Ministry of Forestry

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Forest Research Institute

Carbon Sequestration of Pure Teak (*Tectona grandis* Linn f.) and Mixed Species Plantations in Bago Yoma Region of Myanmar

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မြန်မာနိုင်ငံ ပဲခူးရိုးမဒေသတွင် တည်ထောင်စိုက်ပျိုးထားသော ကျွန်းသီးသန့်စိုက်ခင်းနှင့် သစ်မျိုးစုံစိုက်ခင်းများ၏ ကာဗွန်စုတ်ယူသိုလှောင်နိုင်မှုစွမ်းရည်အား လေ့လာခြင်း

ဒေါက်တာသောင်းနိုင်ဦး
လက်ထောက်ညွှန်ကြားရေးမှူး
သစ်တောဦးစီးဌာန

စာတမ်းအကျဉ်း

သစ်တောစိုက်ခင်းများသည် စီးပွားရေးဖွံ့ဖြိုးတိုးတက်ရန်နှင့် တည်ငြိမ်စေရန်အတွက် အရေးပါရုံ သာမက ရာသီဥတုပြောင်းလဲမှု လျော့ကျစေရေးနှင့် လိုက်လျောညီထွေရှိစေရေး တွင်လည်း အလွန်ပင် အရေးပါလှပါသည်။ သစ်တောစိုက်ခင်းများသည် လေထုအတွင်းရှိ ကာဗွန်ဒိုင်အောက်ဆိုက်ဓာတ်ငွေ့များကို စုတ်ယူသိုလှောင်ခြင်းဖြင့် ရာသီဥတုပြောင်းလဲမှုကို လျော့ကျ စေပါသည်။ သစ်တော ပြန်လည်ထူထောင်ရေး စီမံကိန်းလုပ်ငန်းများ ဆောင်ရွက် နေသော်လည်း သစ်မျိုးစိတ်များ၏ ကာဗွန်စုတ်ယူသိုလှောင်နိုင်မှုစွမ်းရည်နှင့် စိုက်ခင်းအဆင့် ကာဗွန်စုတ်ယူ သိုလှောင်နိုင်မှု စွမ်းရည်ဆိုင်ရာ သတင်းအချက်အလက်များမှာ ရှားပါးလျက် ရှိနေပါသည်။ ယခုသုတေသန စာတမ်းသည် သက်တမ်း ၂၆ နှစ်ရှိ စီးပွားရေးအရ အရေးပါသော သစ်မျိုး (၇) မျိုး၏ ကာဗွန်စုတ်ယူ သိုလှောင်နိုင်မှုနှင့် ၆ နှစ်၊ ၁၆ နှစ်၊ ၂၆ နှစ် သက်တမ်း ၃ မျိုးရှိ ကျွန်းစိုက်ခင်းများ၏ ကာဗွန်စုတ်ယူ သိုလှောင်နိုင်မှုစွမ်းရည်များကို လေ့လာတင်ပြထားပါသည်။ အပင်များကို ခုတ်လှဲပြီး အပင်အစိတ်အပိုင်း အသီးသီး၏ ဇီဝဒြပ်ထုကို တိုင်းတာခြင်း၊ အပင်များ၏ အမြင့်နှင့် ရင်စို့အချင်းကို အခြေခံ၍ ဇီဝဒြပ်ထုနှင့် အပင်အတိုင်းအတာတို့၏ ဆက်စပ်မှုညီမျှခြင်းများကို ဖေါ်ထုတ်ခဲ့ပါသည်။ အဆိုပါ ညီမျှခြင်းများကိုပင် အသုံးပြု၍ စိုက်ခင်းအဆင့် ဇီဝဒြပ်ထု တနည်းအားဖြင့် ကာဗွန် သိုလှောင်မှုပမာဏအား တွက်ချက် တင်ပြ ထားပါသည်။ သုတေသနတွေ့ရှိချက်အရ ၂၆ အရွယ်ရှိ သစ်မျိုးစုံစိုက်ခင်းသည် တစ်ဟက်တာ လျှင် ပျမ်းမျှကာဗွန် ၅၉.၇ တန်၊ ၆ နှစ်၊ ၁၆ နှစ် နှင့် ၂၆ နှစ်ရှိ ကျွန်းစိုက်ခင်းများသည် ၂၇.၁ တန်၊ ၅၆.၆ တန် နှင့် ၅၅.၀ တန် အသီးသီး စုတ်ယူသိုလှောင် ထားပါသည်။ ၆ နှစ်သားမှ ၂၆ နှစ် အရွယ်စိုက်ခင်းများ၏ နှစ်စဉ်ပျမ်းမျှ ကာဗွန်စုတ်ယူသည့်နှုန်း (Mean Annual Carbon Sequestration Rate) မှာ တစ်ဟက်တာလျှင် ၄.၅ တန်မှ ၁၀.၉ တန် အထိ ရှိပါသည်။ အကယ်၍ နှစ်စဉ်ပျမ်းမျှ ကာဗွန်စုတ်ယူသည့် နှုန်း ၁၀.၉ တန်အား ဆက်လက် ထိန်းထား နိုင်ပါက စိုက်ခင်းအသက် ၃၈ နှစ် အရွယ်တွင် သဘာဝတောများ စုတ်ယူသိုလှောင်နိုင်သည့် ပမာဏနှင့် ညီမျှမည်ဖြစ်ပါသည်။ နှစ်စဉ်ပျမ်းမျှ ကာဗွန်စုတ်ယူသည့်နှုန်းအား စိုက်ခင်းသက်တမ်း တစ်လျောက် ထိန်းထားနိုင်ရန် အတွက် စိုက်ပင်ပန္နက် အကွာအဝေး လျော့ခြင်း (ဥပမာ ၂ မီတာ x၂ မီတာ)၊ ကာဗွန်စုတ်ယူ ထိန်းသိမ်းခြင်း ရည်ရွယ်ချက်အတွက် ပင်ကြပ်နှုပ်မှုနှုန်း လျော့ချခြင်း နှင့် မြေဆီလွှာကာဗွန်ကို ထိန်းရန်အတွက် သစ်တောအလွှာအဆင့်အဆင့်ကို ထိန်းသိမ်းခြင်း လုပ်ငန်းများကို ဆောင်ရွက်သင့်ကြောင်း တင်ပြထားပါသည်။

Carbon Sequestration of Pure Teak (*Tectona grandis* Linn f.) and Mixed Species Plantations in Bago Yoma Region of Myanmar

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Abstract

Forest plantations are not only an important strategy for financial stability and growth, they are also critical in mitigating climate change through carbon sequestration. Reforestation projects are being implemented in Myanmar, and information is still scare on carbon storage potential of plantations due to the lack of assessment on species-level and plantation-level biomass accumulation. This study aims to estimate the carbon storage of a 26-year-old plantation (seven mixed species) and three age groups of pure teak (*Tectona grandis* Linn f.) plantation areas. The destructive method was used to measure the biomass of tree components of each species. A regression equation was performed to estimate the plantation-level tree biomass (carbon storage) using diameter and tree height. The total tree carbon recorded 59.70 ton ha^{-1} in the mixed species plantation. Whereas, that in 6-, 16-, and 26-year-old pure teak plantations scored 27.07, 56.61 and 54.96 ton ha^{-1}, respectively. The mixed species plantation site contains high rate of litter fall, undergrowth and soil organic carbon (SOC) than the pure teak plantations. Mean annual increment (MAI) decreased from 10.9 ton ha^{-1} $year^{-1}$ at the age of 6 years to 4.5 ton ha^{-1} $year^{-1}$at the age of 26 years. If carbon storage MAI of 10.9 ton ha^{-1} $year^{-1}$ of 6-year-old teak plantation could be grown until the age of 38 years, carbon storage would be 414 C ton ha^{-1}, which is approximately the same amount of carbon accumulated by the tropical deciduous forests. To accomplish of maintaining high MAI, narrow tree spacing (e.g. 2 m × 2 m) should be utilized for high initial stock density; and thinning intensity should be reduced in order to have higher stock density for carbon sequestration purpose. Understory vegetation should be conserved in order to maintain soil fertility and to control soil erosion.

