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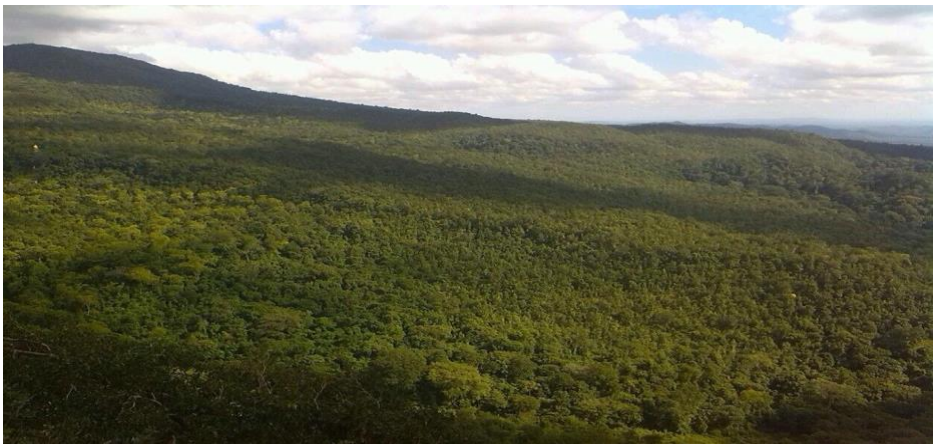
Investigation of the Ecological Characteristics of Forests and Development of Site-specific Carbon Storage Model of Species across Different Rainfall Regions in Myanmar



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မိုးရေချိန်အလိုက် သစ်တောများ၏ ဂေဟဗေဒဆိုင်ရာ အချက်အလက်များနှင့် ကာဗွန်သိုလှောင်မှု ပမာဏ ကွဲပြားမှုများကို လေ့လာခြင်းနှင့် ကာဗွန်သိုလှောင်မှု မိုဒယ်တည်ဆောက်ခြင်း

ဒေါက်တာ အင်ကြင်းခိုင် (ဦးစီးအရာရှိ) ၊ သစ်တောဖွံ့ဖြိုးရေးဌာနခွဲ ၊
သစ်တောသုတေသနဌာန၊
Su Young Woo (Ph.D), Professor, Department of Environmental Horticulture, College of Natural Sciences, University of Seoul, South Korea

စာတမ်းအကျဉ်း

သစ်တောများသည် သဘာဝပတ်ဝန်းကျင်ကောင်းများဖြစ်ပေါ်စေပြီး ရာသီဥတုညီညွတ်မှုတစေဖို့နှင့် ဂေဟဗေဒဆိုင်ရာ ထာဝစဉ် တည်တံ့စေဖို့အတွက် အဓိက အခန်းကဏ္ဍမှ ပါဝင်နေသည့်အတွက် သစ်တောများကို ထိန်းသိမ်းကာကွယ်ခြင်းသည် အလွန်အရေးကြီးပါသည်။ ထိုသို့ သစ်တောများကို စနစ်တကျထိန်းသိမ်းရန်အတွက် အခြေခံလိုအပ်ချက် တစ်ခုမှာ ရာသီဥတုဆိုင်ရာ ပြောင်းလဲမှုများနှင့် သစ်တောများ၏ ကာဗွန်သိုလှောင်နိုင်မှု၊ ဖွဲ့စည်းပုံ၊ ကြီးထွားမှု၊ အပင်မျိုးစုံမျိုးကွဲ စသည့် ဂေဟဗေဒ ဆိုင်ရာ လက္ခဏာရပ်များ မည်သို့မည်ပုံ ဆက်စပ်ပြောင်းလဲနေသည်ကို လက်တွေ့ကျကျ သုတေသနပြုလေ့လာထားသော ရလာဒ်များ ရရှိထားရန် ဖြစ်ပါသည်။ သို့ဖြစ်ပါ၍ ဤသုတေသနတွင် နှစ်စဉ်မိုးရေချိန်ရရှိမှု မတူညီသော ဒေသများအတွင်း (၂,၀၃၅ မီလီမီတာ မှ ၆၂၅ မီလီမီတာ အတွင်း) သစ်တောများ၏ ဂေဟဗေဒဆိုင်ရာ ပြောင်းလဲမှုနှင့် ရာသီဥတု ဆိုင်ရာ အချက်အလက် များသိသာစွာ ဆက်စပ်နေမှုများကို correlation and correspondence အရ ဖော်ထုတ်ထားပါသည်။ အသေးစိတ်အားဖြင့် မိုးရေချိန် ၂,၀၀၀မှ ၁,၄၀၀ မီလီမီတာ ဝန်းကျင်အတွင်း ဒေသတစ်ခုနှင့် တစ်ခု မိုးရေချိန်ရရှိမှု ကွာခြားချက် ၄၀၀ မီလီမီတာ ရှိသည်အထိ သစ်တောများ၏ အပင်မျိုးစုံမျိုးကွဲ ဖွဲ့စည်းပုံကို သိသာစွာ ပြောင်းလဲမှု မရှိပါ။ သို့သော် မိုးရေချိန် ၁,၄၀၀မီလီမီတာ အောက် မိုးရေချိန် ၂၀၀ မီလီမီတာ ထပ်မံလျော့သွားသည်နှင့်တစ်ပြိုင်နက် သစ်တောများ၏ အပင်မျိုးစုံမျိုးကွဲ ဖွဲ့စည်းပုံများ သိသိသာသာ ပြောင်းလဲသွားသည်ကို တွေ့ရှိရပါသည်။ ထို့အတူ ဂေဟဗေဒ ဆိုင်ရာ အကွာအဝေးများအရ သစ်တောများကို အမျိုးအစား သုံးမျိုးခွဲခြားခဲ့ပါသည်။ မိုးရေချိန် ၂,၀၀၀ မှ ၁,၄၀၀ မီလီမီတာ အထိ အုပ်စု ၁၊ မိုးရေချိန် ၁,၀၀၀ မှ ၈၄၀ မီလီမီတာ အထိ အုပ်စု ၂၊ မိုးရေချိန် ၆၀၀ ဝန်းကျင်ရှိသော ဒေသတွင် တွေ့ရသော တောများကို အုပ်စု ၃ စသည်ဖြင့် ခွဲခြားခဲ့ပါသည်။ ထို့အပြင် စာရင်းကောက်ဒေသများ၏ နေရာ တော်တော်များများတွင် တွေ့ရသော ပျဉ်းကတိုးသစ်မျိုး၏ ကာဗွန်သိုလှောင်သည့် ပမာဏကို တွက်ချက်နိုင်သည့် မိုဒယ် အသစ်ကို တည်ဆောက်နိုင်ခဲ့ပါသည်။

Investigation of the Ecological Characteristics of Forests and Development of Site-specific Carbon Storage Model of Species across Different Rainfall Regions in Myanmar

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Abstract

Forest plays an important role for environmental stability and ecological sustainability because it could be a sink of carbon while it could be a source of carbon emission. Conservation of forest ecosystem is essential for climate change regulation. To do so, understanding the reciprocities among climate change, forest growth, species diversity and carbon storage of forest is necessary for ecosystem conservation. This could be the reason of why the researchers relating about forest growth and structure, composition, climate and carbon have been given a special attention in recent years in each specific region. An understanding of how species diversity, richness, structural pattern, and carbon storage of forests vary across different environmental regions is crucially important for tropical ecology. Therefore, the changes of these ecological parameters across various rainfall regions in Myanmar (with annual rainfall ranging from 625 to 2,035 mm) were explored in this study. The study revealed that the climatic factors were strongly correlated with species diversity, stand structure and above-ground carbon storage of forests. However, a difference in annual rainfall of approximately 400 mm among sites did not significantly affect the species diversity of tropical forest across a precipitation gradient (annual rainfall = 1,411 ~ 2,035 mm). But a significant effect of rainfall on species diversity occurred between two rainfall ranges; (1) annual rainfall of 1,411 ~ 2,035 mm, and (2) annual rainfall of 625 ~ 1,029 mm. Species distributions were different between high and low rainfall regions, and the dominance of species was absolutely different between the two forests when a difference of annual rainfall between two sites was approximately 1,200 mm. Within a precipitation gradient of this study, the forests could be categorized into three groups in accordance with the similarity (ecological distance): the forests with annual rainfall of 1,411 to 2,035 mm could be considered one group (group I); the forests with annual rainfall of 843 to 1,029 mm could be considered another group (group II); and the forests with 625 mm of annual rainfall could be clarified as group III. Moreover, the new carbon storage model that would be the best fit for *Xylia xylocarpa* Roxb. Taub. species was developed by this study.

Keywords: Aboveground carbon; annual rainfall; climatic factors; ecological distance; new model; species diversity; structure; *Xylia xylocarpa* Roxb. Taub.

I. Investigation of the Ecological Characteristics of Forests and Development of Site-specific Carbon Storage Model of Species across Different Rainfall Regions in Myanmar

II. Introduction

Nowadays global warming caused by environmental pollution is one of the major problems that need to be controlled as a worldwide problem. Noticeable changes of weather and climate have been found since a few decades ago (IPCC 2014). Carbon dioxide emission is one of the main reasons of global warming. There are many sectors that emit CO_2. Among them deforestation and forest degradation have been occurred as a main source of carbon emission. Global forest areas decreased from 4,128 M ha to 3,999 M ha (1990 ~ 2015) (Keenan et al. 2015), and generally, 0.9 Pg C yr^{-1} came from the emission of CO_2 from forest degradation and deforestation (IPCC 2013). On the other hand, forests could be considered as a sink of carbon because it can be estimated that the world forests stored over 500 Pg of carbon (FAO 2016). Therefore, forest conservation plays a vital role for climate change regulation. For this, researches relating on species distribution, structure and their response to environmental factors have been broadly accepted as core concepts of ecological study (Toledo et al. 2012; Condit et al. 2013; Amissah et al. 2014) as well as a pivotal role for the regulation of climate change (Khaine and Woo 2015; Sevegnani et al. 2016).

Many researchers agreed that we still need to learn about the variation in species diversity, stand structure and carbon storage of forests through different rainfall areas since forests always vary with locality and climate (Kyaw 2003; Kalacska et al. 2004; Feroz et al. 2015; Johnson et al. 2017; Nlung-Kweta et al. 2017). Additionally, the outputs from species-environmental relationships can be used as indicators for environmental conditions, and the patterns and species diversity of forests can be used to clarify ecological phytogeography (Diekmann 2003; Toledo et al. 2011b).

