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Biomass and carbon storage in an age-sequence of *Acacia mangium* plantation forests in Southeastern region, Vietnam

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Abstract

Aim of study: The major objective of this study was to estimate the biomass increment and carbon (C) storage of the main ecosystem components in an age-sequence of three *Acacia mangium* plantation stands.

Area of study: Chang Riec Historical - Cultural Forest, Southeastern region, Vietnam.

Material and methods: In order to assess the biomass of different tree components, 36 trees with diameter at breast height ranging from 13.38 to 22.87 cm were harvested from the different aged stands. Biomasses of understory (shrubs and herbs), and litter were also determined. Carbon storage in the trees and understory biomass, litter, and mineral soil (0-50 cm) were determined by analyzing the C content of each compartment.

Main results: The biomass in trees, understory vegetation, litter, and ecosystem increased with stand age. Soil C represented 61.99% of the total, aboveground tree biomass C made up 26.73%, belowground tree biomass C accounted for 7.01%, and litter comprised 2.96%, whereas only a small amount (1.30%) was associated with understory vegetation. The average C content of total tree (47.97%) was higher than those of understory and litter. Soil organic C stock in the top 50 cm depth in 4-, 7- and 11-year-old stands of *A. mangium* were 86.86, 126.88 and 140.94 Mg C ha⁻¹ respectively. Soil C concentration decreased continually with increasing soil depth. Total C storage of three planted forests ranged from 131.36 to 255.86 Mg C ha⁻¹, of which 56.09 - 67.61% of C storage was in the soil and 26.88 - 40.40% in the trees.

Research highlights: These results suggest that *A. mangium* is a promising afforestation tree species with fast growing, high biomass accumulation and high C sequestration potential.

Keywords: *Acacia mangium* plantations; Biomass; Ecosystem carbon storage; Age-sequence; Vietnam.

Abbreviations used: SOC (soil organic carbon); DBH (diameter at breast height); H (height); Dm (stand mean diameter); C_s (soil carbon stocks); SBD (soil bulk density); Sd (soil depth); AGB (aboveground tree biomass); BGB (belowground tree biomass); TB (total tree biomass, including aboveground and belowground tree biomass); VAGB (understory vegetation aboveground biomass); VBGB (understory vegetation belowground biomass); TVB (total understory vegetation biomass); AGBC (aboveground tree biomass carbon stock); BGBC (belowground tree biomass carbon stock); TBC (total tree biomass carbon stock, including aboveground and belowground tree biomass C stock); VAGC (understory vegetation aboveground biomass carbon stock); VBGC (understory vegetation belowground biomass carbon stock); TVC (total understory vegetation carbon stock).

Authors' contributions: Conceived and designed the experiment: Xu, X., Thanh, N., and Cuong, L.; Performed the experiment and drew the site map: Cuong, L., Hung, B., and Thang, B.; Analyzed the data: Cuong, L., Bolanle-Ojo, O.T., Chai, L., Legesse, N., and Wang, J.; Drafting of the manuscript: Cuong, L.; Editing and discussing the manuscript: Hung, B., and Bolanle-Ojo, O.T.; Critical revision and editing: Xu, X. and Thanh, N. The authors read and approved the final manuscript.

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Introduction

Emissions of CO₂ and other GHG have been increasing during the past century (IPCC, 2007); hence, posing environmental issues (Xu *et al.*, 2007; Cheng *et al.*, 2015), and leading to concerns of climate change and their mitigation strategies. Sequestering carbon (C) through forests is considered as a mitigation path for climate change (Dixon *et al.*, 1994; Lal, 2005; Pan *et al.*, 2011). Forests can maintain C balance via their substantial amount of C sequestration (Fan *et al.*, 1998; Houghton, 2007; Pugh *et al.*, 2019). Forests ecosystem have an irreplaceable role in minimizing accumulation of atmospheric CO₂ and maintaining global climate stability (Fang *et al.*, 2001; Härkönen *et al.*, 2011).

The global total amount of C in soil and vegetation is about 1912.2 Pg C, of which soil C content is 2.8 times higher than the amount of C stored in vegetation biomass (Scharlemann *et al.*, 2014), showing the importance of soil in C sink. Tropical forests play a crucial role in driving the global C cycle (Zelazowski *et al.*, 2011; Ngo *et al.*, 2013). The accurate estimation of C storage in forest soils over time can help to understand the amount of C removed from the atmosphere through plants (Eglin *et al.*, 2011).

According to FAO (2016), plantation forests cover an area of 291 million hectares and accounts for 7% of the global forest area. Planted forests are regarded as effective tools for countering climate change due to their ability to absorb C and they also play an increasingly important role in regulating climate in the future (Canadell *et al.*, 2007). China has the largest forest plantation area in the world (~ 69 million hectares) (Xu *et al.*, 2010). Most of these plantations are still immature and indicate a significant potential for C sequestration (Huang *et al.*, 2012). Xu *et al.* (2007) revealed that the C sink function of vegetation in Chinese forests mainly came from the contribution of plantations. Thus, strengthening relevant studies on C stocks in plantations will have an extremely important guiding role in predicting and maintaining the long-term productivity of the system and minimizing atmospheric CO₂ concentration accumulation.

Biomass equations will be a key part of future C measurements and assessments in addressing the issues of climate change as biomass is a crucial component in determining forest C stocks and accumulation rates (Temesgen *et al.*, 2015). The *DBH* is a commonly used variable in allometric equations because it has a close relationship with biomass and is easy and correctly identified (Brown, 1997; Brown *et al.*, 1989; Snowdon *et al.*, 2000; Phuong, 2011). Although some authors have shown that the inclusion of *H* in biomass allometries compared to the only use of *DBH*, substantially improves biomass assessment (Chave *et al.*, 2005; Hunter *et al.*, 2013). The accurate determination *H* in closed canopy

forests is often challenging because it is difficult to decipher between adjacent trees and the tree to be measured (Chave *et al.*, 2014). As a result, current methods to assess *H* result in estimates with high degrees of random and systematic error.

Acacia mangium Willd. is a fast-growing tree species native to parts of Australia, Papua New Guinea and Indonesia. It has been widely cultivated in Southeast Asia, Tropical America and many African countries in large-scales (Forss *et al.*, 1996; Ren & Yu, 2008; Herdiyanti & Sulistyawati, 2009; Koutika & Richardson, 2019) mainly due to its fast growth, drought tolerance, adaptation to different soil types and pH, good wood quality for timber and energy production (NRC, 1983). These attributes make *A. mangium* a candidate tree species for afforestation or reforestation programs. *A. mangium* was introduced into Vietnam in 1980 (Turnbull *et al.*, 1998) and it's now one of the most important afforestation tree species in some of the eight important forestry-ecological regions and Southeastern region in Vietnam (MARDa, 2014). It plays an important role in the national and regional ecosystem C cycles because its plantation area is over 600,000 hectares, accounting for approximately 16% of the total plantations in Vietnam (MARDb, 2014). These plantations are predominantly established on agricultural lands and degraded forest lands, and these are managed on a rotational length of 5–12 years for the production of both pulps and timbers (MARDb, 2014). *A. mangium* was an excellent afforestation tree species with fast growing, high yielding and high comprehensive utilization of whole trees. Besides producing woods for industries, *A. mangium* plantations also has role in providing environmental service such as felling negative effects on C cycle through the uptake and storage of C. Thus, there is need for accurate information regarding the C storage in *A. mangium* planted forests. Although numerous studies have been conducted in *A. mangium* plantations; growth and wood properties (Dhamodaran & Chacko, 1999), biomass and productivity (Ren & Yu, 2008), allometric biomass equations and C sequestration (Hai *et al.*, 2009; Herdiyanti & Sulistyawati, 2009; Ilyas, 2013), microbial activity in litter and soil (Bini *et al.*, 2013), soil nutrients (Lee *et al.*, 2015), biological nitrogen fixation (Paula *et al.*, 2015), soil C storage (Thanh & Cuong, 2017), benefits and its negative impacts on biodiversity (Koutika & Richardson, 2019). However, the biomass and C sequestration of *A. mangium* plantations in Southeastern region of Vietnam are largely unknown, which is critical to predict the responses of regional and global C balance to future climate change. Hence, the present study investigated the changes in biomass and C storage in *A. mangium* plantations across three different ages in Southeastern region, Vietnam. Specifically, the focuses of this study were: (i) to quantify the biomass of the ecosystem compartments across an age-sequence