Keywords: Above-ground biomass; Allometric equations; Below-ground biomass; Teak plantation; Re-afforestation; Root/shoot ratio; Soil organic carbon

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1. Introduction

Forestry sector strategies with the purpose of mitigating world climate change have the potential to provide the several multi-benefits including biodiversity conservation, carbon sequestration and sustainable rural development. Nowadays, carbon sequestration projects in developing nations such as Myanmar could partially receive investments from companies and governments willing to offset their emissions of greenhouse gases through the Kyoto Protocol's Clean Development Mechanism (CDM) and Reducing Emissions from Deforestation and Forest Degradation (REDD+). Thus, estimating the carbon sequestration of forest plantations could contribute to the planning and implementation of management processes in mitigation of climate change and global warming.

A rapid rate of deforestation and degradation of natural forests has been observed in Myanmar as a result of shifting cultivation, excessive fuel wood cutting, expansion of agricultural lands and development of infrastructure (Tint, 2002). In Myanmar, the most severe environmental degradation (forest degradation) can be found in the central Dry Zone. Forest degradation is a kind of canopy gap forming process. Natural disasters and human activities cause retrogressive actions against plant succession process. The Ministry of Forestry has tried over successive periods through national conservation approaches to prevent desertification and forest degradation.

Large-scale plantation forestry, especially teak plantations, began in 1980 in order to supplement the natural forests. From 1981-2009, the total area of commercial plantations (both pure and mixed plantations) reached 1,113,120 ha representing 53.74% of the total planted areas (Forest Department, 2010-unpublished). Commercial plantations are mainly composed of three species: Teak (*Tectona grandis*), Pyinkado (*Xylia xylocarpa*) and Padauk (*Pterocarpus macrocarpus*). *T. grandis* plantation constituted 373, 407 ha (44.5% of the total planted area) while *X. xylocarpa* and *P. macrocarpus* constituted 62,350 ha (7.4% of the total planted area) and 16,263 ha (1.9 % of the total planted area), respectively (Forest Department, 2006). In addition to the conventional plantation establishment, other promising reforestation methods including enrichment planting (line planting and gap planting), agroforestry, community forestry, and assisted natural regeneration (ANR) methods are used for restoring ecosystem system functions in the degraded forest lands. In order to supplement the natural forests, and to compensate the deforestation, the Forest Department of Myanmar has been implementing a large-scale reforestation/restoration program since the 1980s, and currently the annual planting rate has reached over 23,000 ha (45,000 ha including dry zone plantations). These plantations have the capacity to sequester a substantial amount of carbon but little is known about their potential. Hence, the objectives of this study were:

- to measure the carbon storage capacity of tropical commercial tree species (seven species);
- to compare the carbon storage capacity of different age classes of pure teak (*Tectona grandis* Linn f.) plantations; and
- to estimate the plantation-level carbon storage of a harvestable age of pure teak (*Tectona grandis* Linn f.) plantations and mixed species plantation.

2. Materials and Methods

2.1. Study sites

This study was conducted using three age classes of pure teak plantations in the Kabaung unclassified forest 16 (1atitude l8° 49.50" N and longitude 96° 11.29" E) of the Oktwin Township and mixed species plantation of Compartment 72 of the Ngalaik Reserved Forest (latitude 19° 56" N and longitude 95° 56" E) in Pyinmana Township (Figure 1).

The soil and climatic conditions of the mixed species plantation site are generally similar to those of the pure teak plantations. Both areas have a tropical monsoon climate with mean annual rainfall of 1,993 mm and 1,329 mm while mean temperature of 28.5° C and 29.3° C in the Oktwin and Pyinmana Township, respectively. The rainy season starts from May/June to October/November. A pronounced dry season extends from December to April. According to FAO (1988) classification system, the soil of the study areas is classified as Xanthic Ferralsols (yellow brown forest soils). All sites had well-drained soil texture ranging from silt loam to clay loa m (Pritchett and Ohn, 1981). The areas have a soil pH of approximately 6, which is slightly acidic for teak, since it usually occurs on soil with a pH range of 6.5-7.5 (Pritchett and Ohn, 1981; Tewari, 1992).

The pure teak plantations covered three different age groups with 10 years interval, such as 6 years, 16 years, and 26 years. The mixed species plantation was mainly composed of seven indigenous species: Teak (*Tectona grandis*), Pyinkado (*Xylia xylocarpa*), Padauk (*Pterocarpus macrocarpus*), Thinwun (*Millettia pendula*), Taukkyan (*Terminalia tomentosa*), Yemane (*Gmelina arborea*) and Yinma (*Chukrasia tubularis*). Each of seven species was planted block by block consecutively and there was no marked boundary to delineate the species (block). In all plantations, the initial spacing of 3 m × 3 m was used. All the studied plantations were established to restore the degraded forests of the Bago Yoma Region of Myanmar. These species have good growth and adaptability, and are the most valuable and commercial species widely used in reforestation of degraded forest areas in Myanmar. Therefore, these species were chosen to reflect the range and popularity of establishment across the country.

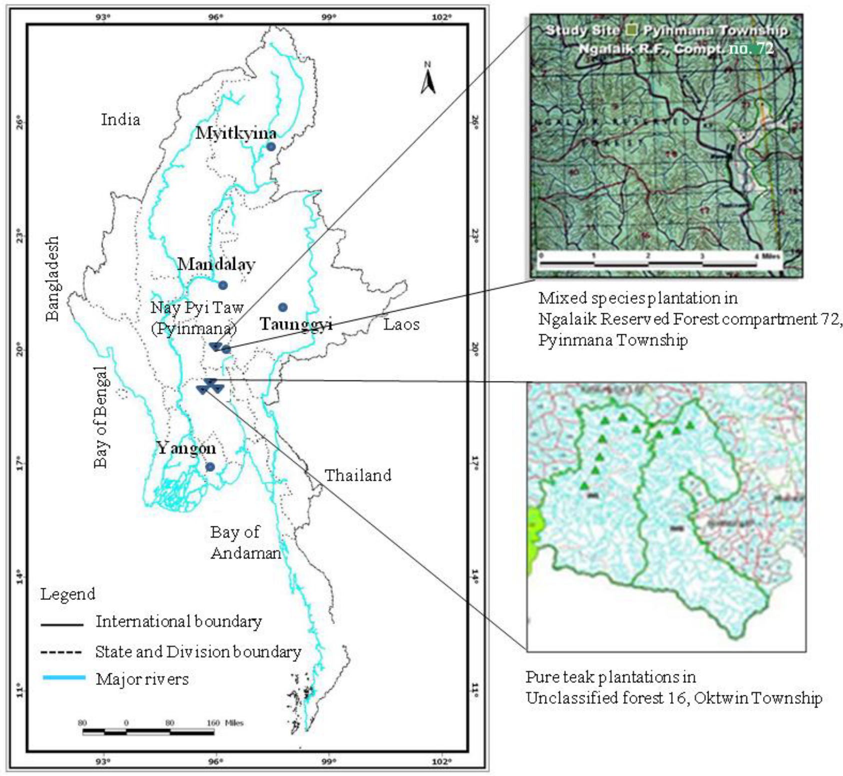


Figure 1. Map of Myanmar showing the particular study site

2.2. Estimation of biomass and carbon sequestration

The carbon storage in the plantations was investigated in two different levels: (i) tree level and (ii) plantation level. The destructive method was used to estimate the biomass (carbon accumulation) of the three age groups of pure teak plantations and the 26-year-old mixed plantation. Tree component biomass and carbon sequestration were measured to describe the relationship between diameter at breast height (dbh) and tree height (D^2H) *vs* dry biomass (carbon storage) including the root biomass of individual trees. The allometric regression equations were constructed for each species. The resulting regression equations were used to estimate the carbon storage at the stand level in each plantation site. This was supplemented by litter, undergrowth and soil carbon. The total carbon storage of each plantation site was estimated.