Although this kind of investigation has been critically important for tropical ecology, detailed data focused on tropical forests are very limited (Rui-Jaen and Potvin 2010; Toledo et al. 2011b; Thompson et al. 2014; Khaine and Woo 2015; Chheng et al. 2016). In Southeast Asian regions, particularly in Myanmar which has one of the highest forest coverage and the richest in biodiversity of Indo-Pacific region due to the variety of climatic conditions throughout the country, the floristic diversity of tropical forests in relation to different climates, which can be used to elucidate the ecological phytogeography, remains poorly understood. Most of the researches explored the changes of diversities under different management systems such as natural forests and plantation (or) reserve forest and unprotected forests (Htun et al. 2011; Khai et al. 2016; Tun et al. 2016) or focusing on a particular region (Khaing and Mitloehner 2014; Tun et al. 2016).

So, it is necessary to find out floristic diversity and patterns of tropical forests for elucidating the ecological phytogeography, and to explore the rainfall difference between two regions that make a significant variation of diversity and structure of forests between the two regions.

In cases of developing above-ground carbon storage models, one of the major origins of errors in the estimation of the above-ground carbon storage, especially in tropical regions, was the dearth of standard or site-specific or species-specific models for one particular site or species (Chave et al. 2005; Shettles et al. 2015). Several studies, in general, quantified the carbon storage by previous published models developed by other countries or organizations as the destructive method makes time consumption and costly in comparison with non-destructive methods. Most of the studies commonly used previously reported models pointed

out by FAO forest assessment, such as models developed by Martinez-Yrizar et al. (1992), Brown et al. (1997), Chave et al. (2005, 2014) and yield tables (Castro-Izaguirre et al. 2016; Fekete et al. 2017; Sullivan et al. 2017).

However, applications of such kinds of formulas in several regions made uncertainty and errors for the estimation of carbon storage because there were various growth patterns and wood formation of several species in different regions throughout the world (Mugasha et al. 2013). In some case it can lead under and over estimations to a serious level. Therefore, the establishment of the model for a particular site or species has been very essential for carbon estimate although it has been seldom developed in the tropical regions, particularly in developing countries. Myanmar, one of the tropical countries, has very few studies in relation to the development of carbon storage regression equation (Oo 2009; Khaine and Woo 2016; Zaw et al. 2016). Moreover, there was a lack of research on the development of models of individual species along with different rainfall gradients in Myanmar.

Therefore, this study examined the species distribution, diversity, and stand structure in various rainfall regions and developing carbon storage model of species in Myanmar. The outputs from the study may offer insight into management and ecological education that would be applicable to tropical countries. To achieve the main goal of the study, three research questions were set up in this study: (1) Do species diversity and stand structure of tropical forests vary along with a precipitation gradient (mean annual rainfall ranging from 625 to 2,035 mm per year) in Myanmar? (2) If so, how do those factors vary? (3)What will be the shape of above-ground carbon storage model of the first most dominant species in the study area?

The main objectives of the study are:

(1) To investigate the variation of species diversity and structure of tropical forests across a precipitation gradient in Myanmar;
(2) To explore the effects of climate on species diversity and structure of tropical forests;
(3) To clarify the most dominant climatic factors that affect the diversity and structure of tropical forests; and
(4) To develop a new above-ground carbon storage model of the most dominant species in the study area.

III. Materials and Methods

3.1. Study area and site description

Implementation of this research was done in six study sites having a range of 625 to 2,035 mm of average annual rainfall (Figure 1). The research area in ‘Yaedashae’ (site 1) was situated between the latitude of 19° 15′N to 19° 23′N and longitude of 95° 51′E to 95° 58′E. The ‘Gyobingauk’ area (site 2) was between the latitude of 18° 15′N to 18° 24′N and longitude of 95° 49′E to 95°59′E. The ‘Nattalin’ area (site 3) was located between the latitude of 18° 28′N to 18° 46′N and longitude of 95° 49′E to 95° 57′E. The ‘Pauk’ (site 4) and ‘Seikphyu’ (site 5) areas were located between the latitude of 21° 38′N to 21° 49′N and longitude of 94° 19′E to 94° 24′E, and between the latitude of 21° 02′N to 21° 11′N and longitude of 94° 18′E to 94° 22′E, respectively. The ‘Nyaung Oo’ (site 6) was situated between the latitude of 21° 06′N to 21° 07′N and longitude of 94° 56′E to 94° 57′E.

The forests in the selected study areas were tropical deciduous forests. A diverse in species composition as well as a variety of forest structural patterns were dispersed for their representative sites. Economically important species were included in the forests, and the forests were managed by the ‘Myanmar selection system’ under a sustainable basis.

The climate of these regions was a tropical savanna climate. Through the thirty-year period (1982 to 2014), the average annual precipitation of six study sites; sites 1 to 6, were 2,035 mm, 1,600 mm, 1,411 mm, 1,029 mm, 843 mm, and 625 mm, respectively (Department of Meteorology and Hydrology of Myanmar). The maximum rainfall was 476 mm (in August) at site 1; 323 mm (in June) at site 2; 290 mm (in June) at site 3; 200 mm (in September) at site 4; 191 mm (in September) at site 5; and 124 mm (in September) at site 6. The average annual temperatures were 27°C (maximum temperature 38.1°C), 27°C (maximum temperature 38.7°C), 27.2°C (maximum temperature 38.8°C), 24.1°C (maximum temperature 34.6°C), 25.7°C (maximum temperature 36.2°C), and 27.2°C (maximum temperature 39.5°C) at sites 1, 2, 3, 4, 5, and 6, respectively.

The temperature difference among six study sites was low under the same climate conditions. Throughout the year, April showed the warmest and January showed the coldest. In this study, we used the phrase 'high' to 'low' rainfall regions to describe site 1 to site 6. At site 6, the trend of annual rainfall distribution over time is irregular; a brief increased and decreased period as it is situated at the dry zone. The climatic variables and seasonal information are shown in Table 1.

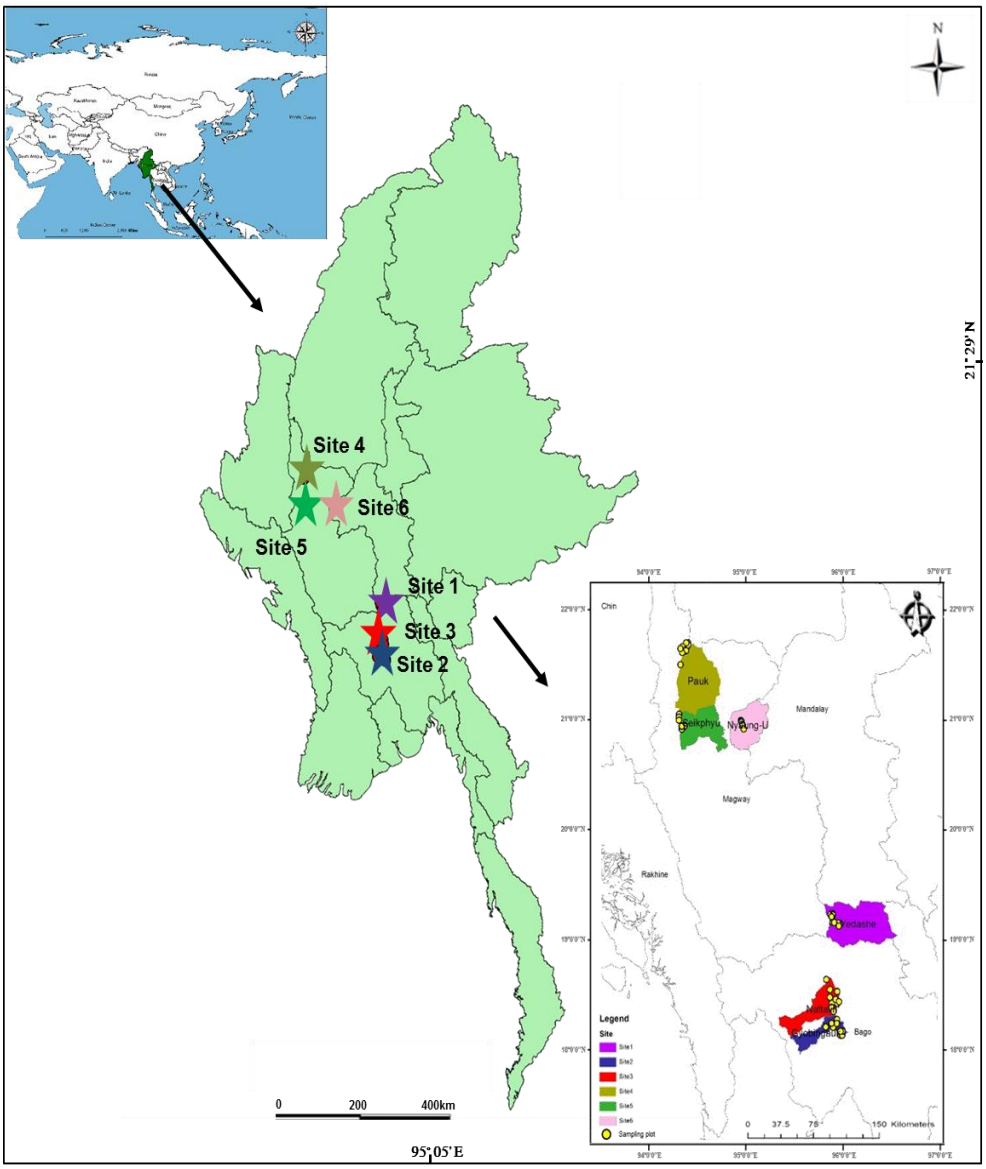

Figure 1. Map showing the study sites in Myanmar.

Climatic index of the study sites calculated by De Martonne's method (De Martonne 1926; Doerr 1963; Grieser et al. 2006) was 55.00 in site 1, 43.24 in site 2, 37.93 in site 3, 30.18 in site 4, 23.61 in site 5, and 16.80 in site 6. De Martonne's method is the widely used method to quantify the aridity (Grieser et al. 2006). The higher the index value, the less the aridity is found. Generally the value below 20 was considered as arid and semi-arid regions, and more specifically, the upper limit line for semi-arid was defined as 22.5 and arid was set as 7.5 in accordance with the study in Sonoran desert region (Doerr 1963; Paltineanu et al. 2007).