of *A. mangium* stands; (ii) to assess the changes in the C concentrations and C stocks of ecosystem compartments with increasing stand age; and (iii) to provide information for analyzing the ecological characteristics of *A. mangium* plantations in Southeastern region.

Materials and methods

Study site

This study was carried out in Chang Riec Historical - Cultural Forest (11°00'30" to 11°35'13"N and 106°00'00" to 106°07'10"E), Tay Ninh Province, Vietnam (Fig. 1). The location has two distinct seasons: the dry season from December to April and the rainy season from May to November. The mean annual temperature is 26.9°C, with the maximum of 35.2°C between April and May and the lowest 21°C from December to February. The mean annual rainfall is 1967 mm with average rainy days of 155. Annual mean humidity is 78.3%, and monthly mean of sunshine is 181-277 hours (IBST, 2009). The terrain in the study area is relatively flat, elevation of 28-53 m a.s.l. with slopes of 3-5°. The soil type is grey brown, developed on ancient alluvium rocks, and soil depth over 100 cm. They are loam in texture with pH (H₂O) of 5.10-5.23. The clay, silt, and sand contents are 12.76, 46.06, and 41.19%, respectively. The predominant planted forests of the area comprise *A. mangium* Willd., *Acacia hybrid* (*Acacia auriculiformis* A. Cunn. ex Benth. × *A. mangium*

Willd.), *Hopea* sp., *Dipterocarpus obtusifolius* Teijsm. ex Miq., and *Tectona grandis* L.f. plantation forests. These plantations accounted for over 39.3% of the total forest area. *A. mangium* occupied approximately 20% of all plantations in this area and plays a crucial role in pulp and timber production. Our site includes a chronosequence *A. mangium* stands with ages of 4-, 7-, and 11-year-old. All the stands were the first rotation and no fertilization was applied. They were established in agricultural lands after the clear-harvesting of previous Cassava (*Manihot esculenta* Crantz). The initial planting density was 4 m × 2.5 m, and thinning operations were done once, twice, and three times for the 4-, 7-, and 11-year-old plantations, respectively. Stand density decreases as the stand age increases due to thinning operation carried out on the plantations. The DBH and *H* tend to increase with stand age (Table 1). Seed provenance from Dongnai Province was used in raising the seedlings of *A. mangium* used for the plantations. The diversity and abundance as well as growth of understory vegetation were well developed, especially for the 7- and 11-year-old plantations. The dominant species of shrub and herb layers in these plantations were *Mallotus apelta* (Lour.) Müll. Arg., *Tetracera scandens* (L.) Merr., *Chromolaena odorata* (L.) R.M. King & H. Rob., *Saccharum arundinaceum* (Retz.), *Mimosa pudica* var. *tetrandra* (Willd.) DC., *Chrysopogon aciculatus* (Retz.) Trin., *Maesa perlaris* (Lour.) Merr., *Lygodium microphyllum* (Cav.) R. Br., *Dryopteris parasitica* (L.) Kuntze, *Helicteres angustifolia* var. *obtusata* (Wall. ex Kurz) Pierre, and *Cynodon dactylon* (L.) Pers.

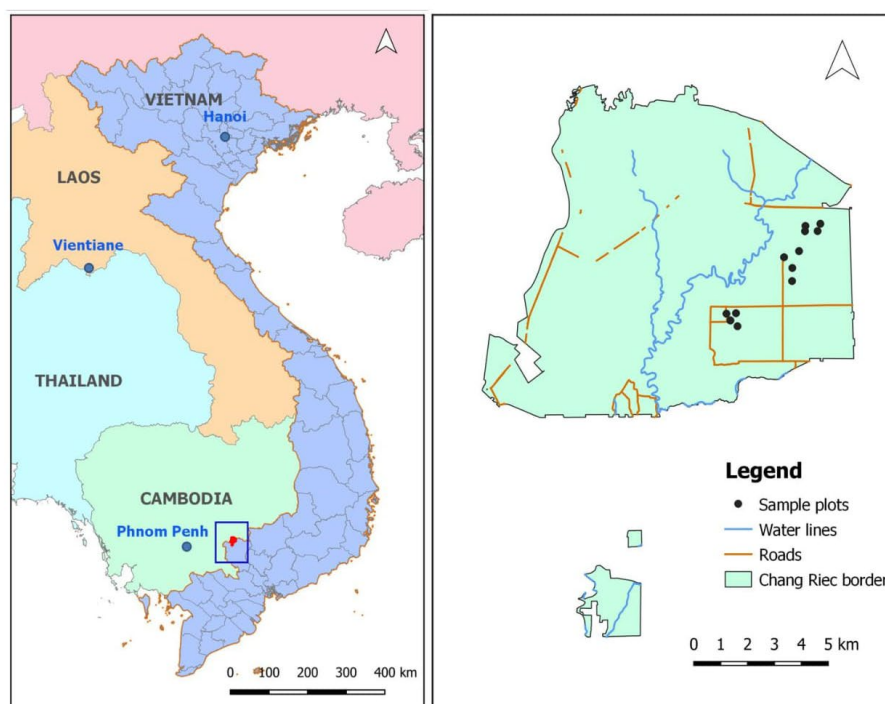


Figure 1. Study sites. Maps of Vietnam (left) and Chang Riec Historical - Cultural Forest (right).

Table 1. Basic characteristics of *Acacia mangium* plantations in Chang Riec Historical - Cultural Forest, Southeastern region, Vietnam

Stand age (years)	Stand area (ha)	Mean DBH (cm)	Mean H (m)	Stand density (tree-ha ⁻¹)	Canopy density	Elevation (m a.s.l.)	Soil depth (cm)
4	2.6	13.78 ± 0.38 ^a	14.72 ± 0.17 ^a	888 ± 30 ^a	0.83 ± 0.01 ^a	38	>100
7	2.2	17.94 ± 0.86 ^b	17.29 ± 0.56 ^b	728 ± 22 ^b	0.81 ± 0.01 ^b	40	>100
11	3.6	21.78 ± 0.85 ^c	18.60 ± 0.21 ^c	610 ± 29 ^c	0.79 ± 0.03 ^b	40	>100

Values shown as mean ± standard deviation (SD). The different lower-case letters in a column indicate significant difference at $p < 0.05$ (one-way ANOVA and LSD test). *DBH*, diameter at breast height; *H*, height

Biomass estimation and C concentration analysis

During 12th February to 30th March in 2019, four sample plots (40 m × 25 m) were established in each *A. mangium* stand. All the sampling plots were 500 - 800 m apart (Fig. 1). The *DBH* (cm) of trees in each plot with *DBH* ≥ 5 cm were measured by using a diameter tape accuracy of 1 mm and their heights (*H*, m) were determined using a Blume-Leiss altimeter. Canopy closure was determined by using a specific smartphone application (Gap Light Analysis Mobile Application software), and 10 points were measured in each plot (Table 1). Three standard trees were chosen based on the mean *DBH* (*Dm*) and logged from each sampling plot for biomass determination, using the segmenting method (Hai *et al.*, 2009; Phuong & Hai, 2011; Ngoan & Chung, 2018). A total of 36 trees were harvested (Table 2). The sample trees were divided into four biomass components (stem, branches, leaves, and *BGB*). The fresh weights of all compartments were measured *in situ*, and samples of every components in each sample tree were collected for moisture content and C concentration analysis. The root biomass was collected through total excavation, extending radially out from the trunk and downwards to soil layer until no roots were visible. The ratio of different biomass components were computed to analyze changes of relative biomass partitioning with stand age.