Five trees from each age group of pure teak plantations (15 trees in total) and 35 trees from the mixed species plantation (5 trees from each species) with different diameter were sampled and cut (stem, branch, bough, leaves, bark and root) for estimation of the above- and below-ground biomass. Trees were cut as close as possible to the ground and the height of the remaining stumps was exposed to about 0.2 - 0.3 m by hand saw. Aboveground biomass was divided into different components: stems, branches, leaves, bough and bark. Samples from each component of the trees were taken.

To estimate below-ground biomass (root biomass and carbon), all the roots of sampled trees (35 trees in total) from the species mixed plantation were excavated, cut and measured. The different sizes of representative trees' samples were collected to measure the oven-dry weight. Samples from each component were pooled, sealed in plastic bags, and transported to the laboratory of Forest Research Institute (FRI) in Yezin, Myanmar.

Samples were dried in an oven at 70°C for a week until constant weights were obtained (Kraenzel et al., 2003). The dry biomass of all components (stem, branch, bough, leaves, bark and root) were summed to produce a total weight of biomass and to estimate the total carbon content of the tree. The carbon content default value of 0.5 was used to estimate the carbon content of tree biomass as proposed by the IPCC (1996). The dry biomass of each tree was calculated by multiplying the ratio of the dry sample weight to the fresh sample weight and total fresh weight in kg. The root/shoot ratios of the dry biomass were also calculated for each species.

2.3. Tree inventory, litter fall and undergrowth

Forest inventory in pure teak plantations and the mixed species plantation was conducted to acquire the basic stand parameters such as mean DBH, tree height and crown diameter. In each site of pure teak plantations, six square plots with an area of 400 m^2 (20 m × 20 m) each were laid out systematically. In the mixed species plantation, 25 plots were established to cover all the species. All trees with DBH ≥ 5 cm and height of all trees were measured.

Litter fall was collected and calculated as part of the aboveground biomass on the plantation level. For this purpose, six plots of size 2 m × 2 m in each plantation site were established randomly under the crown cover. The accumulated mass of litter was used to approximate the annual litter fall. All fresh weights of shrubs, herbs and small trees in the plots were also measured and 200 g samples were taken from each plot. The samples were then oven-dried and calculated as part of the above-ground biomass of the respective plantations.

2.4. Soil organic carbon (SOC)

Soil samples were collected from all four plantation sites (6-, 16- and 26-year-old pure teak plantations and 26-year-old mixed plantation). Three points were selected randomly in each plantation site. At each point, soil samples were collected systematically from five depths, 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm and 40-50 cm. Samples for soil bulk density were also taken from each depth by driving an improvised metal canister into each of the designated soil depths. Soil samples were taken and tested in the soil laboratory of the FRI in Yezin, Myanmar.

2.5. Statistical analysis

Various linear regressions were created using the diameter and tree height (D^2H) to estimate the total tree biomass (total tree carbon). Data from all harvested trees (n=50) was used to develop the regression model. All data was transformed using log to the base 10, as it is commonly done to linearize data of this type (Kraenzel et al., 2003). A one-way analysis of variance (ANOVA) was used to test the differences between the carbon storage (biomass) of various components of trees, between the soil depths, and between the root/shoot ratios of species. A two-way ANOVA was used to test whether bulk density and percentage of soil carbon varied among plantations and depths. A Duncan's multiple range test (DMRT) was performed to examine the rank in mean values of carbon storage in tree components and in soil depths. It was also used to rank the root/shoot ratios of the species. All statistical analyses were performed using SPSS 13.0 and Statistical Analysis System 9.1 for Windows (SAS Institute Inc., 2005).

3. Results

The mean DBH and tree height of the four plantations ranged from 13.6 cm to 27.7 cm and the mean height from 10.9 m to 20.4 m. ANOVA showed that there were significant differences in mean DBH, tree height, and stand density among the plantations ($p<0.0001$) for all parameters. The 6-year-old teak plantation had a smaller mean DBH and tree height but larger number of trees per ha than other three plantations (16- and 26-year old pure teak plantations and 26-year-old mixed species plantation) (Table 1).

Young stage trees of other naturally regenerated species (DBH≥5 cm) were not found in the 6- and 16-year-old teak plantations but 14 species in the 26-year-old pure teak and 25 species mixed species plantations. In the 26-year-old pure teak plantation, other species comprised of 50 individuals (11.2% of the total individuals) covering 0.87 $m^2\ ha^{-1}$ (3.7% of the total BA coverage). In the mixed species plantation, only 1.3 $m^2\ ha^{-1}$ (5.7% of the total BA) of the total basal coverage naturally regenerated, they were comprised of 95 individuals ha^{-1} (19.3% of the total individuals) (Figure 2). It demonstrated that natural regenerations of planted and other species can be expected from both pure and mixed species plantations but only few species/trees were grown during the young age of plantations due to regular silvicultural operations, such as weeding, soil preparation, cleaning of forest floor for protection of fire, thinning, etc. Nevertheless, this study supported the findings of others (Hardner *et al.,* 1999; Parrotta, 1992 and 1995; Singh, 2008) that afforestation and reforestation contributed to co-benefits: carbon sequestration and biodiversity conservation.

Table 1. Basic stand parameters of the pure teak and mixed species plantations

Study sites	Height (m)	DBH (cm)	Crown diameter (m)	Stand density (n/ha)	Basal area (m^2/ha)
6-year-old teak plantation	10.9 (0.43)^c	13.6 (0.75)^c	6.5 (0.34)^c	1,025 (11.02)^a	15.31 (0.55)^c
16-year-old teak plantation	15.5 (1.28)^b	18.5 (1.61)^b	8.8 (0.49)^b	567 (57.15)^b	15.96 (0.93)^b
26-year-old teak plantation	17.2 (0.37)^a	26.1 (0.67)^a	11.5 (0.74)^a	442 (22.86)^b	23.49 (1.10)^a
26-year-old mixed species plantation	16.33 (1.23)^b	23.64 (1.85)^b	10.01 (0.04)^b	492 (29.88)^b	22.78 (0.66)^b

Numbers are the means with stand errors (in parentheses). Different letters indicate significant differences among the respective parameters of plantation according to Duncan's multiple range test at 5% level of probability.