Table 1. Climatic variables at different study sites.

Site	AnR (mm)	MaxR (mm)	MinR (mm)	AnT (°C)	MaxT (°C)	MinT (°C)	Rdif (mm)	Tdif (°C)
Site 1	2,035	476	3	27.0	38.1	15.3	473	22.8
Site 2	1,600	323	1	27.0	38.7	15.4	322	23.3
Site 3	1,411	290	1	27.2	38.8	15.6	289	23.2
Site 4	1,029	200	1	24.1	34.6	12.4	199	22.2
Site 5	843	191	0	25.7	36.2	14.0	191	22.2
Site 6	625	124	0	27.2	39.5	14.5	124	25.0

AnR = mean annual rainfall, MaxR = maximum monthly rainfall, MinR = minimum monthly rainfall, AnT = mean annual temperature, MaxT = maximum temperature, MinT = minimum temperature, Rdif = the difference between the highest rainfall and the lowest rainfall of the year, Tdif = the difference between the highest and the lowest temperature of a year.

3.2. Sampling method and data collection

Sampling plots were laid down at each study site using the stratified sampling. A preliminary survey was performed in each site before establishing the sample plots. Then the forests were stratified depending on the apparent density of forests and the occurrence of minor disturbance (Khaine et al. 2017). In each stratum, the sample plots were laid out randomly so that the sample plots covered and represented the individual sites.

The size of each sample plot was 2,500 m^2 (50 m × 50 m). To obtain reliable information from the samples that were large enough to represent the whole community, the species-area curves were developed to achieve a minimum representative area of a particular community (Figure 2) (Cain 1938; Cencini et al. 2012; Khaing and Mitloehner 2014). According to the species-area curves, the sample size was set up covering 2.75 ha (11 plots) in site 1; 2.25 ha (9 plots) in site 2; 2.5 ha (10 plots) in site 3; 2.5 ha (10 plots) in site 4; 1.5 ha (6 plots) in site 5; and 1.5 ha (6 plots) in site 6.

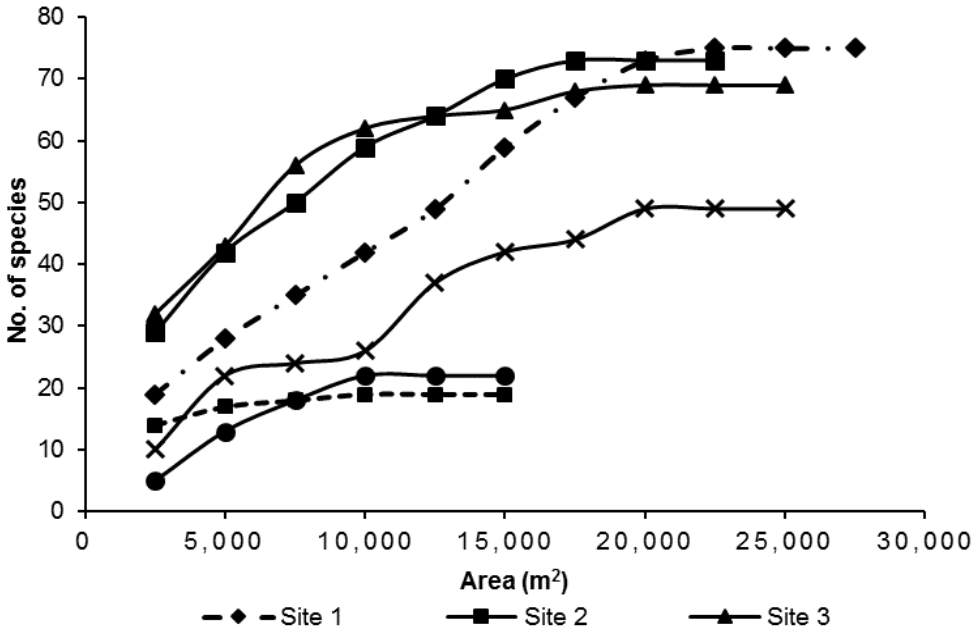

Figure 2. Species-area curves of forests at six study sites.

The measurement of tree diameter at breast height (dbh) and the height of trees greater than 5 cm in diameter was done in all of the sample plots (50 m × 50 m) at each site, covering a total of 13 ha for this study. The measurement was carried out line by line in each sample plots. The forest growth was assessed in terms of quadratic mean diameter, diameter class distribution, top height and forest layer classification. The measurement data was used to compute the quadratic mean diameter of forests and to arrange the diameter classes by 10 cm intervals. The layers of tree height were divided into three clusters: upper layer (greater than two-third of the top height), middle layer (the interval between the height of less than two-third of the top height and the height greater than one-third of the top height), and lower layer (less than one-third of the top height) (Lamprecht 1989; Oo 2009).

3.3. Data analysis

In this study, frequency diagrams were built depending on the occurrence of species (frequency class I = 1 ~ 20%, II = 20 ~ 40%, III = 40 ~ 60%, IV = 60 ~ 80% and V = 80 ~ 100%) (Lamprecht 1989; Khaing and Mitloehner 2014) because it can be used to determine the heterogeneity of the forest. The frequency of a given species was calculated as its percentage occurrence across sample plots in a particular site.

The importance value index (IVI) was also calculated to determine the dominant species of a forest (Lamprecht 1989; Oo 2009). Undoubtedly, screening of dominant species in a forest has been accepted as a core of forest ecology and management. The highest IVI value of species in a forest stand points out the most dominant species of that forest. The IVI was calculated by the following formula (Lamprecht 1989; Oo 2009):

$$IVI = RD + RF + RC$$

where, IVI = important value index
RD = relative density
RF = relative frequency
RC = relative coverage

For characterization of forests, the relative density, basal area, relative frequency and relative coverage in each forest type were expressed on a hectare basis. Identification of species was performed using "Forest flora of British Burma" (Kurz 1877) and "A checklist of the trees, shrubs, herbs and climbers of Myanmar" (Kress et al. 2003). Species richness was assessed using Jackknife species richness (Heltshe and Forrester 1983).

Duncan's multiple range test (DMRT) in one-way analysis of variance (ANOVA) was applied for the comparison of different factors such as diameter, height, basal area, and density of trees among study sites. Additionally, an independent-samples *t*-test was used to compare the composition between lower and higher frequency classes.

In case of species diversity, two commonly accepted diversity indices, namely, Shannon index (Shannon and Weaver 1949) and Simpson index (Simpson 1949) were calculated. The diversity index could be defined as a mathematical measure of species diversity of a forest. The Shannon diversity index give a favor for rare species, while the Simpson diversity index give a more outweigh to the common species (Heip et al. 1998; Oo 2009; Hakkenberg et al. 2016). Both indices are the products of the richness of species and the abundance of individual species in a forest. Duncan's multiple range tests was used to express the differences among indices.

The formula for Shannon's diversity index is as follows:

$$H' = \sum_{i=1}^{s} (Pi)(\ln Pi),$$

where, H' = Shannon's diversity index
s = the number of species in the sample
Pi = the proportion of the total sample belonging to the i^{th} species
ln = the natural logarithm

The formula for the Shannon evenness index is as follows:

$$E\ (\%) = 100\ (H'/\ln H_{max})$$

where, E = the Shannon evenness index in percentage
H' = Shannon's diversity index
H_{max} = the number of total species

The formula for Simpson's diversity index is as follows:

$$D = \sum_{i=1}^{s} \{n_i\ (n_i - 1)/N\ (N - 1)\}$$

where, $(1 - D)$ = Simpson's index of diversity
n_i = the number of individuals of species i
s = the number of species in the sample
N = the total number of individuals in the sample

To evaluate the structural diversity among various forest types, Cox index which is a measure of horizontal distribution of forest structure was used. Cox index is a product of the ratio of the variance to average density of sample plots at each site (Neumann and Starlinger 2001). So it describes the horizontal stand structure.

The similarity of forests among different sites depending on presence/absence comparison and the abundance of species was also examined. Sorenson's similarity index (Lamprecht 1989), Lamprecht modification's index (Lamprecht 1989) and Sorenson's quantifiable index (Magurran 1988) were used in this study. Sorenson's index can get from parameters; the number of species at each sites and the common species to both of the respective sites, which states the presence or absence of species, while Lamprecht modification's index and Sorenson's quantitative index were formed by the presence/absence and abundance data between two designated sites. Cluster analysis in R program was used for the classification of forest type based on ecological distance (Bray measure) among forests. Agglomerative cluster analysis using the Agnes-algorithm was applied for forest type classification.

Holdridge complexity index (HI) has been the widely used measure for the determination of ecosystem complexity (Lugo et al. 1978; Kalacska et al. 2004). ANOVA test (Duncan's multiple range test) was run for the comparison of ecosystem complexities among study sites.

Structure inequality was determined by Gini coefficient (Bose et al. 2016; Hakkenberg et al. 2016). Several studies have been proved that the inequality coefficient was very relevant to evaluate size inequality of forest structure for most ecological questions (Dixon et al. 1987; Bose et al. 2016; Hakkenberg et al. 2016). Accurate confidence intervals for variance of Gini coefficient are difficult to demonstrate that the variances of Gini coefficient are generally poor or difficult to express as numerical values, therefore the confidence intervals were calculated by bootstrap procedure (Dixon et al. 1987; Mills and Zandvakili 1997).

The formula for Gini coefficient is as follows:

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}|x_i - x_j|}{2n^2\mu}$$

where, G = Gini coefficient
x_i = the i^{th} position of individual stems of a forest stand
x_j = the $(i-1)^{th}$ position of individual stems of a forest stand
n = total individuals of a forest stand
μ = mean stem size of a forest stand

Size distribution was evaluated by the skewness and Kurtosis functions of the representative data. The skewness and Kurtosis functions have been found as the effective distinguished methods of size distribution in multi-cohort stands (Knox and Peet 1989; Hakkenberg et al. 2016). Therefore, the shape of size distribution was performed by skewness and Kurtosis of distributions.

The difference in the abundance of species and their distribution along with different rainfall regions were exemplified on the basic of species and site scores at the first two axis of the correspondence analysis (CA).

The correlations between climatic variables (average annual rainfall, maximum rainfall, average annual temperature, and the difference between maximum temperature of the warmest month and minimum temperature of the coldest month), and the attributes of diversity, richness, growth and structure of forests were evaluated based on Pearson correlation coefficient. The statistical analyses were performed using the R program (Version 3.4.2, R Foundation for Statistical Computing, Vienna, Austria, 2017) and SPSS statistical software (Version 24, International Business Machines Corporation (IBM), United States, 2016).

