
	extr. Ca	extr.Mg	extr.K	extr.Na	extr. bases
Very low	<2.0	<0.3	<0.2	<0.1	<2.6
Low	2 - 5	0.3 – 1.0	0.2 – 0.3	0.1 – 0.3	2.6 – 6.6
Medium	5 – 10	1.0 – 3.0	0.3 – 0.6	0.3 – 0.7	6.6 – 14.3
High	10 -20	3.0 – 8.0	0.6 – 1.2	0.7 – 2.0	14.3 – 31.2
Very high	>20	>8.0	>1.2	>2.0	>31.2

10. CEC

Rating	Range ($cmol\ kg^{-1}$)
Very low	<3
Low	3 -5
Moderately low	5 -10
Medium	10 – 15
Moderately high	15 – 20
High	20 – 30
Very high	>30

11.Base saturation

Rating	Range (%)
Low	<35
Medium	35 – 75
High	>75

12. Soil fertility estimation

Soil fertility level	Organic matter (g kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	CEC (cmol kg^{-1})	Base saturation (%)
Low	<15 (1)	<10 (1)	<60 (1)	<10 (1)	<35 (1)
Medium	15 – 35 (2)	10 – 25 (2)	60 – 90 (2)	10 -20 (2)	35 – 75 (2)
high	>35 (3)	>25 (3)	>90 (3)	>20 (3)	>75 (3)

Note: If sum of score ≤ 7 indicates low fertility soil

8 – 12 indicates medium fertility soil

≥13 indicates high fertility soil

CURRICULUM VITAE

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Education	Academic Year	Degree, Major, Institution
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