In this study, the *DBH* was used as a predictive variable. The relationships between dry biomass and *DBH* were tested using linear and nonlinear functions. Accord-

ing to Parresol (1999), biomass data normally exhibit heteroscedasticity. Consequently, biomass data was log-transformed and fitted as linear models to correct the heteroscedasticity of variance. The White's test (White, 1980) was also applied to check variance homogeneity of biomass models (Table 3). It is common that a correction factor (*CF*) would be used to correct for the systematic bias introduced by the anti-log transformation to obtain the expected biomass in original scale when a log-model was fitted to the biomass data ($CF = \exp(SEE^2/2)$) (Baskerville, 1972). However, other studies found that anti-log transformation tended to overestimate biomass if the *CF* is applied, and suggested that the *CF* may be omitted if the bias (*B*) from anti-log was relatively small compared to the overall variation in the estimate of biomass ($B = ((CF-1)/CF) \times 100$) (Madgwick & Satoo, 1975; Zianis *et al.*, 2011). In the present study, the *CF* values of all biomass equations were less than 1.009. The *B* values were also rather small ranging from 0.2 to 0.89% (Table 3). Therefore, the *CF* was not essential for the species in this study. The best biomass equations were selected based on various goodness-of-fit statistics namely the coefficient of determination (R^2), the Akaike information criterion (*AIC*), the root mean squared error (*RMSE*), and the standard error of estimation (*SEE*). We also accounted for the significance of the regression (*p* value) and the significance of parameters. Equations with higher R^2 , smaller *AIC*, *RMSE*, *SEE*, and significant parameters and *p* value ($p < 0.05$) were selected as the best-fitted biomass allometric equations (Akaike, 1974; Adam & Ju-

Table 2. Descriptive statistics (minimum and maximum values) for 36 sampling trees of *Acacia mangium* tree species

Stand age (years)	Variable	Tree component						
		DBH (cm)	H (m)	Stem (kg)	Branches (kg)	Leaves (kg)	BGB (kg)	TB (kg)
4	Range	13.38 - 14.27	14.3 - 14.90	39.67 - 49.48	9.80 - 16.03	3.53 - 5.44	17.13 - 22.10	71.42 - 92.43
7	Range	17.07 - 19.06	16.4 - 18.90	101.41 - 117.87	29.72 - 43.67	5.54 - 8.94	42.40 - 51.98	179.64 - 222.33
11	Range	20.76 - 22.87	18.6 - 19.20	169.22 - 201.25	78.30 - 101.32	10.49 - 16.67	52.90 - 63.06	318.92 - 376.14

DBH, diameter at breast height; *H*, height; *BGB*, belowground tree biomass; *TB*, total tree biomass

soh, 2018). The *RMSE*, and *AIC* were defined as in the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n}} \quad (1)$$

$$AIC = \ln(RMSE) + 2p \quad (2)$$

where: *n*, number of trees used for model development; *y_i*, observed biomass (kg); *ŷ_i*, predicted biomass (kg); *p*, number of model parameters to be estimated.

Biomass of shrubs and herbs was estimated by a destructive sampling of five 5 m × 5 m subplots. Shrubs (*DBH* < 5.0 cm) were separated into three components: stem plus branches, leaves and roots, and herbs into aboveground and belowground components. In each plot, the litter contribution was obtained from a set of five quadrats (1 m × 1 m) were separately chosen in each of the four corners and the center of the plot. Litter was separated into two components: leaves plus sexual organs and twigs (< 10 mm diameter). All materials were weighed freshly, and approximately 300–500 g of each compartment from each sample (shrubs, herbs, and litter) were taken for moisture and C analysis.

The abovementioned samples were taken to the laboratory of Centre of Forestry Research and Climate Change at the Vietnam National University of Forestry and oven-dried at 70°C to a constant weight, then ratios of dry/fresh biomass were calculated and used to convert fresh biomass into dry biomass. The C contents of the components from the tree component samples, understory, and litter were determined by the dichromate oxidation method (Nelson & Sommers, 1982).

Soil sampling and analysis

Soil samples were taken at fixed depth (0–10, 10–20, 20–30 and 30–50 cm) using a soil corer with four replicates for each age stand. The *SBD* of the different soil layers was determined by using a soil bulk sampler with a volume of 100 cm³ stainless-steel cutting ring. The sample was dried to 105°C to constant weight and weighed to determine *SBD* (Blake & Hartge, 1986). The *SOC* was analyzed by using the dichromate oxidation method (Nelson & Sommers, 1982).

Carbon stock estimation

Plant biomass C stocks (*C_{vs}*) was calculated as following equation:

$$C_{vs} = B \times P_c \quad (3)$$

where: *C_{vs}*, plant C stocks (Mg·C ha⁻¹); *B*, plant dry biomass (Mg·ha⁻¹); *P_c*, plant biomass C concentration (%).

It should be noted that organic C in soil is usually only calculated as organic C that exists in organic materials with a diameter (< 2 mm) (IPCC, 2003; Deng *et al.*, 2017; Thanh & Cuong, 2017), so *C_{st}* was calculated following the equation:

$$C_{st} = SOC \times SBD \times S_d \times 10^{-1} \quad (4)$$

where: *C_{st}* soil C stocks (Mg·C ha⁻¹); *SOC*, soil organic C concentration (g·kg⁻¹); *SBD*, soil bulk density (g·cm⁻³); and *S_d*, soil depth (cm).

Statistical analysis

One-way analysis of variance (ANOVA) followed by the least significant difference and then the (LSD) test was used to detect the mean difference in biomass and C stocks among different stand ages. In ANOVA, assumptions of normality and homogeneity of variances were tested with significance level at *p* < 0.05 confidence interval. Due to the focus of this study on analyzing allometric relationships between tree component biomass and *DBH* across stand ages, additivity of the biomass equation was not considered (Zianis & Mencuccini, 2004; Yang *et al.*, 2019). Statistical analysis of data and regression analysis for developing allometric equations were conducted using SPSS 25.0 software package (IBM Corp, 2017).

Results

Allometric biomass models for biomass of *A. mangium* plantations

The allometric equations using power functions (stem, branches, *BGB*, and *TB*) and exponential function (leaves) correlating biomass were established for the various components with *DBH* (Table 3 and Fig. 2). The allometric equations that were developed interpreted over 92% of the variability for the tree compartments (*p* < 0.001). The equations were most fitted for the *AGB* and *TB* among the various tree components (*p* < 0.001). The parameters of the equations varied with tree biomass compartments.