For the development of the carbon storage model for the first most dominant species, we explored the first dominant species of the forest and then selected that species. Five sample trees with different diameters were chosen in each forest for the destructive measurement of carbon storage of trees. One sample tree of each species which was not included in the development of carbon storage models was used for cross validation.

The trees were cut at the bottom of stems to be as close to the surface of the ground as possible. After cutting a tree, the stems and branches of a tree were cut and the leaves were picked off from a tree, and then placed the stems, branches, and leaves, separately. The stems were cut into meta-log sections. After that, the fresh weight of the stem, branches, leaves, and barks of trees were measured. The stem and branch were cut into slices. The stems were sliced into 4 cm long dich and put them into the oven at 70°C. The similar approach was applied for ovendrying of branches. 200 g of fresh leaves were used for ovendrying. After the oven-dried process, the dry stems, branches, and leaves were weighed again. Then, the dry and fresh weight ratio was explored. The biomass was obtained by multiplying that ratio with the fresh weight of a tree.

The three growth parameters, namely, diameter, height, and basal area of trees were used as tentative independent variables for the development of carbon storage model. Then the most influencing parameters on the development of models were selected in order to reduce the redundancy or error propagation of parameters in developing a model. The selection of the most influencing parameters was performed using both parameter step-wise selection and correlation/regression analysis.

The type of model form was facilitated. All types of basic linear model forms, known as linear, logarithmic, quadratic, and cubic, were considered for the establishment of carbon storage model. In addition, multilinear model and the type of model developed by Brown et al. (1989) and Martinez-Yrizar et al. (1992) were applied, also.

Although there were three growth variables for the establishment of carbon storage models, 'height' was excluded based on the results of screening independent variables process as shown in the above paragraph. Therefore, only two independent variables were applied for the establishment of carbon storage models. The model validation was carried out using the variables such as the root of mean square error and the bias.

IV. Results and Discussions

4.1. Species diversity

A total of 75 species (32 families), 73 species (30 families), and 69 species (26 families) were found at sites 1, 2 and 3, respectively, while 49 species (24 families), 22 species (12 families), and 19 species (13 families) were found at sites 4, 5 and 6. The values of the Jackknife species index at sites 1 ~ 6 were 75.83, 73.79, 69.73, 49.81, 23.00, and 20.00, respectively. Species were richer at site 1, where higher annual rainfall was occurred, in comparison with other sites, where lower annual rainfall occurred.

Diversity of forests was assessed with Shannon and Simpson diversity indices (Table 2). The Shannon index and evenness tended to increase from low to high rainfall regions. Similar results appeared in the case of the Simpson index. According to ANOVA analysis, the first three sites showed noticeable higher diversities than the other three sites ($p < 0.05$). The lowest diversity was found at the study site 5 in which one or two species were significantly overwhelming over other species.

Table 2. Different diversity indices and species richness of forests among six study sites.

Site	Shannon diversity index	Simpson diversity index	Shannon evenness	Species richness	Jackknife species index
Site 1	3.05 ± 0.25 [a]	0.95 ± 0.02 [a]	93.65 ± 1.84 [a]	75	75.83 [a*]
Site 2	3.16 ± 0.24 [a]	0.96 ± 0.02 [a]	94.74 ± 2.26 [a]	73	73.79 [a*]
Site 3	3.20 ± 0.06 [a]	0.96 ± 0.01 [a]	95.33 ± 1.52 [a]	69	69.73 [a*]
Site 4	2.26 ± 0.54 [bc]	0.87 ± 0.08 [bc]	87.93 ± 7.87 [b]	49	49.81 [b*]
Site 5	2.03 ± 0.41 [c]	0.83 ± 0.10 [c]	87.56 ± 7.65 [b]	22	23.00 [c*]
Site 6	2.47 ± 0.04 [b]	0.91 ± 0.01 [ab]	91.38 ± 1.80 [ab]	19	20.00 [c*]

Mean value ± standard deviation. Different lowercase letters indicate the difference among the sites was significant by Duncan's multiple range tests (DMRT) at $p < 0.05$. Asterisks (*) specify that the comparison among the sites was done by classification analysis.

4.2. Ecosystem complexity and structural diversity

Ecosystem complexity was assessed among the sites using Holdridge complexity index (HI). Ecosystem complexities among forests situated within a rainfall range (1,411 to 2,035 mm) were similar, likewise, those within a rainfall range (625 to 1,029 mm) were alike. However, a significant difference of ecosystem complexities was found between two different rainfall ranges (Figure 3). HI values of the first three sites showed above 20 while the values of other sites (3 to 6) displayed lower than 10.

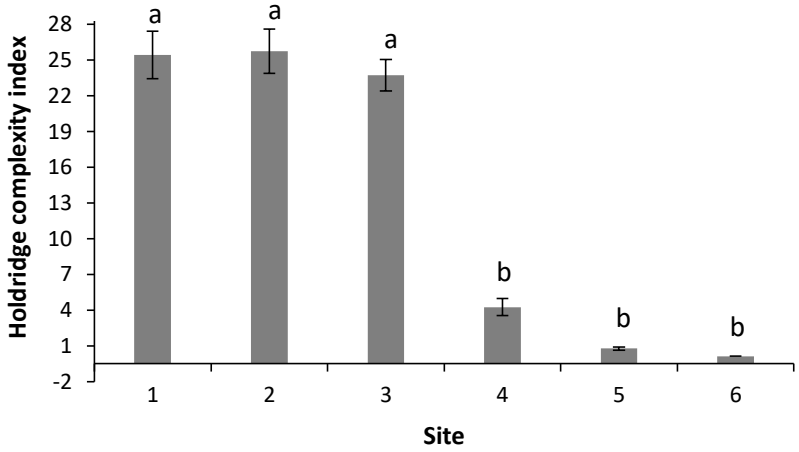

Figure 3. Holdridge complexity index of six study sites. Error bars represent standard deviations of mean values. Different lowercase letters indicate the differences among the sites was significant by Duncan's multiple range tests at $p < 0.05$.

Higher ecosystem complexity was occurred in regions with annual rainfall of 1,411 ~ 2,035 mm in tropical forests. Within the annual rainfall range of 625 ~ 1,029 mm, low ecosystem complexity was found. Then, when the annual rainfall was approximately 600 mm, the ecosystem complexity was significantly low in that region. The environmental factors showed relations (such as $r = 0.849$ by average annual rainfall, $r = 0.792$ by maximum rainfall, and $r = 0.581$ by average temperature, with the exclusive of temperature differences between maximum and minimum, at $p < 0.01$) to ecosystem complexity.

To quantify the horizontal stand structure, the structural diversity of forests among study sites was shaped by Cox index of clumping (CI). Structural diversity can be used to describe the level of dispersion in a forest (Neumann and Starlinger 2001; Good et al. 2013).

Cluster distribution or irregular distribution was found neither in higher rainfall regions nor lower rainfall regions. Structural diversities of forests over different rainfall regions in this study demonstrated as regular distributions (Figure 4). Among them, the study site 1 where the CI value resulted into 0.995, revealed as the random distribution. The CI values of sites 1 ~ 6 were 0.995, 0.612, 0.454, 0.891, 0.584, and 0.064, respectively (Figure 4). The abundance of plants among sample plots should be considered as the important parameter for managing CI structural diversity.

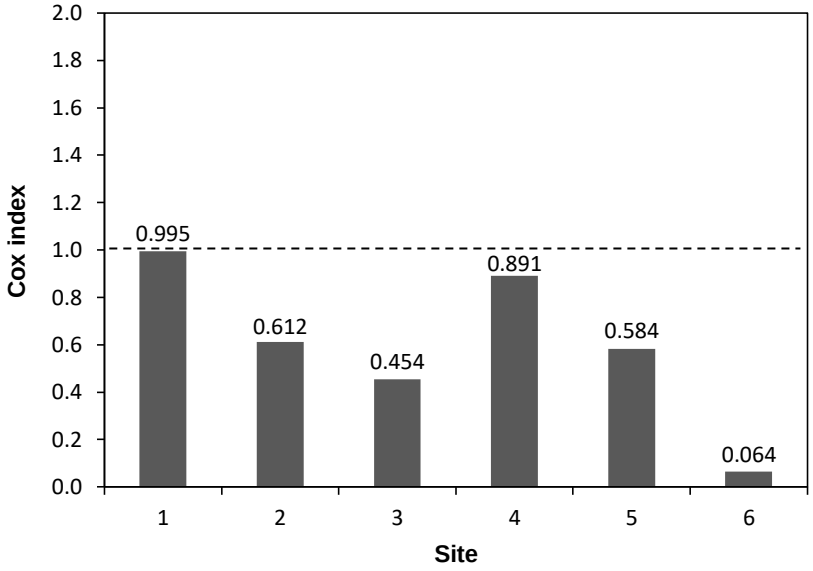

Figure 4. Cox index values among different rainfall regions showing regular distribution in forests. The point that the dotted line appears in the graph (Cox index value = 1) demonstrates the random distribution of a forest stand.

4.3. Species composition and distribution

Xylia xylocarpa, *Tectona grandis*, *Protium serrata*, *Mitragyna rotundifolia*, and *Lagerstroemia tomentosa* were the five most dominant species at site 1 (annual rainfall of 2,035 mm), showing the highest IVI values. However, in region where the annual rainfall was approximately 400 mm lower than that at site 1, the dominant species and their portions changed. For example, the result showed that *X. xylocarpa*, *Cordia grandis*, *M. rotundifolia*, *Dalbergia cultrata*, and *Lannea grandis* were the dominant species at site 2 where the annual rainfall was 1,600 mm, while *Tectona grandis*, which was one of the five most dominant species at site 1, was the ninth dominant species here. Similarly, the species dominance at site 3 was different from site 1 and site 2, with *X. xylocarpa*, *Terminalia tomentosa*, *M. rotundifolia*, *Tectona grandis*, and *P. serrata* being the five most dominant species, among which *Terminalia tomentosa* was in the 24th and 26th position of the species dominance at site 1 and site 2, respectively. The important value index, relative density, relative frequency and relative coverage of 20 dominant species of forests at the six study sites are shown in Appendices 1 ~ 6.