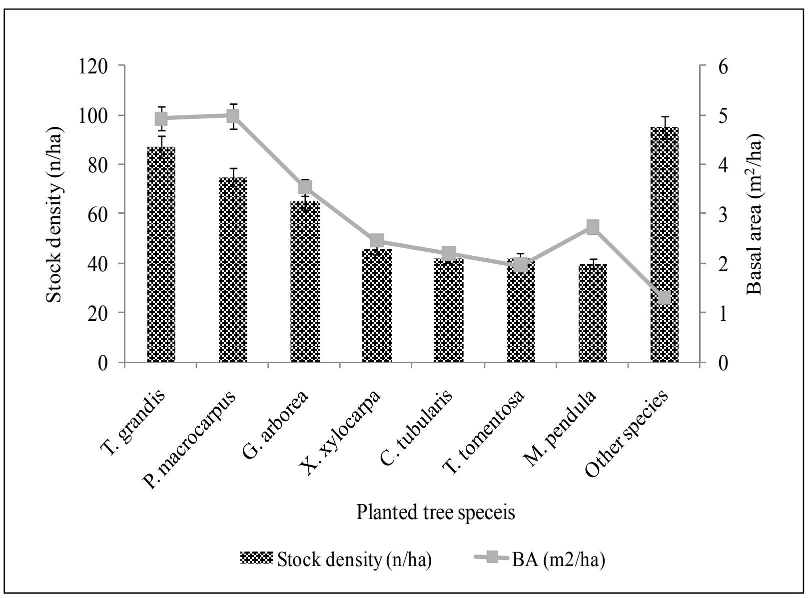


Figure 2. Composition of mixed species plantation. Open bar indicates the standard error.

3.1. Biomass and carbon sequestration of tree components

The mean biomass storage of the 50 harvested trees from 6-, 16-, and 26-year-old pure teak plantations and 26-year-old mixed plantation ranged from 35.10 kg to 270.07 kg (Table 2). Stem biomass (17.56 - 170.52 kg) scored the highest mean values among the biomass weights of tree components of the four plantations. Next to the stem biomass, root biomass (6.41- 44.95 kg) contributed the highest amount to the total biomass of tree.

ANOVA was performed to test the proportion of weight of different components' biomass (carbon) in total tree biomass (carbon) among the four plantations. Significant differences were found the proportions of stem, leaves, and bark among the four plantations (p<0.0001 for all components). However, the proportions of branch, bough and root biomass were not significant among the plantations (F=1.59, p=0.242; F=3.19, p=0.063; F=2.75, p=0.089, respectively).

Table 2. Biomass accumulation in each component of sampled trees of the four plantations

Measurements of tree components	6-year-old teak plantation	16-year-old teak plantation	26-year-old teak plantation	26-year-old mixed species plantation
No. of sampled trees	5	5	5	35
Diameter range (cm)	7.5-14.0	16.0-19.4	21.0-30.0	11-43.6
Height range (m)	6.7-12.1	14.0-15.5	15.1-19.7	9.8-16.2
Crown diameter range (m)	5.2-7.5	7.4-9.6	9.4-13.8	8-13.7
Stem biomass (kg)[a]	17.56 (4.78)	70.24 (7.43)	134.32 (21.16)	170.52 (12.61)
Branch biomass (kg)[a]	3.27 (1.17)	16.78 (1.66)	22.63 (1.04)	27.42 (3.83)
Bough biomass(kg)[a]	0.52 (0.17)	2.69 (0.63)	4.21 (1.04)	5.56 (0.84)
Leaves biomass (kg)[a]	2.12 (0.56)	9.98 (1.39)	16.02 (0.53)	9.53 (2.09)
Bark biomass (kg)[a]	5.21 (1.58)	8.41 (0.93)	14.02 (1.68)	12.09 (1.18)
Root biomass (kg)[a] (Below-ground biomass)	6.41 (2.06)	25.74 (2.89)	44.71 (7.13)	44.95 (5.21)
Above-ground biomass (kg)[a]	28.68 (7.68)	108.10 (12.56)	191.20 (30.50)	225.12 (16.55)
Average biomass of a sampled tree (kg)[a]	35.10 (10.11)	133.84 (15.44)	235.91 (37.51)	270.07 (18.58)

[a]Numbers are the means with standard errors (in parentheses).

Simple linear regressions of log D^2H versus log dry biomass of each species showed that these relations were strong and yielded coefficients of determination (R^2) ranging from 0.91 to 0.99 (Table 3). Alternatively, the linear regression of log D^2H versus log dry biomass of all sample trees of seven species (Figure 3) also shows the strong relationship that can be used for the explanation of biomass accumulation by the diameter and height of trees.

Table 3. Parameter values and regression statistics for the allometric model (log Y=a + b log X; Y= total tree biomass (kg); X= $(DBH)^2$ × height

Species	Biomass (Y)	a	b	R^2	Prob. Level	S.E.
Mixed species plantation						
X. xylocarpa	Total tree biomass	0.834	-0.820	0.93	$p<0.01$	0.090
P. macrocarpus	Total tree biomass	0.838	-0.887	0.93	$p<0.01$	0.126
T. tomentosa	Total tree biomass	0.865	-1.007	0.96	$p<0.005$	0.089
M. pendula	Total tree biomass	0.648	-0.097	0.95	$p<0.005$	0.084
G. arborea	Total tree biomass	0.732	-0.690	0.98	$p<0.005$	0.048
C. tubularis	Total tree biomass	0.950	-1.368	0.97	$p<0.005$	0.109
T. grandis	Total tree biomass	0.746	-0.628	0.91	$p<0.05$	0.047
Pure teak plantations						
6-year-old *T. grandis*	Total tree biomass	0.953	-1.437	0.99	$p<0.001$	0.044
16-year-old *T. grandis*	Total tree biomass	1.332	-2.758	0.99	$p<0.001$	0.015

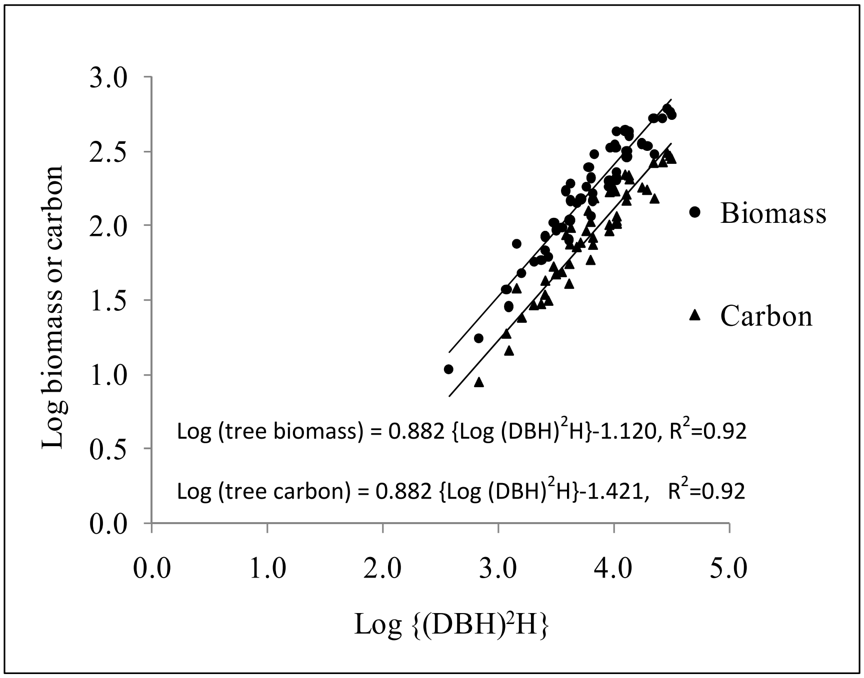
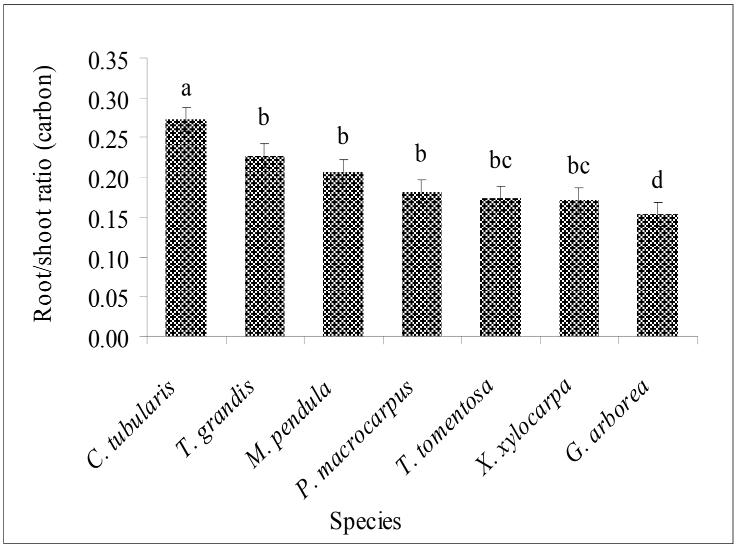