Biomass distribution in different components of *A. mangium* plantations

With increasing stand age, the biomass of most *A. mangium* tree components increased, including *AGB*,

Table 3. Biomass equations for tree components across three *Acacia mangium* stands

Tree Component	Equation form	a (SE)	b (SE)	White's test (<i>p</i>)	R ²	SEE	AIC	RMSE	CF	B	<i>p</i> (a)	<i>p</i> (b)
Stem	Power	0.015 (0.003)	3.072 (0.076)	0.142	0.980	0.086	93.645	12.063	1.004	0.398	<0.001	<0.001
Branches	Power	0.0002 (0.0001)	4.219 (0.093)	0.186	0.984	0.106	67.771	5.879	1.006	0.596	<0.001	<0.001
Leaves	Exponential	0.634 (0.058)	0.138 (0.005)	0.183	0.956	0.101	-6.571	0.746	1.005	0.498	<0.001	<0.001
AGB	Power	0.010 (0.002)	3.321 (0.062)	0.056	0.988	0.070	101.127	14.850	1.002	0.200	<0.001	<0.001
BGB	Power	0.041 (0.014)	2.386 (0.116)	0.701	0.926	0.132	67.154	5.779	1.009	0.892	<0.005	<0.001
TB	Power	0.023 (0.004)	3.130 (0.060)	0.064	0.988	0.068	106.684	17.328	1.002	0.200	<0.001	<0.001

Equation is expressed as $Y_i = a \times DBH^b$ (Power) or $Y_i = a \times e^{b \times DBH}$ (Exponential); *i*, biomass of each tree component (kg); *DBH*, diameter at breast height; *a* and *b* are the equation parameters. All allometric equations were statistically significant at $p < 0.001$. *AGB*, aboveground tree biomass (kg); *BGB*, belowground tree biomass (kg); *TB*, total tree biomass (kg); *SE*, standard error of the parameter estimate (kg); *R*², coefficient of determination; *SEE*, standard error of estimation (kg); *AIC*, Akaike information criterion; *RMSE*, root mean squared error (kg); *CF* (correction factor) = $\exp(SEE^2/2)$; *B* (percent bias) = $((CF-1)/CF) \times 100$; *n* = 36 per component

stem, branches, *BGB*, and *TB* (Table 4). The *AGB* ranged from 55.08 to 175.17 Mg·ha⁻¹ in the different aged stands and *BGB* from 17.64 to 35.40 Mg·ha⁻¹. There was a significant difference in *TB* between 11-, 7-, and 4-year-old stands ($p < 0.05$), with the highest values in the 11-year-old stand (210.57 Mg·ha⁻¹), and the lowest in the 4-year-old stand (72.72 Mg·ha⁻¹). Fo-

liage biomass increased gradually with age, with values of 3.98, 5.11, and 8.03 Mg·ha⁻¹ in the 4-, 7-, and 11-year-old stands. The overall biomass of the ecosystem increased significantly with stand age ($p < 0.05$). The litter biomass ranged from 11.43 Mg·ha⁻¹ in the 4-year-old stand to 13.29 Mg·ha⁻¹ in the 11-year-old stand, and did not differ between the different stands ($p > 0.05$). There were significant differences in the biomass of each tree component among the stands with the exception of the foliage biomass between 4- and 7-year-old stands ($p < 0.05$). For the 4- and 7-year-old stands, the biomass decreased as stem > *BGB* > branches > leaves. However, for the 11-year-old stand, biomass decline was in the order as stem > branches > *BGB* > leaves (Fig. 3a). In the understory vegetation, the *VAGB*, *VBGB*, and *TVB* were significantly different in different ages ($p < 0.05$), indicating similar trends of increasing with stand age (Table 4). The *TVB* was the highest (5.99 Mg·ha⁻¹) in 11-year-old stand and the lowest (4.86 Mg·ha⁻¹) in 4-year-old stand. The stem amounted to the largest contribution to *TB* regardless of stand age, accounting for 54.66%, 54.96%, and 53.57% of *TB* for the 4-, 7-, and 11-year-old stands, respectively. The ratio of *BGB* and foliage biomass to *TB* decreased with increasing stand age. Conversely, the contribution of branch biomass to *TB* increased with stand age (Fig. 3a). The *BGB/AGB* ratio was 0.32, 0.31 and 0.2 for 4-, 7-, and 11-year-old stands, respectively (Table 4). The proportions of *TB* of *A. mangium*

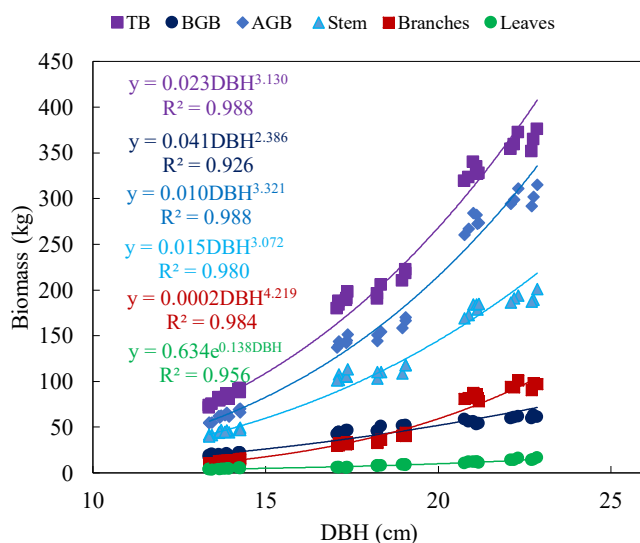


Figure 2. Fitted models for predicting tree biomass components using diameter at breast height as predictor of *Acacia mangium* plantations. *DBH*, diameter at breast height; *AGB*, aboveground tree biomass; *BGB*, belowground tree biomass; *TB*, total tree biomass.

Table 4. Biomass (Mg. ha⁻¹) and its distribution in different components of the different age stands of *Acacia mangium* plantations in Chang Riec Historical - Cultural Forest, Southeastern region, Vietnam

Ecosystem components		Stand age (years)		
		4	7	11
Tree component	Stem	39.75 ± 2.11 ^a	78.9 ± 1.42 ^b	112.8 ± 1.53 ^c
	Branches	11.35 ± 1.64 ^a	25.17 ± 2.71 ^b	54.34 ± 3.2 ^c
	Leaves	3.98 ± 0.44 ^a	5.11 ± 0.84 ^a	8.03 ± 0.88 ^b
	<i>AGB</i>	55.08 ± 3.98 ^a	109.18 ± 4.44 ^b	175.17 ± 5.11 ^c
	<i>BGB</i>	17.64 ± 0.68 ^a	34.38 ± 1.43 ^b	35.40 ± 1.87 ^b
	<i>BGB/AGB</i>	0.32	0.31	0.20
	<i>TB</i>	72.72 ± 4.58 ^a	143.56 ± 5.84 ^b	210.57 ± 6.76 ^c
	<i>VAGB</i>	4.05 ± 0.05 ^a	4.31 ± 0.05 ^b	4.80 ± 0.11 ^c
Understory vegetation	<i>VBGB</i>	0.82 ± 0.02 ^a	0.92 ± 0.02 ^b	1.19 ± 0.02 ^c
	<i>TVB</i>	4.86 ± 0.06 ^a	5.23 ± 0.05 ^b	5.99 ± 0.12 ^c
Litter		11.43 ± 0.91 ^a	11.9 ± 0.55 ^{ab}	13.29 ± 1.16 ^b
Total ecosystem		89.01 ± 5.11 ^a	160.69 ± 6.06 ^b	229.85 ± 7.36 ^c

Means in a row followed by different lower-case letters are significantly different at $p < 0.05$ (one-way ANOVA and LSD test). *AGB*, aboveground tree biomass; *BGB*, belowground tree biomass; *TB*, total tree biomass; *VAGB*, understory vegetation aboveground biomass; *VBGB*, understory vegetation belowground biomass, *TVB*, total understory vegetation biomass. The values shown as mean ± standard deviation (SD).

accounted for total ecosystem biomass were 81.70%, 89.34% and 91.61%, respectively, for the three stands (Fig. 3b).