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In case of species distribution, the types of species distribution could vary among forests. Some types are heterogeneous while the others show homogeneous. In this study, the frequency diagrams exhibited complete representations of species in all of the frequency classes at all of the study sites (Figure 5). The significantly higher numbers of species in lower frequency classes (t = 4.255, p = 0.001) demonstrated the heterogeneity of forests for five study sites, with more than 50% of the total occurrence of species in lower classes and a maximum of 23% of total occurrence in higher classes from sites 1 to 4.

Forests found at the first four sites had greater heterogeneity than that at site 5, because the ratio of the lower classes to higher classes at the four sites was much higher than that at site 5. Thirty-five percent of species fell in higher frequency classes, while 44% of species fell in lower frequency classes at site 5 (> 50% of species was found in the lower frequency classes and up to 23% was found in the higher frequency classes at sites 1 ~ 4, compared with 44% and 35%, respectively, at site 5). However, the forest at site 6, having the least annual rainfall among the study sites, appeared as a homogeneous type. Most of the species at site 6 (73.68 % of total species) were in the higher frequency classes (IV and V).

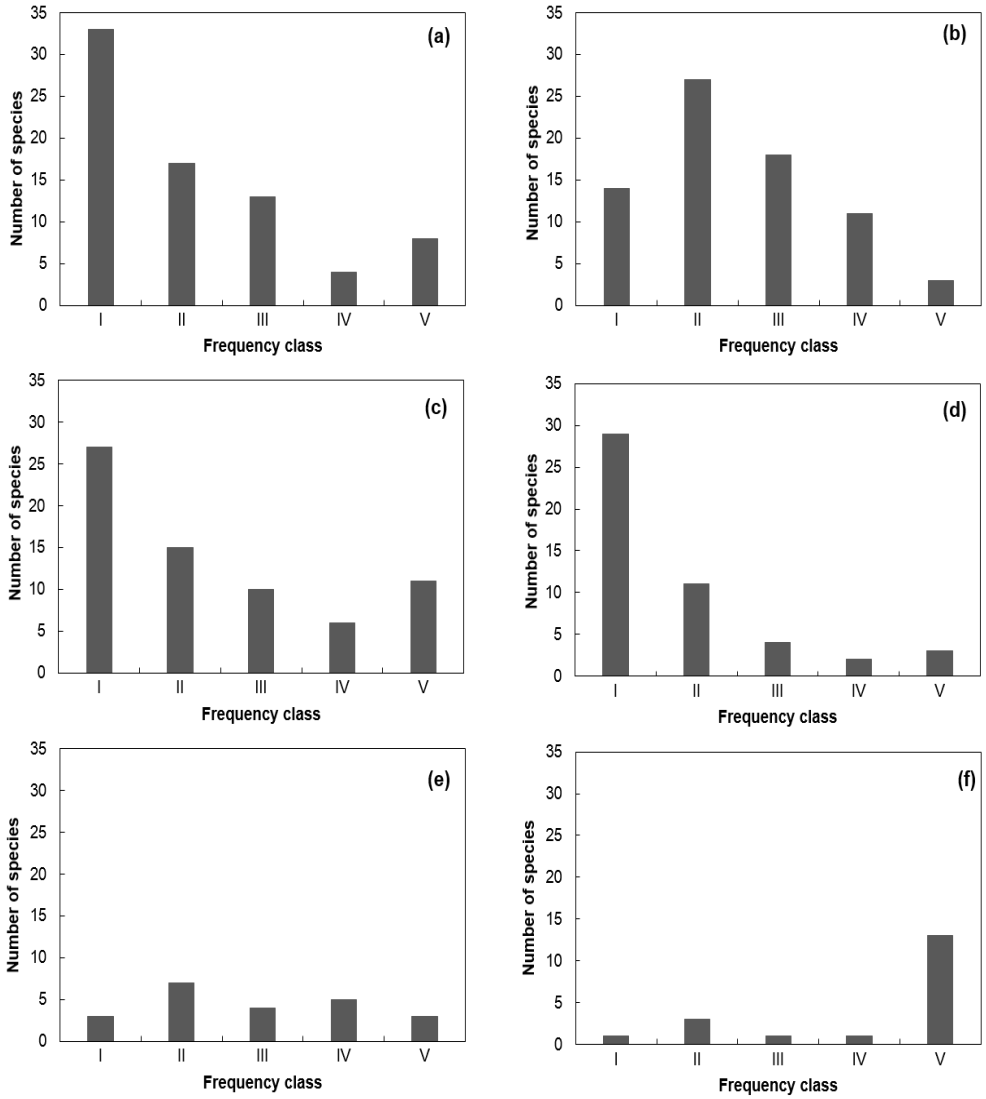

Figure 5. Frequency diagram of forests in (a) site 1; (b) site 2; (c) site 3; (d) site 4; (e) site 5; and (f) site 6.

4.4. Structure

Stand structure shows the distribution of tree growth or species in a forest and can thus reflect the interaction between vegetation growth and environmental conditions (Newton et al. 2007; Kershaw et al. 2017). The forest structure of different stands in this study was focused on both horizontal and vertical stand structures.

Diameter distribution showed positive skewness in all of the forest stands (Figure 11). The diameter size classes decreased in the order of sites 1 ~ 6. Diameter size classes greater than 100-cm comprised 6.41 m^2 ha^{-1} (14.76%) of the total basal area at site 1, 2.06 m^2 ha^{-1} (5.02%) at site 2, and 0.33 m^2 ha^{-1} (0.82%) at site 3, whereas the largest diameter size class at site 4 was 61 ~ 70 cm covering 0.26 m^2 ha^{-1} (1.27%), and the largest diameter size class at site 5 was 51 ~ 60 cm covering 0.58 m^2 ha^{-1} (3.33%) of the total basal area (Figure 11).

Diameter size classes at site 6 showed the smallest amongst the study sites. The largest diameter size class at site 6 was 21 ~ 30 cm (0.42 m^2 ha^{-1}, 19.98% of total basal area). Composition of trees was the highest in dbh 21 cm to 40 cm at site 1 and site 2, dbh 31 cm to 40 cm at site 3, dbh 21 cm to 30 cm at site 4, dbh 11 cm to 30 cm at site 5, and dbh 5 cm to 10 cm at site 6.

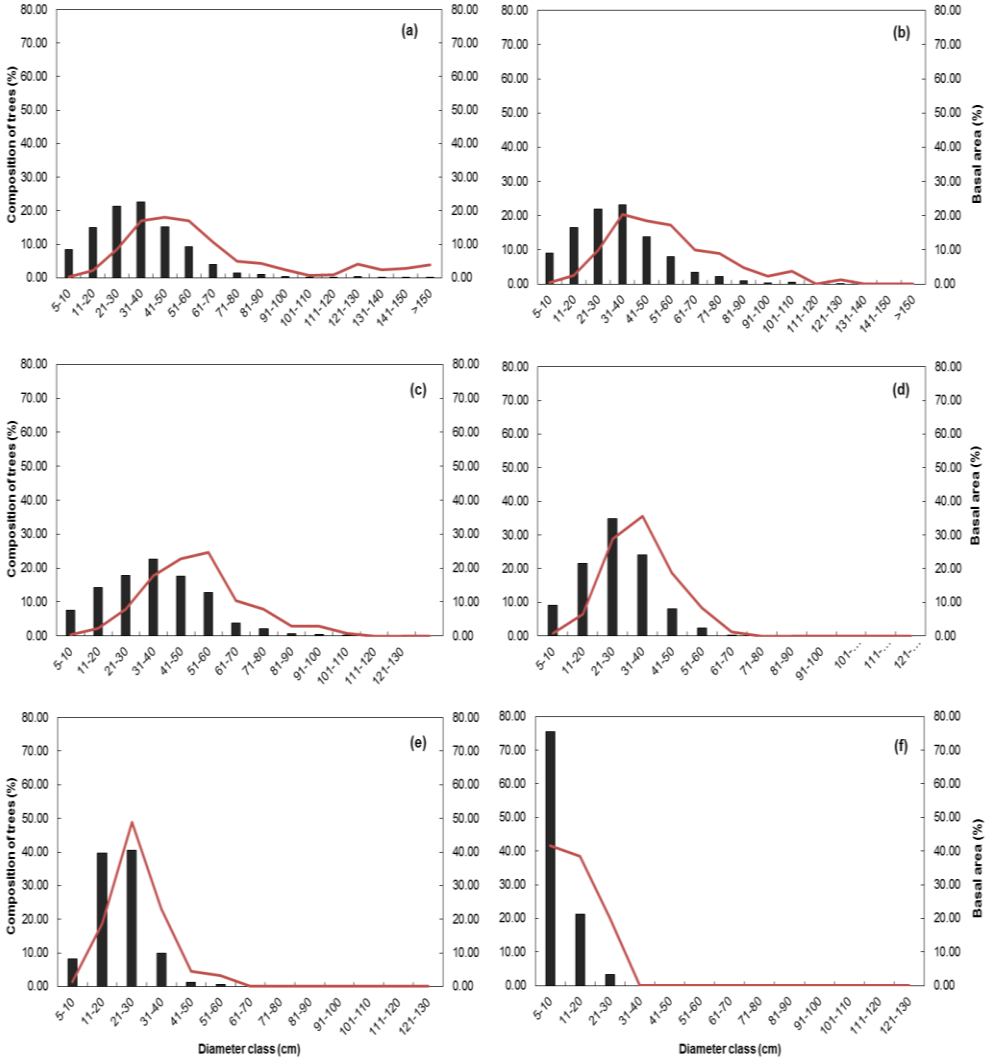

Figure 1. Composition of trees and basal area contribution in different diameter size classes of forests at (a) site 1; (b) site 2; (c) site 3; (d) site 4; (e) site 5; and site 6. Bars indicate composition of trees and red line demonstrates basal area in percent.

In the case of the vertical structure of forests, as with horizontal structure, distributions of height, diameter, basal area and tree density through the upper, middle and lower layers of forests exhibited a decreasing trend from site 1 to site 6 (Table 3). The mean tree heights of the upper, middle and lower layers at site 1 were 49.45 m, 23.35 m, and 12.6 m, respectively, whereas these values were 14.17 m, 8.96 m, and 5.09 m, respectively, at site 5, and 8.02 m, 4.48 m, and 2.93 m, respectively, at site 6. The average tree heights of the upper, middle and lower layers at site 5 were 28.65%, 38.37%, and 40.40% of site 1 while these values at site 6 were 16.22%, 19.19%, and 23.25% of site 1. Additionally, the top height of forests were significantly varied among sites, although site 2 and site 3 were similar ($p < 0.05$). The top height of forest was the highest (55.37 m) at site 1, and the lowest (9.9 m) at site 6.