Figure 3. Liner regressions of D^2H versus total tree dry biomass (●) and total tree carbon storage (▲) of the 50 study trees (all data log-transformed).

3.2. Root/shoot ratio (AGB/BGB) of the sampled trees

The root/shoot ratios ranged from 0.15 to 0.27 (mean of 0.20) in the 35 excavated trees of the seven species in the species mixed plantation: *Tectona grandis* had a mean root/shoot ratio of 0.23 (S.E. 0 .01), *Xylia xylocarpa* (0.17 (S.E. 0.01), *Pterocarpus macrocarpus* 0.18(S.E. 0.02), *Gmelina arborea* 0.15 (S.E. 0.01), *Millettia pendual* 0.21 (S.E. 0.01), *Terminalia tomentosa 0.17* (S.E. 0.01), *and Chukrasia* tubularis 0.27 (S.E. 0.03.).

ANOVA showed that the mean ratios were not significantly different within the same species ($F=1.32$, $p=0.29$). However, significant differences was found among the mean ratios of the seven species ($p<0.001$). It indicated the variation in carbon contributions of different species to the above- and below-ground of the tree. When the carbon concentration of these components is taken into account, 15-27% (average 20%) of the trees' carbon was stored in their roots and 73-85% (average 80%) in their shoots. The Pearson's correlation was computed to measure the strength of correlation between diameter and root/shoot ratio. The correlation value was 0.067, revealing a weak correlation between two variables which was statistically insignificant. It showed that tree size (diameter) did not affect tree root/shoot ratio. Figure 4 shows the root/shoot ratios among the investigated tree species.



Note: Different letters indicate the significant differences in root/shoot ratios among the seven species according to Duncan's multiple range tests at 5% level of probability. The letters are the rank order from highest to lowest value (alphabetically). Open bar indicates the standard error.

Figure 4. Comparison among the root/shoot ratios of the planted trees from the 26-year-old mixed species plantation

3.3. Plantation-level biomass and carbon sequestration

In this study, total carbon storage is the sum of above-ground carbon, root carbon, litter fall carbon, undergrowth carbon, and soil carbon of each plantation site. It was found out that the 26-year-old mixed species plantation sequestered the greatest carbon (125.9 ton ha^{-1}) among the four plantations, and it was followed by 26-year-old teak plantation (116.1 ton ha^{-1}), 16-year-old teak plantation (90.4 ton ha^{-1}) and 6-year-old teak plantation (65.5 ton ha^{-1}) (Table 4). As expected, total carbon storage was significantly different among the four plantations (p<0.001). Mean annual increment (MAI) of total carbon storage of a plantation was determined over the existing age of each plantation. A clear trend was found that MAI decreased from 10.9 C ton ha^{-1}year^{-1} at the age of 6 years to 4.5 ton ha^{-1}year^{-1}at 26 years, whereas MAI of mixed species plantation was 4.8 C ton ha^{-1}year^{-1}.

In terms of standing volume, ANOVA showed that the volume per ha was significantly different between the plantations (p<0.0001). The standing volume of 26-year-old mixed plantation recorded 175.02 m^3 ha^{-1} while 6-, 16-, and 26-year-old pure teak plantations amounted to 56.38 m^3 ha^{-1}, 88.97 m^3 ha^{-1}, and 148.40 m^3 ha^{-1}, respectively. MAI of the 6-year-old teak plantation was 9.40 m^3 ha^{-1}year^{-1}, while that of 26-year-old teak plantation scored 5.71 m^3 ha^{-1}year^{-1}.

Significant differences were found in the mean amounts of litter fall ($p<0.001$) and undergrowth biomass ($p<0.001$) among the four plantation sites. Average dry biomass of litter fall and undergrowth which accumulated in the dry season were 4.17, 3.02, 2.78, and 2.49 Mg/ha in the mixed species plantation, 26-, 16-, and 6-year-old pure teak plantations, respectively (Table 4). Table 5 also shows the total carbon storage of 6-year-old commercial tree species. The analysis suggested that the litter fall and undergrowth biomass increased with the age of the plantations. The proportions of litter fall and undergrowth carbon in total carbon storage were approximately the same in all the study sites.

Table 4. Total carbon sequestration of pure teak and mixed species plantations

Study sites	Above-ground C (ton/ha)	Root C (ton/ha)	SOC (ton/ha)	Litter-fall C ton/ha)	Undergrowth C (ton/ha)	Total C storage (ton/ha)
6-yr-old teak plantation	20.8 (0.83)^{b}	6.2 (0.25)^{b}	35.5 (1.08)^{a}	0.8 (0.02)^{d}	2.2 (0.13)^{d}	65.5^{b}
16-yr-old teak plantation	37.6 (5.98)^{a}	8.7 (1.78)^{a}	39.7 (1.25)^{a}	1.6 (0.15)^{c}	2.8 (0.05)^{c}	90.4^{b}
26-yr-old teak plantation	42.1 (2.10)^{a}	12.6 (0.63)^{a}	55.5 (4.40)^{a}	1.9 (0.08)^{b}	4.1 (0.13)^{b}	116.1^{b}
26-yr-old mixed species plantation	47.8 (1.61)^{a}	11.9 (0.40)^{a}	59.9 (5.77)^{a}	2.1 (0.09)^{a}	4.2 (0.18)^{a}	125.9^{a}

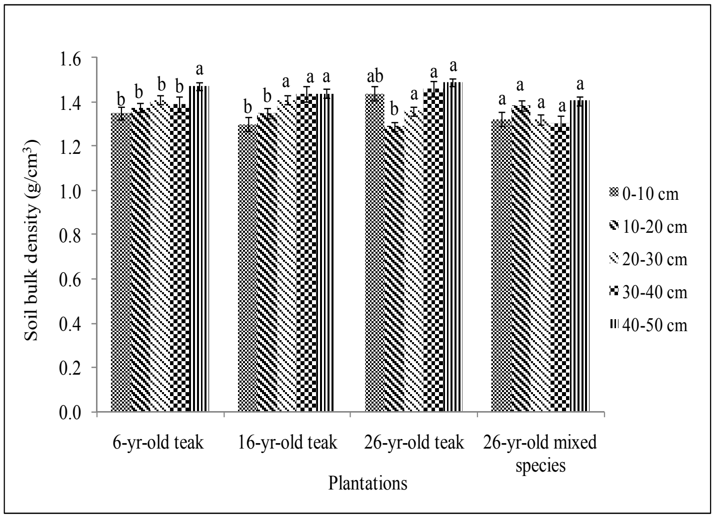
Numbers are the means with standard errors in the parentheses. Different letters indicate the significant differences in carbon storage according to Duncan's multiple range tests at 5% level of probability. The letters are the rank order from highest to lowest value (alphabetically).