Carbon concentration and accumulation in biomass

The C contents of different components (tree, understory, and litter) were summarized in Table 5. There were no significant differences in C concentration

in the tree ($p > 0.05$), understory ($p > 0.05$), and litter ($p > 0.05$) layer with the exception of shrubs (stem plus branches), aboveground herbs, and twigs of litter. Generally, trees had the highest C content while the understory had the lowest. The C concentration varied from 46.72% to 48.63% among components within individual trees. The highest and lowest C content in each stand was recorded for the stem and *BGB*, respectively. The mean C concentration of total tree was 47.97%. The C contents of aboveground components of the shrub and herb layers in all three stands were

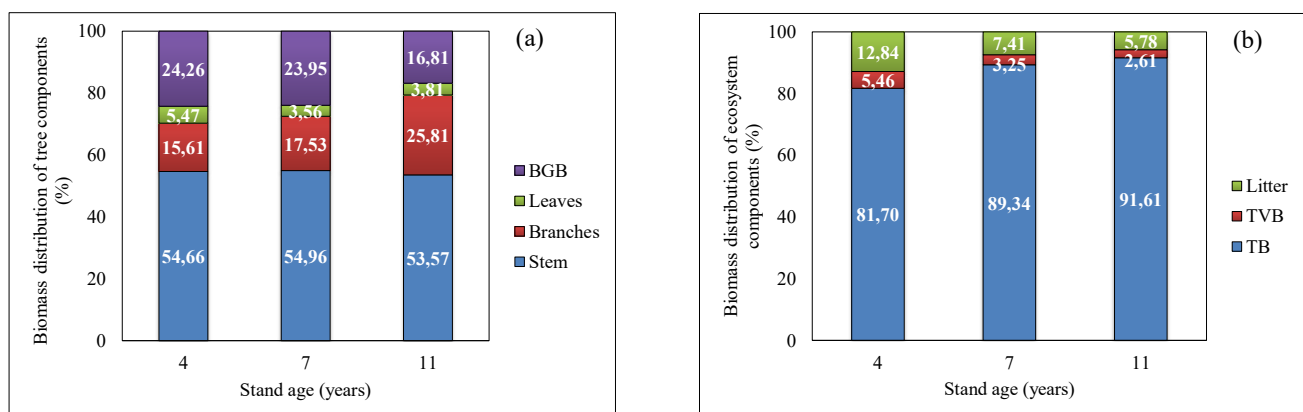
**Figure 3.** Biomass percentage distribution of tree individual components (a) and ecosystem components (b) in the 4-, 7-, and 11-year-old *Acacia mangium* plantations. *BGB*, belowground tree biomass; *TVB*, total understory vegetation biomass; *TB*, total tree biomass.

Table 5. Carbon concentration (%) in the biomass of *Acacia mangium* planted forests

Ecosystem components		Stand age (years)			Mean Value
		4	7	11	
Tree component (n=36)	Stem	47.91 ± 0.84 ^a	48.57 ± 0.49 ^a	48.63 ± 1.06 ^a	48.37 ± 0.80
	Branches	47.08 ± 0.41 ^a	47.81 ± 0.64 ^{ab}	48.25 ± 0.51 ^b	47.71 ± 0.52
	Leaves	47.88 ± 0.45 ^a	48.11 ± 0.76 ^a	48.51 ± 0.76 ^a	48.17 ± 0.66
	BGB	46.72 ± 0.62 ^a	47.68 ± 0.66 ^a	46.73 ± 0.53 ^a	47.05 ± 0.61
Understory vegetation (n=60)	Shrubs (stem plus branches)	45.30 ± 0.55 ^a	46.01 ± 0.41 ^b	47.22 ± 0.34 ^c	46.17 ± 0.43
	Shrub leaves	45.09 ± 0.29 ^a	45.97 ± 0.44 ^b	46.22 ± 0.63 ^b	45.76 ± 0.45
	Shrub roots	42.83 ± 0.20 ^b	41.98 ± 0.39 ^a	42.60 ± 0.56 ^{ab}	42.47 ± 0.38
	Aboveground herbs	43.16 ± 0.31 ^a	43.82 ± 0.57 ^b	45.21 ± 0.21 ^c	44.06 ± 0.36
Litter (n=60)	Belowground herbs	41.86 ± 0.14 ^a	42.16 ± 0.52 ^a	42.78 ± 0.33 ^c	42.27 ± 0.33
	Leaves plus sexual organs	43.98 ± 0.73 ^a	45.59 ± 0.22 ^b	46.27 ± 0.83 ^b	45.28 ± 0.59
	Twigs	42.04 ± 0.62 ^a	43.83 ± 0.56 ^b	44.99 ± 0.71 ^c	43.62 ± 0.63

Means in a row followed by different lower-case letters are significantly different at $p < 0.05$ (one-way ANOVA and LSD test). BGB, belowground tree biomass. The values shown as mean ± standard deviation (SD); n = total number of samples by component analysed

higher than those of their belowground components. The mean C contents of shrubs, herbs, and litter were 44.80, 43.17%, and 44.45%, respectively.

The AGBC averaged was 26.29 Mg·C ha⁻¹, 52.81 Mg·C ha⁻¹, and 84.98 Mg·C ha⁻¹ in the 4-, 7-, and 11-year stands, respectively. The BGBC increased with stand age, from 8.24 Mg·C ha⁻¹ at the 4-year-old stand to 16.40 and 16.54 Mg·C ha⁻¹ at the 7- and 11-year-old stands, representing 23.86%, 23.70%, 16.29% of the TBC in the three aged stand (Table 6). Except for the foliar biomass C between 4- and 7-year-old plantations, significant differences were observed in the biomass C of each tree component at different stand ages ($p < 0.05$). Stem biomass C contributed more to TBC than the other tree components. The ratio of each component to TBC indicated a similar pattern to the ratio of each component to TB (Fig. 4a). Most of the C in the biomass was stored in the TB, and litter, while only a small amount was stored in understory vegetation (Fig. 4b). The total biomass C in trees, understory, and litter increased with stand age. The TBC was 34.53, 69.21, and 101.52 Mg·C ha⁻¹ for the 4-, 7-, and 11-year-old plantations, corresponding to an annual rate of biomass C accumulation of 8.63, 11.56, and 8.08 Mg·C ha⁻¹ year⁻¹ (Table 6).