Table 3. Growth and density of forests in different height layers at 6 study sites.

Site	Parameter	Upper layer	Middle layer	Lower layer
Site 1	Avg. H (m)	49.45 ± 10.09 ^{a,A}	23.35 ± 4.17 ^{b,A}	12.06 ± 3.98 ^{b,A}
	Avg. D (cm)	119.64 ± 26.74 ^{a,A}	52.18 ± 10.55 ^{b,A}	23.93 ± 9.87 ^{b,A}
	Density per ha	6.91 ± 5.25 ^{c,D}	105.82 ± 38.09 ^{b,C}	222.91 ± 61.58 ^{a,A}
	BA per ha (m^2)	8.14 ± 8.63 ^{b,BC}	23.55 ± 7.05 ^{a,A}	11.73 ± 4.02 ^{b,A}
Site 2	Avg. H (m)	29.98 ± 3.82 ^{a,B}	17.82 ± 3.22 ^{b,B}	8.57 ± 2.72 ^{c,B}
	Avg. D (cm)	76.77 ± 13.57 ^{a,B}	40.15 ± 8.81 ^{b,B}	16.67 ± 6.49 ^{c,B}
	Density per ha	24.44 ± 9.89 ^{c,BC}	193.33 ± 20.98 ^{a,A}	150.67 ± 37.09 ^{b,B}
	BA per ha (m^2)	11.66 ± 3.98 ^{b,B}	25.66 ± 2.95 ^{a,A}	3.79 ± 1.12 ^{c,B}
Site 3	Avg. H (m)	25.86 ± 3.21 ^{a,C}	16.61 ± 3.07 ^{b,C}	7.23 ± 2.20 ^{c,C}
	Avg. D (cm)	63.58 ± 10.42 ^{a,C}	36.99 ± 8.18 ^{b,C}	13.46 ± 5.18 ^{c,C}
	Density per ha	50.40 ± 8.88 ^{c,A}	194.40 ± 21.92 ^{a,A}	80.40 ± 21.94 ^{b,C}
	BA per ha (m^2)	16.43 ± 2.33 ^{b,A}	21.92 ± 2.25 ^{a,A}	1.31 ± 0.27 ^{c,C}
Site 4	Avg. H (m)	19.53 ± 2.11 ^{a,D}	12.46 ± 2.29 ^{b,D}	5.96 ± 1.28 ^{c,D}
	Avg. D (cm)	47.33 ± 5.55 ^{a,D}	28.85 ± 5.95 ^{b,D}	11.99 ± 3.32 ^{c,CD}
	Density per ha	26.80 ± 13.47 ^{c,B}	212.00 ± 29.15 ^{a,A}	82.80 ± 20.75 ^{b,C}
	BA per ha (m^2)	4.78 ± 2.66 ^{b,CD}	14.45 ± 1.64 ^{a,B}	1.01 ± 0.35 ^{c,C}
Site 5	Avg. H (m)	14.17 ± 1.99 ^{a,E}	8.96 ± 1.57 ^{b,E}	5.09 ± 0.63 ^{c,E}
	Avg. D (cm)	36.00 ± 5.66 ^{a,E}	21.29 ± 4.42 ^{b,E}	10.46 ± 1.75 ^{c,D}
	Density per ha	26.67 ± 11.77 ^{b,B}	154.00 ± 39.09 ^{a,B}	48.00 ± 14.75 ^{b,C}
	BA per ha (m^2)	2.78 ± 1.54 ^{b,D}	5.72 ± 1.29 ^{a,C}	0.42 ± 0.14 ^{c,C}
Site 6	Avg. H (m)	8.02 ± 1.02 ^{a,F}	4.48 ± 0.76 ^{b,F}	2.93 ± 0.24 ^{c,F}
	Avg. D (cm)	21.19 ± 4.68 ^{a,F}	9.07 ± 2.65 ^{b,F}	6.35 ± 0.72 ^{c,E}
	Density per ha	16.00 ± 5.66 ^{c,CD}	191.33 ± 12.75 ^{a,A}	53.33 ± 13.54 ^{b,C}
	BA per ha (m^2)	0.59 ± 0.08 ^{b,D}	1.34 ± 0.04 ^{a,D}	0.17 ± 0.05 ^{c,C}

Mean value ± standard deviation. Different lowercase letters indicate the significant differences among layers, and different uppercase letters indicate the significant differences among the study sites by Duncan's multiple range test (DMRT) at $p < 0.05$. Upper layer = tree height greater than two-third of the top height of forests, Middle layer = tree height

greater than one-third of the top height of forests but lower than two-third of the top height, Lower layer = tree height lower than one-third of the top height of the forest. Avg.H = average height, Avg.D = average diameter.

4.5. Classification of forests

The forests were classified into three clusters depending on the ecological distance (Figure 6). A dendrogram revealed that the ecological distances between sites 1 and 3 were closer and, the ecological distances between sites 4 and 5 were closer. Site 6 was classified as a separate group. Therefore, the forests with annual rainfall of 1,411 to 2,035 mm could be considered as group I; the forests with annual rainfall of 843 to 1,029 mm could be considered as group II; and the forests with 625 mm of annual rainfall could be clarified as group III.

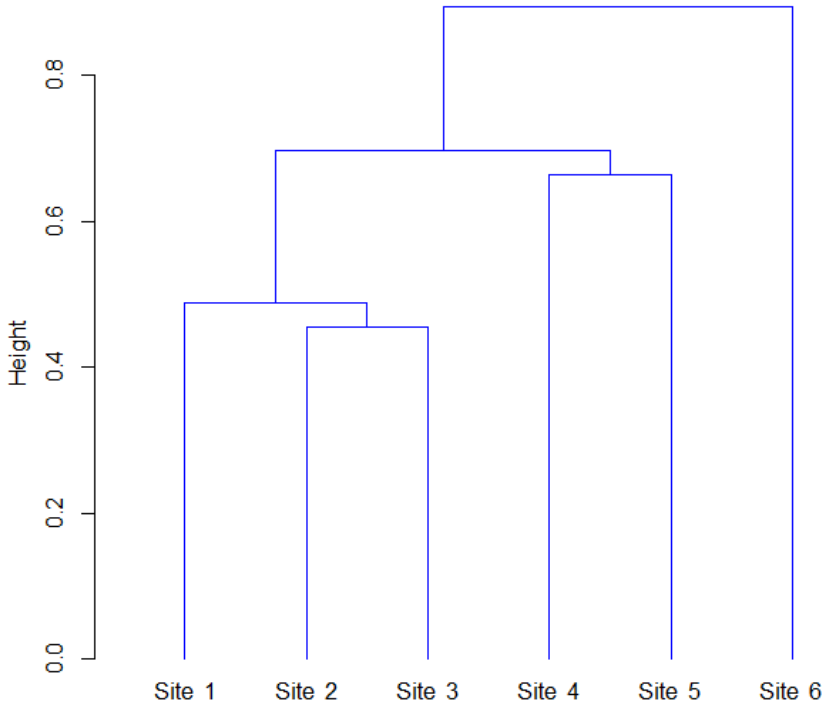

Figure 6. Classification of forests based on ecological distance.

4.6. Effect of climate on diversity and growth

The growth of forests was affected by the environmental factors such as annual rainfall, annual temperature, maximum rainfall, and temperature difference. The significant correlation of species richness and diversity with the climatic factors (namely, the annual rainfall, maximum rainfall and average temperature) were occurred in this study. Whereas, forest growth parameters were significantly corrected with only two climatic factors, namely, annual rainfall and maximum rainfall (Table 4).

Within a range of average annual rainfall from 625 mm to 2,035 mm and a range of mean annual temperature from 24.1°C to 27.2°C, rainfall strongly affected to the growth of forests more than temperature, though both rainfall and temperature were important for the growth of forests. The temperature difference between the highest and the lowest temperature of the year (T dif) did not vary greatly (22.2 ~ 25.00°C) among the six sites. Therefore, T dif did not show a significant correlation with forest growth.

Table 4. Pearson correlation coefficients between forest growth and environmental factors.

Growth parameter	Avg. R	Max. R	Avg. T	T dif
Diameter (upper)	0.987**	0.996**	0.293	ns
Diameter (middle)	0.982**	0.961**	0.183	ns
Diameter (lower)	0.974**	0.987**	0.215	ns
Height (upper)	0.981**	0.994**	0.274	ns
Height (middle)	0.989**	0.968**	0.224	ns
Height (lower)	0.986**	0.992**	0.236	ns
Species richness	0.685**	0.621**	0.603**	ns
Shannon diversity	0.639**	0.580**	0.626**	ns
Simpson diversity	0.501**	0.457**	0.561**	ns
Shannon evenness	0.386**	0.350*	0.496**	ns

** and * demonstrate the relation is considered significant at $p < 0.01$ and $p < 0.05$, respectively; 'ns' shows no correlation between the respective parameters. Avg. R = mean annual rainfall, Max. R = maximum rainfall, Avg. T = mean annual temperature, T dif = the difference between the highest and the lowest temperature of a year.

The correspondence analysis (CA) indicated a clear correlation between species distribution, abundance and the effects of annual rainfall (Figure 7). The first and second CA axes performed 61.44% of total fitted variation. The weighted average scores of species under different rainfall values varied to a great extent in terms of abundance and distribution, scattering into different quarters of the ordination graph.

Rainfall parameter that has position close to the species in the graph was expected to have high abundance for that species. For example, *Pentacme siamensis* (Pens) occurred abundantly in the region where rainfall was 1,029 mm (Figure 7). The region where the rainfall was 2,035 mm was not the proper habitat for that species. It may be due to the non-adaptability of *P. siamensis* species in high rainfall regions. A small vector angle between species indicated a strongly positive association, and a 180-degree vector angle between species indicated a negative correlation.