Table 5. Total carbon sequestration of 26-year-old commercial tree species

No.	Species*	Mean DBH (cm)	Tree C* (ton /ha)	SOC (ton/ha)	Litter-fall C (ton/ha)	Undergrowth C (ton/ha)	Total C (ton/ha)
1	Teak	26.0	54.7	59.9	2.1	4.2	116.1
2	Pyinkado	24.6	71.5	59.9	2.1	4.2	137.7
3	Padauk	27.7	72.7	59.9	2.1	4.2	138.9
4	Thinwun	27.6	72.5	59.9	2.1	4.2	138.7
5	Taukkyan	22.8	53.8	59.9	2.1	4.2	120.0
6	Yemane	25.0	36.3	59.9	2.1	4.2	102.5
7	Yinma	24.0	63.1	59.9	2.1	4.2	129.3

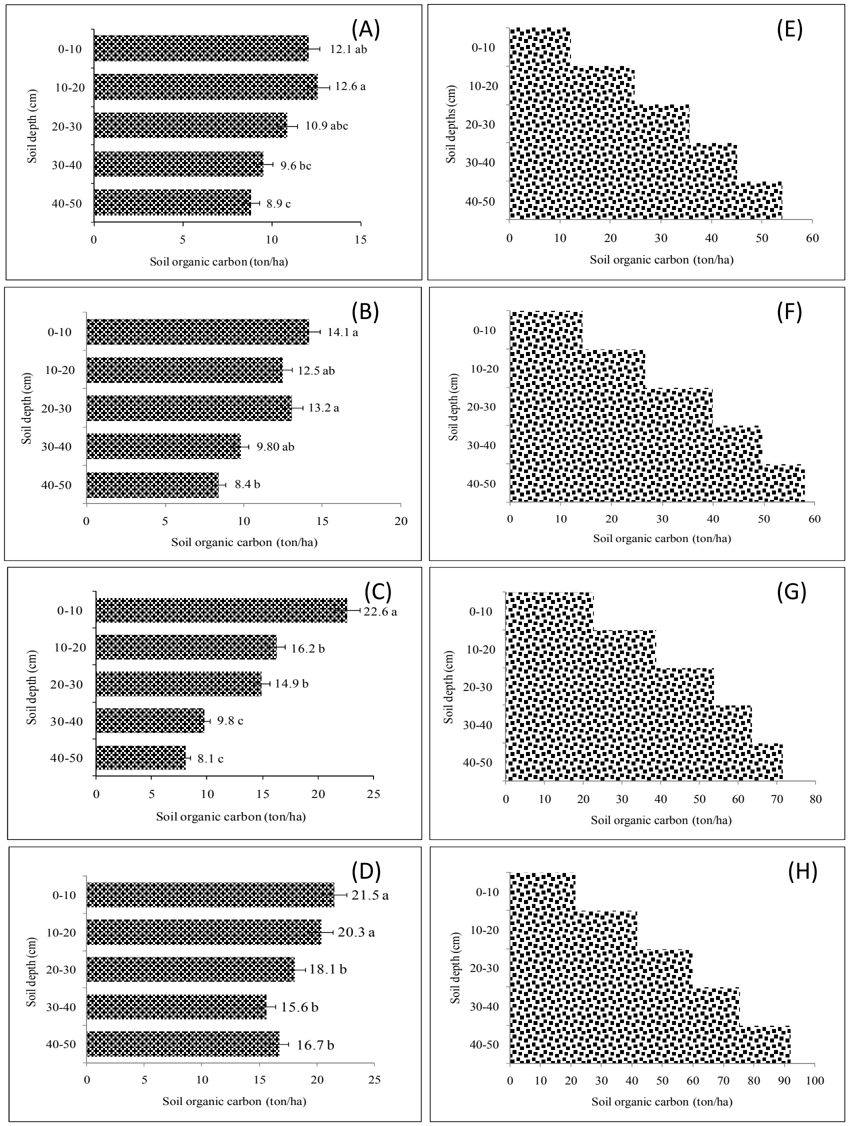
Note: *Teak = *Tectona grandis*, Pyinkado = *Xylia xylocarpa*, Padauk = *Pterocarpus macrocarpus*, Thinwun = *Millettia pendula*, Taukkyan = *Terminalia crenulata*, Yemane = *Glemina arborea*, Yinma = *Chukrasia velutina*

Significant differences were found in SOC (p<0.0001) and soil bulk density (p<0.0001) among plantations (Figure 5). The total SOC (up to 30 cm) accumulated by the 26-year-old mixed species plantation amounted to 56.92 ton ha^{-1} while that of the 6-, 16- and 26-year-old pure teak plantations varied from 35.52, 35.74, and 55.48 ton ha^{-1}, respectively (Figure 6). Soil bulk density ranged from 1.56 g/cm^3 to 1.70 g/cm^3 in all the plantation sites (average 1.55 g/cm^3). Likewise, both SOC and soil bulk density changed significantly with depth (p<0.0001 for both). Duncan's multiple range test showed that SOC decreased with increasing soil depth while soil bulk density increased with increasing soil depth.



Note: Different letters indicate the significant differences in soil bulk density among the study sites according to Duncan's multiple range tests at 5% level of probability. The letters are the rank order from highest to lowest value (alphabetically). Open bar indicates the standard error.

Figure 5. Comparison of soil bulk density among the plantations



Note: Different letters indicate the significant differences in SOC among the soil depths according to Duncan's multiple range tests at 5% level of probability. The letters are the rank order from highest to lowest value (alphabetically). Open bar indicates the standard error.

Figure 6. Soil organic carbon and cumulative carbon storage in different soil layers of 6-year-old teak plantation (A and E), 16-year-old teak plantation (B and F), 26-year-old teak plantation (C and G), and 26-year-old mixed species plantation (D and H).

In terms of proportion of carbon storage at the plantation-level, soil organic carbon stored about 50% of total carbon in all the sites but above-ground carbon varied from 31.8% to 41.6% among the plantations. Root carbon contained about 10% of the total carbon storage while litter-fall and undergrowth carbon composed only about 3% and 2%, respectively, of the total carbon storage of the plantation. Figure 7 shows the average proportion of carbon represented by the components of the 26-year-old plantations.