Carbon concentration and storage in soil

The SOC concentration was reduced significantly with increasing soil depth in all three stands ($p < 0.05$; Fig. 5a). The SOC content of the upper 0-10 cm soil layer was the highest in all three stands, and the values for each stand

were 12.70, 20.08, and 21.90 g·kg⁻¹, respectively. The SOC content of the four sampled soil layers (0-10 cm, 10-20 cm, 20-30 cm, and 30-50 cm) increased significantly with increasing stand age ($p < 0.05$). Figure 5b describes trends in the soil layer C stock across the *A. mangium* stand age-sequence. The Cst in the 30-50 cm soil layer followed an significant increasing trend with stand age ($p < 0.05$, Fig. 5b). Although Cst in the three soil layers (0-10 cm, 10-20 cm, and 20-30 cm) increased with age, the relationship was not significant. The Cst found in the 0-50 cm soil layer was 86.86, 126.88, and 140.94 Mg·C ha⁻¹ in the 4-, 7-, and 11-year-old stands, respectively. More than 60% of soil C was stored within 0-30 cm soil layer of each stand (Fig. 5b).

Carbon storage in the plantation ecosystem

Mean total ecosystem C stock of 128.47, 203.77, and 251.27 Mg·C ha⁻¹ were observed in the 4-, 7-, and 11-year-old plantations (Table 6). The total ecosystem C stock increased with stand age, and there were significant differences in the ecosystem C storage ($p < 0.05$). The C stock fractions across the three stands was in the following order: soil layer (56.09-67.61%) > tree layer (26.88-40.40%) > litter layer (2.42-3.84%) > understory layer (1.09-1.67%) (Fig. 6). Averaging across stands, 61.99% of the total C was in the soil, 33.75% in the trees, 2.96% in the litter, and 1.30% in the understory layer. The proportion of C accumulated in soil decreased with increasing age and the proportion accumulated in biomass increased.

Table 6. Carbon stock in biomass ($\text{Mg} \cdot \text{C ha}^{-1}$) and soil ($\text{Mg} \cdot \text{C ha}^{-1}$) of *Acacia mangium* plantations in Chang Riec Historical - Cultural Forest, Southeastern region, Vietnam

Ecosystem components		Stand age (years)		
		4	7	11
Tree component	Stem	19.04 ± 0.84 ^a	38.32 ± 0.48 ^b	54.86 ± 1.55 ^c
	Branches	5.35 ± 0.81 ^a	12.04 ± 1.37 ^b	26.22 ± 1.62 ^c
	Leaves	1.91 ± 0.22 ^a	2.46 ± 0.40 ^a	3.90 ± 0.41 ^b
	<i>AGBC</i>	26.29 ± 1.73 ^a	52.81 ± 2.20 ^b	84.98 ± 2.23 ^c
	<i>BGBC</i>	8.24 ± 0.35 ^a	16.40 ± 0.78 ^b	16.54 ^b ± 0.84 ^b
	<i>BGBC/AGBC</i>	0.31	0.31	0.19
Understory vegetation	<i>TBC</i>	34.53 ± 2.00 ^a	69.21 ± 2.93 ^b	101.52 ± 3.00 ^c
	<i>VAGC</i>	1.80 ± 0.02 ^a	1.95 ± 0.03 ^b	2.22 ± 0.05 ^c
	<i>VBGC</i>	0.35 ± 0.01 ^a	0.39 ± 0.01 ^b	0.51 ± 0.01 ^c
	<i>TVC</i>	2.15 ± 0.02 ^a	2.34 ± 0.03 ^b	2.73 ± 0.06 ^c
Litter		4.93 ± 0.33 ^a	5.34 ± 0.23 ^a	6.08 ± 0.50 ^b
Soil C stock		86.86 ± 2.62 ^a	126.88 ± 1.78 ^b	140.94 ± 2.56 ^c
Total ecosystem		128.47 ± 2.52 ^a	203.77 ± 2.46 ^b	251.27 ± 2.73 ^c

Means in a row followed by different lower-case letters are significantly different at $p < 0.05$ (one-way ANOVA and LSD test). AGBC, aboveground tree biomass carbon stock; BGBC, belowground tree biomass carbon stock; TBC, total tree biomass carbon stock; VAGC, understory vegetation aboveground carbon stock; VBGC, understory vegetation belowground carbon stock; TVC, total understory vegetation carbon stock. The values shown as mean $\pm$ standard deviation (SD).

Discussion

Biomass C of *A. mangium* stands at different ages

Stand age plays an important role in the distribution of biomass and C (Xie *et al.*, 2016; Justine *et al.*, 2017; Zhang *et al.*, 2019). Results of this study show

that the biomass and C of *A. mangium* in both aboveground and belowground parts increased significantly with increasing stand age. Similar results were reported in previous studies (*e.g.* Hai *et al.*, 2009; He *et al.*, 2009; Cao *et al.*, 2012; Justine *et al.*, 2015; Zhang *et al.*, 2018). Furthermore, the accumulation rate of TBC was much higher in 4- and 7-year-old plantations than

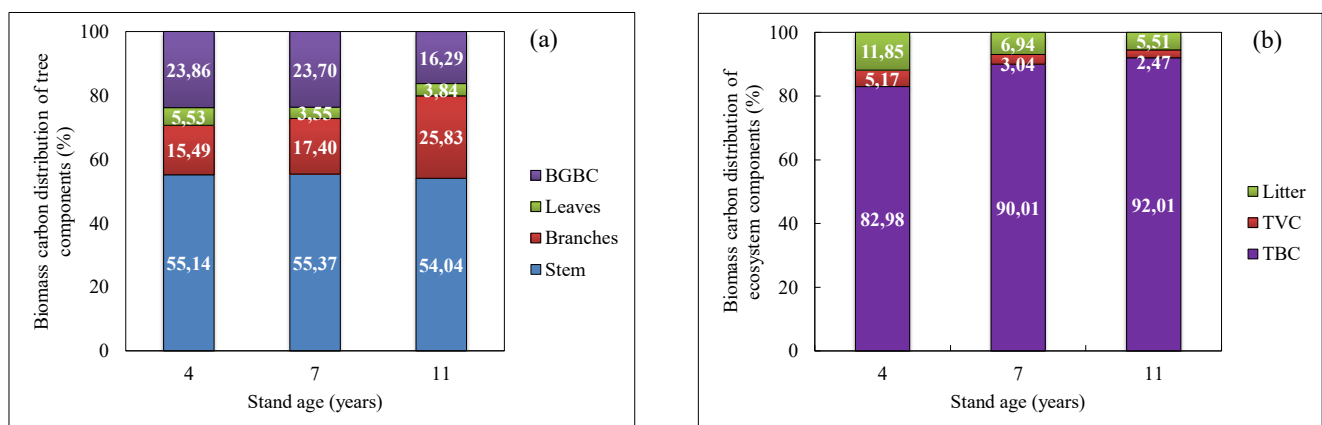


Figure 4. Biomass carbon percentage distribution of tree individual components (a) and ecosystem components (b) in the 4-, 7-, and 11-year-old *Acacia mangium* plantations. BGBC, belowground tree biomass carbon stock; TVC, total understory vegetation biomass carbon stock; TBC, total tree biomass carbon stock.