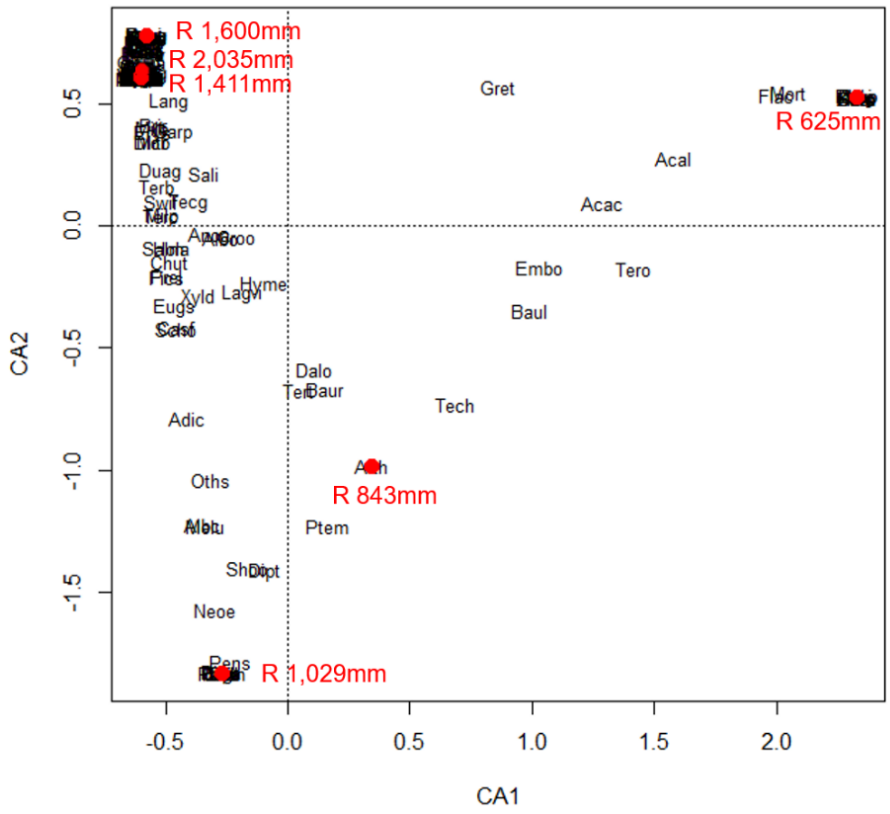

Figure 7. Correspondence analysis of species variables in relation to different annual rainfall regions. (The letters expressed in the figure are the abbreviations of species names, for example, Pens = *Pentacme siamensis*). Species names and their abbreviations are shown in Appendix 7.

4.7. Above-ground carbon storage

Total above-ground carbon storage of forests at sites 1 ~ 6 were 267.39 ± 48.55, 232.74 ± 18.13, 221.81 ± 15.26, 50.53 ± 8.58, 12.23 ± 1.12, and 2.88 ± 0.04 Mg C ha^{-1}, respectively. The above-ground carbon storages among the sites were statistically distinct at 95% confidence interval (ANOVA, $p < 0.05$). The above-ground carbon storage of forest was the highest (267.39 ± 48.55 Mg C ha^{-1}) at site 1 and the lowest (2.88 ± 0.04 Mg C ha^{-1}) at site 6 in comparison with the other sites (DMRT, $p < 0.05$).

Among three strata, the above-ground carbon storage of the middle stratum was the highest at all study sites (DMRT, $p < 0.05$). The patent difference among strata was visible and so as for sites (ANOVA, $p < 0.05$) (Table 5). The trend of above-ground carbon storage in all forests was middle stratum > upper stratum > lower stratum. For example, the upper stratum stored 92.85 ± 87.21 Mg C ha^{-1}, the middle stratum stored 140.95 ± 40.20 Mg C ha^{-1}, and the lower stratum stored only 50.47 ± 17.79 Mg C ha^{-1} at site 1. The upper stratum of site 2 stored 0.81 ± 0.11 Mg C ha^{-1}, the middle stratum stored 1.84 ± 0.06 Mg C ha^{-1}, and the lower stratum stored only 0.23 ± 0.07 Mg C ha^{-1}.

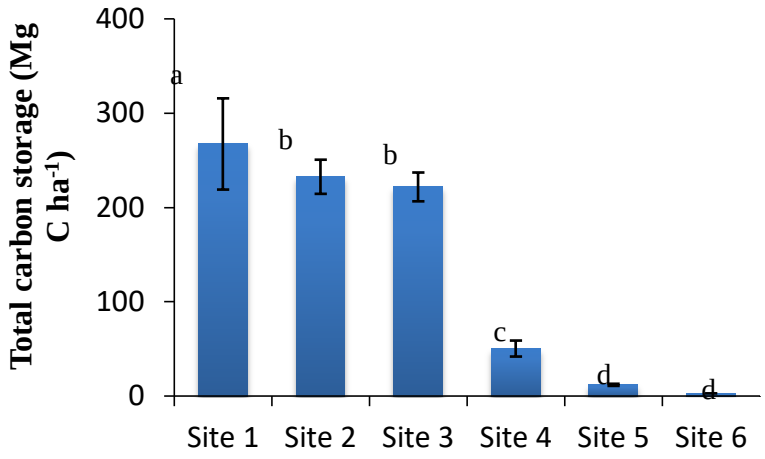

Figure 2. Total above-ground carbon storage (Mg C ha^{-1}) of forests among studies sites. Error bars show standard deviations of mean values. Different letters indicate significant differences among the sites by Duncan's multiple range test at $p < 0.05$. The carbon conversion factor, 0.47, was used in accordance with IPCC guidelines (IPCC 2006).

Table 5. Distribution of above-ground carbon storage in three strata of forests at 6 study sites.

Site	Upper stratum (Mg C ha^{-1})	Middle stratum (Mg C ha^{-1})	Lower stratum (Mg C ha^{-1})
Site 1	92.85 ± 87.21 ^{ab,A}	140.95 ± 40.20 ^{a,A}	50.47 ± 17.79 ^{b,A}
Site 2	84.92 ± 27.62 ^{b,A}	134.44 ± 16.60 ^{a,A}	13.38 ± 4.29 ^{c,B}
Site 3	107.83 ± 16.71 ^{a,A}	109.85 ± 11.35 ^{a,B}	4.13 ± 0.87 ^{b,C}
Site 4	13.45 ± 7.65 ^{b,B}	35.20 ± 4.10 ^{a,C}	1.88 ± 0.68 ^{c,C}
Site 5	3.81 ± 2.11 ^{b,B}	7.84 ± 1.76 ^{a,D}	0.58 ± 0.19 ^{c,C}
Site 6	0.81 ± 0.11 ^{b,B}	1.84 ± 0.06 ^{a,D}	0.23 ± 0.07 ^{c,C,}

Mean carbon storage ± standard deviation. Different lowercase letters indicate significant differences among layers, and different uppercase letters indicate significant differences among the sites by Duncan's multiple range test at $p < 0.05$.

To investigate the effect of climate on forest carbon storage, we apply the environmental factors such as the average annual rainfall, the average annual temperature, the maximum rainfall, and the temperature difference between the highest and the lowest temperature of the year. Based on the results, the carbon storage of forests was strongly correlated with the average annual rainfall, the maximum rainfall and the average annual

temperature at 99% confidence interval ($p < 0.01$). However, the temperature difference did not showed the correlation with carbon storage of forests (r = -0.074, $p = 0.60$).

4.8. Screening parameters for above-ground carbon storage model

The diameter of *X. xylocarpa* used for the development of the aboveground carbon storage model ranged from 6.00 ~ 32.50 cm in diameter. The total above-ground carbon storage of *X. xylocarpa* at site 1 ranged from 6.52 to 255.46 kg tree^{-1} with a range of diameter of 6.50 ~ 28.00 cm, and the total above-ground carbon storage of *X. xylocarpa* at site 2 ranged from 6.60 to 254.56 kg tree^{-1} with a range of diameter of 6.60 ~ 28.00 cm. While the total above-ground carbon storage of *X. xylocarpa* at site 3 was 4.73 ~ 370.37 kg tree^{-1} with a range of 6.00 ~ 32.50 cm in diameter, those of *X. xylocarpa* at site 4 was 4.71 ~ 149.84 kg tree^{-1} with a range of 6.40 ~ 28.40 cm in diameter.

Screening the tentative parameters was the important tool at the beginning stage of the model establishment. The error and much complexity of a model can be reduced and controlled by trimming the parameters which affect the target variables insignificantly or extra addition to a model by screening the tentative parameters. In this study, all three growth parameters, namely, diameter, basal area and height, were included in a screening test for the establishment of above-ground carbon storage model.

The results from the correlation analysis showed all three parameters have strong relations to the carbon storage without showing big differences among three parameters ($0.955 < r < 0.999$. Similarly, both coefficients of determination and adjusted coefficients of determination of three parameters were high which meant the effects of all parameters were very strong and significant. The basal area showed the higher person correlation coefficient, coefficient of determination and adjusted coefficient of determination than other two parameters. Nonetheless, those values of the two parameters, namely, diameter and height, were similar. In the livelihood analysis, diameter and basal area were found much more influences on models at all study sites than tree height. By summarizing the results of all analytical values, the two parameters, diameter and basal area, were the most suitable and effective parameters in the development of above-ground carbon storage models.

3.9. Development of above-ground carbon storage models

Totally, thirteen models were established for each species. Most of the models evaluated at site 1 for *X. xylocarpa*. species were highly significant at $p < 0.05$ with high coefficient of determination values (adj. $R^2 = 0.87$ to 0.99), except three models (Eq. 8, 12, and 13, site 1; at $0.10 < p < 0.14$). The coefficient of determination measured the precision of a regression models. So, high values pointed out high precisions of a model.

But, the coefficient of determinations (R^2) cannot take into account the scattered pattern, heterogeneous variance, etc. The livelihood function such as AIC and FI, and the CF can image such kinds of factors. The values increase with the departure from the regression line, large residual value and the heterogeneity of variances. The basic quadratic model (Eq. 1, site 1) was found to be the best fit model for the carbon estimation of *X. xylocarpa* at site 1. It showed the minimum AIC, sum square residual (SSR), FI and CF. The AIC value of Eq. 1 at site 1 was -36.64, FI was 0.06, and CF was 1.0000285. The best three models and the coefficients of parameters in individual models were shown in Table 6.

For *X. xylocarpa* species at sites 2 and 3, most of the models except three models (Eq. 5, 12, and 13, sites 2 and 3) were highly significant at $p < 0.05$, expressing high coefficient of determinations (adj. $R^2 = 0.90$ to 0.99 at site 2; adj. $R^2 = 0.93$ to 0.99 at site 3). The basic

cubic models (Eq. 1, sites 2 and 3) were found to be the best fits for carbon estimation of *X. xylocarpa* at sites 2 and 3, with the minimum AIC, sum square residual (SSR), FI and CF. The AIC value of the best fit model for *X. xylocarpa* species at site 2 was -41.60, and that of site 3 was -41.60, which were the lowest value among thirteen tentative models.