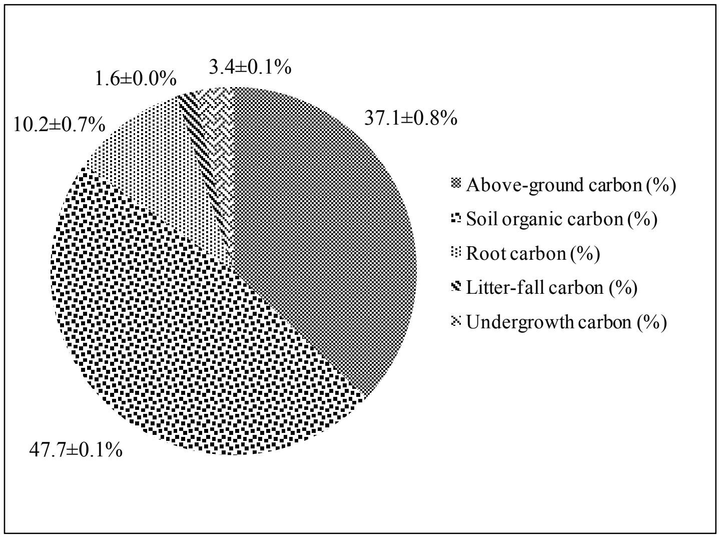


Figure 7. Average proportion of carbon represented by the components of the 26-year-old plantations

4. Discussion

4.1. Carbon storage of pure teak and mixed species plantations

Figure 7 clearly illustrates the carbon storage of the whole components of the plantation as a system. Average carbon storage in the trees of four plantations amounted to 49.52 Mg/ha and much of the tree's carbon was located in above-ground. Average litter fall and undergrowth carbon (1.58 and 3.3 Mg/ha, respectively) of this system contained a moderate amount when compared to the tree carbon and SOC (Figure 7). The figure suggested that most of the carbon in the system is in the soil, averaging 45.92 Mg/ha, bringing the total carbon in each hectare of these plantations to 100.31 Mg.

The dry biomass of stem, branch, leaves, bough, bark and roots increased with increasing tree size (diameter) as well as age of the trees indicating that teak and other species still produced and accumulated biomass at the age of 26 (Table 4). It was because these trees have not reached a maximum age for the greatest production. This study is similar with the findings of Perez Cordero and Kanninen (2003) on the above-ground biomass of 8-47 age series teak trees in Costa Rica. They found that the components of tree biomass increased with increasing tree size and age and teak trees have not reached its maximum until the age of 47. Tint et al., (1993) and Htun et al., (1999) reported that the teak plantations in the Bago Yoma Region of Myanmar reached its maximum production at the age of 60. Accordingly, the four plantations under this study have tendency to produce more biomass until they reach their maximum age of production.

In this study, the strength of site specific regression equations relating individual tree's dbh and tree height (D^2H) to total tree biomass allows confident use of the equations for estimating carbon storage in trees of 6-, 16-, and 26-year old pure teak plantations and 26-year-old mixed species plantation (Table 3). Similarly, since the general regression equation based on 50 sampled trees of seven species showed strong relationship between D^2H and tree carbon storage, it could be used for the estimation of carbon storage (Figure 3) for all investigated plantations. Brown et al., (1989) and Kwon and Lee (2006) reported that diameter and tree height can be used as reliable parameters for the estimation of tree biomass. These may useful both for application in existing plantations, as well as for prediction of potential storage when combined with site-index, which predict productivity of various sites in terms of tree size (Kraenzel et al., 2003).

Perez Cordero and Kanninen (2003) reported that per ha biomass in teak plantation is influenced by stand density. The same pattern was observed in this study that older trees 26-year-old teak and mixed species plantations have lower densities than younger ones. Therefore, they accumulated more individual-tree biomass. Due to the higher stand density of younger age plantations (6- and 16-year-old teak plantations), per ha biomass (carbon) can be compared with older age ones (Table 4). It indicates that stand density is equally important as tree size in sequestering carbon. On the other hand, the carbon storage of teak plantations could be influenced by the differences in tree size (diameter and tree height). Stand density could be influenced as well if the effect of age is eliminated.

Similar with this study, per ha tree carbon storage of teak plantations varied in Bangladesh and Panama. The average tree carbon storage (49.52 Mg/ha) of the four plantations in this study was lower than 120 Mg/ha of the 20-year-old harvest-age teak plantation in Panama (Kraenzel *et al.*, 2003) and 223.89 Mg/ha in Bangladesh (Shin et al., 2007). Even total tree carbon storages of 26-year-old teak (54.69 Mg/ha) and mixed species plantations (59.70 Mg/ha) were lower than their estimations. This might be due to the combined effects of differences in growth rate, stand density, climatic and edaphic factors. The results of this study were similar to that of Karmacharya and Singh, who reported that the above-ground biomass of 4-year-old, 14-year-old and, and 30-year-old teak plantations at Chakia, India were 25.3 Mg/ha (12.6 Mg C/ha), 39.9 Mg/ha (19.9 Mg C/ha) and 77.0 Mg/ha (38.5 Mg C/ha), respectively. If the root carbon is added to the above-ground carbon estimation, the total amount of carbon storage of those plantations would be approximately the same as the estimation of this study. In fact, their study site was much drier (762 mm of average annual rainfall) compared to this study's sites (Table 1). Therefore, the differences in biomass accumulation and carbon estimation of plantations could be due to the wide range of factors including stand conditions such as age, stand density, tree size, intensity of silvicultural operations, like thinning and pruning, climatic and edaphic conditions.

The amount of litter fall and undergrowth carbon of the mixed plantation was relatively higher than that of the pure teak plantations (Table 4). Some species of the mixed species plantation may have larger leaf area and may produce more litter fall than pure teak plantations. However, the values of carbon estimated in litter fall and undergrowth of this study showed relatively lower value than 6 Mg/ha/year and 3.44 Mg/ha/year in the 20-year-old teak plantations of Panama (Kraenzel et al., 2003) and Bangladesh (Shin et al., 2007), respectively. These differences may be mainly due to the annual forest fires (surface fire) and soil erosion that are common in the study sites.

4.2. Root/shoot ratio

The relationship between the dry biomass of root and shoot provided a reliable ratio for each species (Figure 4). It can be used to estimate the below-ground biomass of the trees as well as of the plantation. The amount of carbon stored in tree's roots is often substantial, but is still unknown for many species (Kraenzel et al., 2003). Regardless of species, the root/shoot ratio (0.15~0.27) of the seven species was greater than 0.22~0.30 in Australia (Specht and West, 2003). The mean root/shoot ratios of teak (0.23) and that of the seven species (0.20) were closer to the ratio of other tropical forest biomass, which is 0.24 (Cairns et al., 1997). The root/shoot ratio of teak (23% of above-ground biomass) in this study was higher than 15% in Bangladesh (Shin et al., 2007), and 0.16% in Panama (Kraenzel et al., 2003). Although there was no relationship between root/shoot ratio and diameter in this study, this trend may be linked more directly to the development with age than tree size (diameter).

4.3. SOC storage in the plantations

Decreasing SOC with increased soil depths is the general pattern of SOC distribution in all the plantation sites of this study (Figure 6). The amount of soil carbon contributed to all the plantations is approximately equal to 50% of the total carbon storage of each plantation. However, soil carbon storage of older age plantations such as 26-year-old pure teak and mixed plantations were higher than that of 6- and 16-year-old pure teak plantations. Because the plantations were established in degraded forests, young plantation generally has lower SOC, and may increase when the plantation matures. There is a tendency for SOC to change and become higher than the present value of each plantation by the end of rotation period 40-60 years). Lugo and Brown (1993), Paul et al. (2002), and Turner and Lambert (2000) also suggested that by the end of rotation age, SOC may change further to be ultimately higher or lower than its value at the time of plantation establishment, depending on the site and its management. Similar to other studies (Brown and Lugo, 1982; Brown and Lugo 1992; Lugo, 1992), SOC of the mixed species plantation was relatively higher than that of the 26-year-old pure teak plantation. It might be due to the species composition of the plantation. Some species produced or accumulated more litters or roots, and decomposed more easily than others. These differential rates of organic matter production eventually influence SOC.