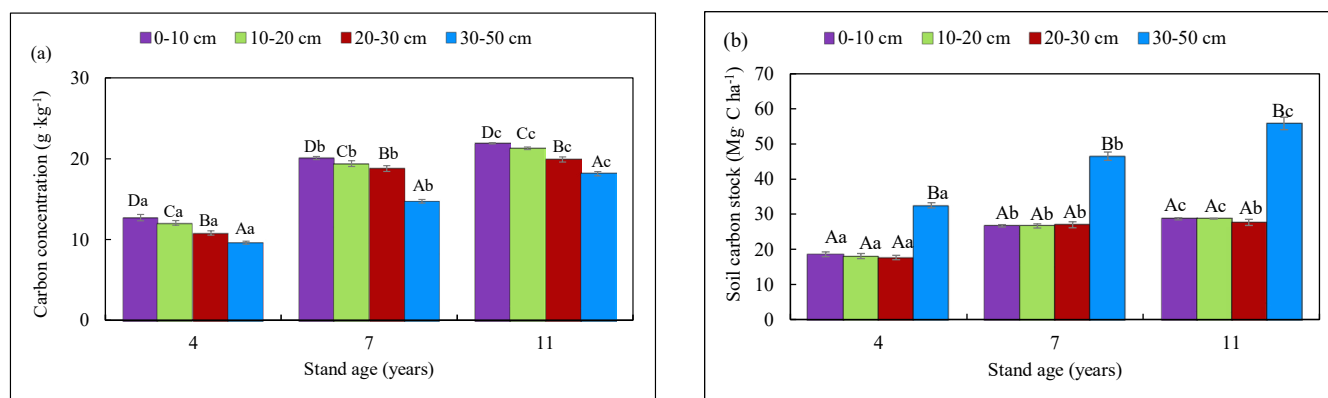


Figure 5. Distribution patterns of the carbon concentration (a) and carbon stock (b) at different depths of the soil profile for 4-, 7-, and 11-year-old *Acacia mangium* plantations. Different uppercase and lower-case letters are significantly different between soil layers in the same stand ages and between stand ages in the same soil layers ($p < 0.05$), respectively (error bars show the SD).

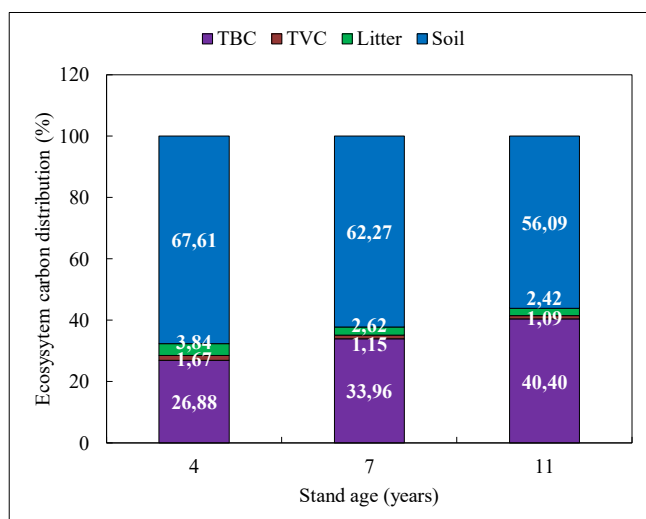


Figure 6. Percentage distribution of ecosystem carbon storage in *Acacia mangium* plantations of three different ages. TVC, total understory vegetation biomass carbon stock; TBC, total tree biomass carbon stock.

in 11-year-old plantation. The highest accumulation rate of TBC was found in the 4-7-year-old (11.56 Mg·C ha⁻¹), in line with previous studies for *A. mangium* forests (Hai *et al.*, 2009; He *et al.*, 2009), demonstrating a fast biomass C accumulation of trees in this stage. The mean TBC of 68.4 Mg·C ha⁻¹ in this study was much greater than those reported for 4-12-year-old *A. mangium* plantations (39.8 Mg·C ha⁻¹) and 2-12-year-old *A. auriculiformis* forests (21.5 Mg·C ha⁻¹) in Vietnam conducted by Hai *et al.* (2009), and *Acacia* plantations of less than 6 to over 16 years (57.3 Mg·C ha⁻¹) in the Pearl River Delta region of Southern China (Zhang *et al.*, 2018), slightly lower than that the 71.5 Mg·C ha⁻¹ in 4-11-year-old *A. mangium* forests in Guangxi Province of China (He *et al.*, 2009), but within the range of 34.4-85.6 and 44.8-118.2 Mg·C ha⁻¹ reported for Asian and Global forests (FAO, 2010). The different rate of

accumulated biomass C stock could be attributive to the effect of climatic conditions, plant species, stand age, stand density, biomass, soil nutrient, and water availability (Herdiyanti & Sulistyawati, 2009; Lee *et al.*, 2015; Zribi *et al.*, 2016). Our data demonstrated that the *A. mangium* plantation in Southeastern region can accumulate large amounts of biomass C in both aboveground and belowground parts. Moreover, fertilization was not done in these plantations. This suggests that *A. mangium* can grow well in soils without fertilization, has great biomass C accumulation potentials in this region.

The present study illustrated changes in biomass and C partitioning with plantation age. We observed an increase in C accumulation in branches along with a decrease in BGB and foliage while relatively stable in ratio of stem biomass C to TBC. This result was in accordance with findings for *Acacia auriculiformis* (Hai *et al.*, 2009) and *Cunninghamia lanceolata* (Xie *et al.*, 2016). This allocation pattern may be interpreted by the strategies that trees use to survive during stand development. The fractions of BGB and leaves in early stages of growth are crucial for the survival of young seedlings and the likelihood that they survive to the next developmental stage. With the development, tree foliar biomass productivity no longer increases, resulting in declined demand for water and nutrient supply from BGB (Vaninen *et al.*, 1996). On the contrary, Hai *et al.* (2009) reported that the fraction of biomass C stored in stem of *A. mangium* increased during 4-12 years, while the proportion of biomass C stored in branches, leaves, and BGB decreased. He *et al.* (2009) found an increase in the stem biomass C partitioning along with a decrease in branch and foliar biomass C partitioning for *A. mangium* stands. The biomass C partitioning into different components can be affected by both biological and environmental conditions. Particularly, in the tree crown, which is characterized spread and lengths of branches, is

partly associated with aerial growing space, the branch biomass C proportion might be expected to reflect the stand density. For instance, differences of stand density in the 11-year-old plantation (610 tree·ha⁻¹) used in the current study and Hai *et al.*'s 12-year-old plantation (825 tree·ha⁻¹), and He *et al.*'s 11-year-old plantation (775 tree·ha⁻¹) might interpret the different the allocation patterns with age.

In this study, decline in the *BGB/AGB* ratio with age might be related to root rot and death in the older trees resulting to alleviated *BGB* and therefore greater *BGB/AGB* ratio in the younger than in the other stands. The *BGB/AGB* ratio average value of 0.28 observed here is within the range of 0.28–0.31 and 0.20–0.33 reported in the Asian and Global forests (FAO, 2010) but higher than the values of 0.23, 0.24, and 0.17 reported for *A. mangium* plantations by Qin *et al.* (2007), Ren & Yu (2008), and Hai *et al.* (2009), respectively. These different values might arise due to the *BGB/AGB* ratio dependent on forest age (Peichl & Arain, 2006; Xie *et al.*, 2016), tree species (Hai *et al.*, 2009; Ruiz-Peinado *et al.*, 2012), and vegetation category (Mokany *et al.*, 2006). Nevertheless, the *BGB* accounted for approximately one-quarter of the *TB* in this chronosequence study, which emphasizes the importance of *BGB* in the accurate estimation of the biomass and C of *A. mangium* planted forests.