Table 6. Akaike's information criterion (AIC) parameters, Furnival index, evaluation values, and the coefficient of determination (R^2) of the carbon storage model at 95% confidence interval.

Model	Eq	AIC	R^2	SSR	Adj. R^2	*p*	FI	CF
Site 1								
$y = \beta_0 + \beta_1 BA + \beta_2 BA^2$	1	-36.64	0.99	0.000057	0.99	0.0001	0.06	1.0000285
$y = \beta_0 + \beta_1 BA + \beta_2 BA^2 + \beta_3 BA^3$	2	-34.64	0.99	0.000057	0.99	0.0001	0.06	1.0000285
$y = \beta_0 + \beta_1 D + \beta_2 D^2 + \beta_3 D^3$	3	-28.71	0.99	0.000251	0.99	0.0001	0.09	1.0001255
Site 2								
$y = \beta_0 + \beta_1 BA + \beta_2 BA^2 + \beta_3 BA^3$	1	-41.60	0.99	0.00001	0.99	0.0001	$8.2x10^{-7}$	1.0000050
$y = \beta_0 + \beta_1 D + \beta_2 D^2 + \beta_3 D^3$	2	-32.39	0.99	0.0001	0.99	0.0001	$1.3x10^{-6}$	1.0001000
$y = \beta_0 e^{\beta 1 D}$	3	-4.89	0.97	0.263	0.95	0.017	6.36	1.0682267
Site 3								
$y = \beta_0 + \beta_1 BA + \beta_2 BA^2 + \beta_3 BA^3$	1	-41.60	0.99	0.00001	0.99	0.0001	$1.6x10^{-6}$	1.000005
$y = \beta_0 + \beta_1 D + \beta_2 D^2 + \beta_3 D^3$	2	-40.55	0.99	0.00	0.99	0.0001	$2.1x10^{-7}$	1.000005
$y = e^{\beta 0 + \beta 1 \ln(D)}$	3	-2.54	0.99	0.47	0.99	0.01	0.59	1.1258068
Site 4								
$y = \beta_0 + \beta_1 BA + \beta_2 BA^2 + \beta_3 BA^3$	1	-41.60	0.99	0.00001	0.99	0.0001	$7.2x10^{-7}$	1.000005
$y = \beta_0 + \beta_1 D + \beta_2 D^2 + \beta_3 D^3$	2	-40.87	0.99	0.0001	0.99	0.0001	$4.2x10^{-7}$	1.000005
$y = e^{\beta 0 + \beta 1 \ln(D)}$	3	-7.08	0.99	0.15	0.99	0.01	0.44	1.0387312

Eq = equation number, AIC = Akaike's information criterion, R^2 = coefficient of determination at $p < 0.05$, SSR = sum square of residuals, Adj.R^2 = adjusted coefficient of determination, *p* = probability value, FI = Furnival index, CF = correction factor, D = tree diameter in centimeter, BA = basal area in square meter.

For *X. xylocarpa*. species at site 4, three models (Eq. 7, 12, and 13, site 4) did not show the significance of a model at 95 percent confidence interval. Except those models, the other models evaluated in this study had high coefficient of determination (adj. R^2 = 0.92 to 0.99), demonstrating the significance of model at $p < 0.05$. As similar with the best fit model form of *X. xylocarpa* at sites 2 and 3, the basic cubic model (Eq. 1, site 4) showed as the most suitable model for *X. xylocarpa* species at site 4. The AIC, sum square residual (SSR), FI and CF of the basic cubic model stated the minimum values among the models.

In this study, the types of models developed by Brown et al. (1989) and Martinez-Yrizar et al. (1992) were found to be unsuitable to use for the dominant species in the study areas when compare with other tentative models. The basic quadratic model (independent variable - basal area) was the most suitable for the above-ground carbon storage of *X. xylocarpa* at site 1, and the basic cubic model (independent variable - basal area) was the most suitable for *X. xylocarpa* at sites 2 ~ 4.

Among the tentative models, the strength of the best fit models varied among different species and sites. Some best fit models had other alternative models that to be considered as suitable models for individual species at the same site although they were not as good as the best fit model. However, some best fit models had no alternative models that could be consider as suitable for that individual species.

This study evaluated whether there was any other alternative models for each species determined by the strength of best fit model to others. Evidence ratio and Δi was applied for the evaluation. The lower the values, the closer the strength of the respective model to the best fit model was found. For example, ER value of Eq. 2 at site 1 was 2.72 ($\Delta i = 2.0$), which meant that the suitability of Eq. 2 model was 2.72 times lower than the most suitable model (Eq. 1, site 1) (Table 38). However, Eq. 3 model was 52.72 times lower than the most suitable model (Eq. 1, site 1) because the ER value of Eq. 3 model was 52.71 ($\Delta i = 7.93$). Therefore, Eq. 2 could be considered as the alternative models for *X. xylocarpa* at site 1 while Eq. 3 was unsuitable.

For *X. xylocarpa* at sites 2, there were no other models that could be considered as alternatives. But for *X. xylocarpa* at sites 3 and 4, the quadratic models (Eq. 2) could be considered as alternative models (ER = 1.69, $\Delta i = 1.05$ at site 3, ER = 1.44, $\Delta i = 0.73$ at site 4).

The bias of the best fit models showed less than -0.00013% and so it was found as non-significant.

The best fit models were established as follows:

(a) *X. xylocarpa* Roxb. Taub, at site 1,

$$y = -3.0558 + 2809.8BA + 22550.857\,BA^2,\ R^2 = 0.99$$

(b) *X. xylocarpa* Roxb. Taub, at site 2,

$$y = -1.937 + 2345.631BA + 45000.286BA^2 - 250816.49BA^3,\ R^2 = 0.99$$

(c) *X. xylocarpa* Roxb. Taub, at site 3,

$$y = -2.914 + 2615.217BA + 31432.052BA^2 - 105064.918BA^3,\ R^2 = 0.99$$

(d) *X. xylocarpa* Roxb. Taub, at site 4,

$$y = -1.326 + 1834.277BA + 13713.139BA^2 - 78894.462BA^3,\ R^2 = 0.99$$

where, y = above-ground carbon storage of tree (kg);
BA = basal area (m^2); and
D = diameter (cm).

3.10. Validation of models

To know the accuracy of the best fit models, the best fit model of each species was tested using the actual observed value by destructive measurement which was not used for the establishment of models. The mean observed value was 50.36 kg tree^{-1} and the mean predicted value was 51.13 kg tree^{-1}. The comparison between the predicted and actual observed values showed that the best fit models of each species were strong enough to use for the calculation of carbon storage. The root of mean square error (RMSE) ranged from 0.11 to 1.17, and the bias ranged from -2.59 to 2.32%. Neither RMSE nor bias showed any big errors that deviate from the fitness of a model.

To show the tendency of the best fit model, the relative error of the model against the standardized predicted value was plotted. The interaction between standardized predicted values and standardized residuals showed no trend (positive or negative). The residual variables appeared as independently scattered over standardized predicted values. This factor is one of most pivotal factors that should be considered in the development of models. In this study, standardized residuals against predicted values demonstrated the reliability of the model performance.

V. Conclusion

Species diversity was significantly correlated with annual rainfall, maximum rainfall and average temperature, whereas, forest growth parameters were significantly corrected with annual rainfall and maximum rainfall. If we want to assess both structure and diversity of forests, the rainfall variables will be more suitable to use for estimation because the rainfall showed strong correlation with both diversity and structure of forests.

The species diversity, richness and ecosystem complexity of forests within a range of annual rainfall of 1,411 ~ 2,035 mm was significantly higher than that of the forests with annual rainfall of 625 ~ 1,029 mm. The mean diameter and height of all vertical stand layers were significantly different among six study sites. However, the basal area was the highest in the middle layer, and the density was the highest in the lower layer at all study sites.

The mean annual rainfall ($r = 0.974 \sim 0.989$, $p < 0.01$) and maximum rainfall ($r = 0.968 \sim 0.996$, $p < 0.01$) were the most effective parameters for the estimation of forest growth, while the average annual rainfall ($r = 0.639 \sim 0.685$, $p < 0.01$) was found to be the most influencing factors in the estimation of species richness and diversity of forests. Most of the size distribution parameters could not be used for the assessment of species richness and diversity in tropical regions of Myanmar.

Species distribution varied among different rainfall regions. High rainfall regions (1,411 to 2,035 mm) could not be the habitat of *R. Paniculata, Boscia variabilis*, *M. tinctoria*, *A. leucophloea*, *T. hamiltoniana*, and *T. oliveri* species, seldom occurred in regions with 1,029 mm of annual rainfall. The species distribution also varied with elevation and seasonal variation. This study pointed that the species composition of forests at site 2 varied about 41.33% from site 1.The species at sites 3 ~ 6 varied about 45.33%, 64.00%, 82.67%, and 92.00% from site 1, respectively.

The study revealed that the climatic factors were strongly correlated with species diversity, stand structure and above-ground carbon storage of forests. However, a difference in annual rainfall of approximately 400 mm among sites did not significantly affect the species diversity of tropical forest across a precipitation gradient (annual

rainfall = 1,411 ~ 2,035 mm). But a significant effect of rainfall on species diversity occurred between two rainfall ranges; (1) annual rainfall of 1,411 ~ 2,035 mm, and (2) annual rainfall of 625 ~ 1,029 mm. Within a precipitation gradient of this study, the forests could be categorized into three groups in accordance with the similarity: the forests with annual rainfall of 1,411 to 2,035 mm could be considered one group (group I); the forests with annual rainfall of 843 to 1,029 mm could be considered another group (group II); and the forests with 625 mm of annual rainfall could be clarified as group III.

The shapes of new best fit above-ground carbon storage models for individual species across different rainfall regions were the quadratic model for *X. xylocarpa* at site 1 and the cubic model for *X. xylocarpa* at sites 2 ~ 4. Screening the parameters before developing the models was compulsory for getting the strongest parameter that influenced the model most. It was very important for the development of models because it can reduce the error propagation and data redundancy. The present study gave a notification that the determination factors such as AIC, FI, and CF should also be taken into consideration with the inclusive of the R^2 value.

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