5. Conclusions

This study was concerned mainly with the estimation of sequestered carbon in plantations on a single occasion. Estimates of change over time would be based on repeated measurements of the plantations. This study assessed the carbon storage of the existing stocks of pure teak plantations with three age groups and a mixed species plantation. Based on the estimations and comparisons with other studies, both pure teak plantations and the mixed species plantation have appreciable carbon storage capacities of 65.52~116.06 Mg/ha and 122.90 Mg/ha, respectively. This study showed a high correlation among diameter and tree height *vs* total tree biomass (carbon sequestration). This information is helpful in the prediction of plantation biomass using inventory data (non-destructive method). The root/shoot ratio of the seven species also provided an alternative option to estimate the root biomass of trees in the plantation using above-ground biomass. The SOC content of teak plantations (30.83 Mg/ha to 55.48 Mg/ha) and the mixed species plantation (56.92 Mg/ha) also clearly displayed the significant role that reforestation plays in the sequestration of soil carbon. However, it is recognized that more sample trees for each species are needed to construct more accurate regression models. Particularly, sampled teak trees with various age classes should be taken from various regions of the country in order to construct allometric regression models accurately, which could then be extrapolated beyond the range of actual observations.

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APPENDIX

Biomass regression equations for seven species of 26-year-old mixed species plantation

***Y* = *a (DBH)* + *b* where, *Y*= C biomass (kg), *a* and *b* = correlation coefficients**

No.	Species	Regression coefficients y (biomass) = *a* (DBH)+*b*		R^2
		a	*b*	
1	Teak	15.58	- 137.70	0.95
2	Pyinkado	25.22	- 261.70	0.94
3	Padauk	16.73	- 99.94	0.93
4	Thinwun	16.26	- 86.44	0.98
5	Taukkyan	24.93	- 299.2	0.92
6	Yemane	10.22	- 74.01	0.96
7	Yinma	21.56	- 202.00	0.95

Note: Diameter at Breast Height (DBH) range of sample trees (harvested trees) was 7.5cm to 43.6 cm.

Biomass regression equations for seven species of 26-year-old mixed species plantation

Log *Y* = *a* + *b* Log *X* where, *Y*= C biomass (kg), *X* = $(DBH)^2*H$, *a* and *b* = correlation coefficients

Teak (*Tectona grandis*)

Parameters (y)	a	b	R^2	Prob. Level	S.E.
Stem biomass	0.874	-1.402	0.90	p<0.05	0.058
Branch biomass	0.216	0.522	0.79	p<0.05	0.022
Bough biomass	1.059	-3.446	0.94	p<0.01	0.053
Leaves biomass	0.295	0.024	0.93	p<0.01	0.017
Bark biomass	0.711	-1.724	0.96	p<0.005	0.031
Root biomass	0.802	-1.594	0.80	p<0.05	0.081
Above-ground biomass	0.733	-0.664	0.92	p<0.01	0.042
Total biomass	0.746	-0.628	0.91	p<0.05	0.047

Pyinkado (*Xylia xylocarpa*)

Parameters (y)	a	b	R^2	Prob. Level	S.E.
Stem biomass	0.987	-1.654	0.97	p<0.005	0.074
Branch biomass	0.617	-0.797	0.78	p<0.05	0.129
Bough biomass	0.743	-2.013	0.94	p<0.01	0.076
Leaves biomass	0.756	-1.759	0.78	p<0.05	0.160
Bark biomass	0.697	-1.626	0.87	p<0.05	0.107
Root biomass	0.769	-1.403	0.89	p<0.05	0.104
Above-ground biomass	0.845	-0.933	0.93	p<0.01	0.090
Total biomass	0.834	-0.82	0.93	p<0.01	0.090

Padauk (*Pterocarpus macrocarpus*)

Parameters (y)	a	b	R^2	Prob. Level	S.E.
Stem biomass	0.922	-1.404	0.94	p<0.01	0.132
Branch biomass	0.675	-1.169	0.78	p<0.05	0.201
Bough biomass	0.270	-0.537	0.88	p<0.05	0.057
Leaves biomass	0.742	-2.279	0.91	p<0.05	0.127
Bark biomass	0.572	-1.267	0.92	p<0.01	0.093
Root biomass	0.753	-1.382	0.92	p<0.01	0.125
Above-ground biomass	0.854	-1.020	0.93	p<0.01	0.131
Total biomass	0.838	-0.887	0.93	p<0.01	0.126

Taukkyan (*Terminalia tomentosa*)

Parameters (y)	a	b	R^2	Prob. Level	S.E.
Stem biomass	0.838	-1.106	0.99	$p<0.001$	0.049
Branch biomass	0.998	-2.470	0.89	$p<0.05$	0.173
Bough biomass	1.235	-4.202	0.91	$p<0.05$	0.193
Leaves biomass	0.915	-2.647	0.92	$p<0.01$	0.130
Bark biomass	0.772	-1.895	0.91	$p<0.05$	0.120
Root biomass	0.97	-2.249	0.97	$p<0.005$	0.080
Above-ground biomass	0.846	-1.004	0.95	$p<0.005$	0.092
Total biomass	0.865	-1.007	0.96	$p<0.005$	0.089

Thinwun (*Millettia pendula)*

Parameters (y)	a	b	R^2	Prob. Level	S.E.
Stem biomass	0.726	-0.58	0.96	$p<0.005$	0.086
Branch biomass	0.471	-0.517	0.83	$p<0.05$	0.121
Bough biomass	0.184	0.088	0.78	$p<0.05$	0.056
Leaves biomass	0.496	-1.209	0.94	$p<0.01$	0.071
Bark biomass	0.509	-0.997	0.84	$p<0.05$	0.125
Root biomass	0.600	-0.680	0.89	$p<0.05$	0.118
Above-ground biomass	0.658	-0.214	0.96	$p<0.005$	0.078
Total biomass	0.648	-0.097	0.95	$p<0.005$	0.084

Yemane (*Gmelina arborea*)

Parameters (y)	a	b	R^2	Prob. Level	S.E.
Stem biomass	0.728	-0.829	0.99	p<0.001	0.029
Branch biomass	0.988	-2.786	0.84	p<0.05	0.185
Bough biomass	0.718	-2.536	0.84	p<0.05	0.135
Leaves biomass	0.785	-2.592	0.91	p<0.05	0.105
Bark biomass	0.541	-1.262	0.91	p<0.05	0.074
Root biomass	0.702	-1.455	0.95	p<0.01	0.070
Above-ground biomass	0.737	-0.770	0.98	p<0.005	0.047
Total biomass	0.732	-0.690	0.98	p<0.005	0.048

Yinma (*Chukrasia tubularis*)

Parameters (y)	a	b	R^2	Prob. Level	S.E.
Stem biomass	0.993	-1.76	0.95	p<0.005	0.143
Branch biomass	0.666	-1.381	0.92	p<0.05	0.129
Bough biomass	0.868	-2.779	0.90	p<0.05	0.183
Leaves biomass	0.774	-2.170	0.91	p<0.05	0.154
Bark biomass	0.885	-2.427	0.98	p<0.005	0.079
Root biomass	1.025	-2.329	0.98	p<0.005	0.099
Above-ground biomass	0.928	-1.385	0.96	p<0.005	0.119
Total biomass	0.95	-1.368	0.97	p<0.005	0.109