Understory vegetation plays a crucial role in stabilizing the ecosystem and sequestering CO₂ (Xu *et al.*, 2000), but their biomass C stock account only approximately 1.09–1.67% (median 1.30%) of the total ecosystem C stock in the *A. mangium* plantations (Fig. 6), which represents a relatively small proportion in the ecosystem. Gao *et al.* (2014) demonstrated that absence of the computation for understory vegetation could lead to underestimation of C sequestration capacity. Previous studies found that the biomass C storage in understory vegetation did not show a clear changing trend with stand age (Cheng *et al.*, 2014; Deng *et al.*, 2017; Yue *et al.*, 2018; Zhang *et al.*, 2019). In this study, however, the C stock of the understory vegetation increased with stand age, which was in accordance with the results of He *et al.* (2009) and Zhang *et al.* (2018). The distinction in species ecological characteristics, light, and nutrients probably contributed to this difference (Abdallah & Chaieb, 2012). Perhaps in the other previous studies that understory biomass C storage did not clearly increase with stand age was due to the more intense competition for light and nutrients. Our results indicated that the C stock in understory were dependent on stand age.

We found that the biomass C storage of the litter increased with stand age, which was consistent with results from previous studies (Deng *et al.*, 2017; Zhang *et al.*, 2018). In contrast, other investigations found that the litter C stock did not correspond clearly to stand age (Ming *et al.*, 2014; Yue *et al.*, 2018). In general, litter C stock is determined by the balance between litter input and de-

composition, hence any elements impacting the amount of input and decomposition rate would influence the litter C storage. The lower quantity of C stored in litter in the 4-year-old stand development was due to decreased leaves, branches, and understory biomass standing in the period. In the present study, it was also found that the C stock of the litter in each stand is greater than that of the total understory vegetation, with the largest proportion of 3.8% in the 4-year-old stand, demonstrating that forest litter should be regarded as an important component in plantation ecosystems.

Carbon concentration

A factor of 50% is commonly used for biomass - C conversion (Brown, 1997; IPCC, 2003). However, it was showed that the C content of different plant compartments might be either above or below 50% (e.g. Thomas & Martin, 2012; Cheng *et al.*, 2014; Zhang *et al.*, 2019). The mean C concentration of total tree of 47.97% in this study is within the range of 40.15–55.87% and 45.54–49.45% reported for the same tree species (Hai *et al.*, 2009; He *et al.*, 2009) but lower than that for *A. auriculiformis* (49.32%), *A. hybrid* (51.22%), and *Eucalyptus urophylla* (53.11%) (Hai *et al.*, 2009). Previous investigations indicated that the C concentrations of planted forests are closely associated with their sample chemical compositions, tree components, wood type, geographical location, climate, and soil conditions (Bert & Danjon, 2006; He *et al.*, 2013). Hence, all of these factors must be taken into account when assessing C contents under different edaphic and climatic conditions. The mean C concentrations of shrubs, herbs, and litter were lower than 45%. Thus, using a coefficient of 50% may result to large errors in up-scaling of C pool. For example, assuming 50% C content for understory in the 7-year-old plantation and for litter in the 11-year-old plantation would result in a difference of 2.62 Mg·ha⁻¹ (11.75%) and 6.65 Mg·ha⁻¹ (9.29%), respectively. Therefore, we suggest that a component-specific C content value for individual compartments is suitable for assessing forest C pool among all stands.

Soil organic C in *A. mangium* plantations

Among the three plantation development stages of this study, the soil C concentration was the highest in the surface soil layer (0–10 cm) and indicated a decreasing trend with depth (Fig. 5a). Soil organic matter is the dominant source of soil C and is greater in topsoil (Du *et al.*, 2015). The C concentrations of the top soil layers (0–10 cm, 10–20 cm, and 20–30 cm), and the deep layer (30–50 cm) significantly increased with stand age, probably due to the increasing litter productivity in older stands (Ming

et al., 2014; Thanh & Cuong, 2017). This finding contributes to interpret the increase C stocks in belowground as stands age.

Although changes in *Cst* following afforestation and stand age have been widely reported in previous studies, there still exist great deals of controversies concerning the effects of stand age on *Cst* level. Some studies reported no significant increase in *Cst* with stand age (Uri *et al.*, 2012; Yue *et al.*, 2018). Some studies have shown an increasing *Cst* in the early period after afforestation followed by a gradual decrease with age increment (Noh *et al.*, 2010; Du *et al.*, 2015; Zhang *et al.*, 2019). Some studies indicated a decrease in *Cst* at the early age and then gradually increased with age (Chen *et al.*, 2013; Wang *et al.*, 2013). These discrepancies may be due in part to how much other influencing factors, such as climate, soil characteristics, forest type, forest management, litter input, root metabolism, and previous land use, which could overshadow the effect of stand age (Jandl *et al.*, 2007; Zeng *et al.*, 2013; Thanh & Cuong, 2017). We found *Cst* in the mineral soil layer increased with plantation age. Previous studies about *Cst* with stand age reported same results as our study (Hai *et al.*, 2009; He *et al.*, 2009; Cheng *et al.*, 2015; Deng *et al.*, 2017; Thanh & Cuong, 2017). The increase in *Cst* with stand age might be due to a larger accumulation of organic matter in older stands (*BGB* and litter). Additionally, 0-50 cm soil layer *Cst* accounted for the largest proportion of ecosystem C reservoirs, particularly the *Cst* in the upper 0-30 cm layer. Approximately 60.37% to 63.33% of *Cst* in the 0-50 cm range of soil was stored in the 0-30 cm range, where soils can be disturbed by human disturbances. Therefore, this study suggests that protection of organic C in the topsoil from disturbances of planted forests is important for improving C sequestration. The soil C values in the upper 0-30 were much greater than those for the *Cst* stored in *A. mangium* and *A. auriculiformis* planted forests across all age classes described by Hai *et al.* (2009) for the 0-30 cm upper mineral soil horizon profile.

Ecosystem C storage in *A. mangium* plantations

The results suggested that age plays a crucial role in affecting the overall ecosystem C stock and can provide insight into C sequestration (Cheng *et al.*, 2014; Justine *et al.*, 2015). Total ecosystem C stock in the 11-year-old plantation was twice the amount of the 4-year-old plantation, illustrating a large C sequestration potential during *A. mangium* development. Fractions of ecosystem C stocks in the three stands were in the order of soil layer > tree layer > litter layer > understory layer. It was observed that soil and tree biomass were the main C pools across all stand ages, accounting for 95.74% of C storage in the ecosystem, which is congruent with pre-

vious studies (He *et al.*, 2009; Li *et al.*, 2013; Ming *et al.*, 2014; Du *et al.*, 2015). This highlights the importance of including accurate assess of *Cst* in ecosystem C accounting.

Conclusions

The results of the present study indicated the first complete and thorough assessments of changes in biomass compartments and their C content and C stock of ecosystem compartments for *A. mangium* forests in an age-sequence (from 4- to 11-year-old plantations) in Southeastern region, Vietnam. The biomass of each component of the tree could be predicted from an allometric equation using *DBH* as the independent variable. Tree, understory, litter, and ecosystem biomass increased with stand age. The highest C concentration was observed in tree stem while the lowest was recorded in the tree *BGB*. The use of component-specific C content values other than a fixed factor of 0.5 to convert biomass to C storage is required in order to more precisely evaluate the forest C storage. Soil C content increased significantly with increasing stand age, and the *SOC* concentration decreased continually with increasing soil depth. Carbon stocks across the 0-50 cm soil depth increased with stand age. Trees and mineral soil were two dominant C pools in the age-sequence. Most increases in C stocks in belowground and total ecosystems were attributable to increases in *SOC* and tree biomass. Our findings suggest that *A. mangium* species was a fast-growing afforestation tree species with high potential biomass C sequestration. Therefore, it can facilitate the management of the forest as a C sink.

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