Cuong, L., Thang, B., Bolanle-Ojo, O.T., Bao, T., Tuan N., Sang T., Xu, X., Thanh, N. (2022): Enhancement of soil organic carbon by Acacia mangium afforestation in Southeastern region, Vietnam. Agriculture and Forestry, 68 (2): 133-155. doi:10.17707/AgricultForest.68.2.10

DOI: 10.17707/AgricultForest.68.2.10

Levan CUONG [1], Buivan THANG [2], Oluwasanmi Tope BOLANLE-OJO [2,3], Tranquang BAO [1], Nguyenthanh TUAN [1], Tranvan SANG [4], Xiaoniu XU [2]*, Nguyenminh THANH [1]*

ENHANCEMENT OF SOIL ORGANIC CARBON BY *ACACIA MANGIUM* AFFORESTATION IN SOUTHEASTERN REGION, VIETNAM

SUMMARY

The knowledge about dynamics of soil organic carbon (*SOC*) accumulation and its controls are critical in understanding of the C cycling in forest ecosystems. *Acacia mangium* Willd. is one of the most important fast-growing afforestation tree species in Vietnam, providing significant ecological, economic, environmental, and social benefits. The existing studies offered information limited on the distribution and regulation of *SOC* in the *A. mangium* plantations. The primary purpose of this study was to explore the variation trend of *SOC* and its driving factors in an age-sequence of three *A. mangium* plantation stands in Changriec Historical - Cultural Forest, Southeastern region, Vietnam. The study was conducted to estimate *SOC* content and storage, and soil physicochemical characteristics of three different–aged (4–, 7–, 11–year–old stands) *A. mangium* plantations. The *SOC* content increased significantly from young to older stand, and its maximum concentration occurred in the topsoil layer and decreased continually with increasing soil depth. The *SOC* stocks increased significantly with the stand age. The *SOC* stocks showed obvious surface aggregation, with more than 60% of *SOC* distributed in the soil of 0–30 cm depth. The soil total nitrogen content and soil texture (i.e., soil silt content) were identified as the major factors controlling the *SOC* distribution. The other parameters (i.e., plant biomass, soil *pH*, bulk density, available nitrogen, total phosphorus, available phosphorus, total potassium, and available potassium) also significantly influenced the distribution of *SOC*. These findings suggest that afforestation with *A. mangium* can facilitate *SOC* accumulation, improve soil nutrient regimes, and

---

[1]Levan Cuong, Tranquang Bao, Nguyenthanh Tuan, Nguyenminh Thanh, Faculty of Forestry, Vietnam National University of Forestry, Hanoi 100000, Vietnam

[2]Xiaoniu Xu (*Corresponding author: xnxu2007@ahau.edu.cn), BuivanThang, Oluwasanmi Tope Bolanle-Ojo, School of Forestry & Landscape Architecture, Anhui Agriculture University, Hefei 230036, Anhui, China

[3]Oluwasanmi Tope Bolanle-Ojo, Forestry Research Institute of Nigeria, P.M.B. 5054, Ibadan, Nigeria

[4]Tranvan Sang, Institute of Ecology and Works Protection, Vietnam Academy for Water Resources, Hanoi 100000, Vietnam

Notes: The authors declare that they have no conflicts of interest. Authorship Form signed online.

Recieved:20/12/2021 *Accepted:04/05/2022*

provide a new insight in understanding the factors controlling *SOC* in the Southeastern region of Vietnam.

Keywords: *Acacia mangium* plantations, Soil organic carbon, Environmental variables, Age-sequence, Vietnam

ABBREVIATIONS USED: *SOC* (soil organic carbon); *CS* (soil organic carbon storage); *DBH* (diameter at breast height); *H* (height); *TAGB* (total above-ground biomass); *TBGB* (total below-ground biomass); *BD* (bulk density); *TN* (total nitrogen); *TP* (total phosphorus); *TK* (total potassium); *AN* (available nitrogen); *AP* (available phosphorus); *AK* (available potassium).

INTRODUCTION

Soil is the largest terrestrial organic carbon (C) pool, holds three times as much C as the vegetation C pool and twice as much as the atmosphere (Batjes, 1996; Lal, 2004; Carvalhais *et al*., 2014). Soil C in the Forest ecosystem is a crucial part of the global C reservoir, containing 73% of the global *SOC* pool (Sombroek *et al*., 1993; Six *et al*., 2002b). Thus, minor changes in the C reservoir of forest soil will dramatically influence the global C balance, which impacts global climate change (Albaladejo *et al*., 2013). The *SOC* is principally determined by the balance between C inputs through litterfall and root turnover and loss of C primarily through organic matter decomposition, which processes are controlled by various environmental variables, including vegetation biomass (Wang *et al*., 2013; Zhang *et al*., 2018) and soil physicochemical properties such as soil *N* (Batjes, 1996; Cong *et al*., 2016), soil texture (Jobbágy and Jackson, 2000; Liu *et al*., 2016), soil *P* (Zu *et al*., 2011; Deng and Shangguan, 2017), soil *K* (Zu *et al*., 2011; Zhang *et al*., 2016), soil *pH* (Robson and Foy, 1990; Thomas, 1996; Chen *et al*., 2004), and soil *BD* (Hobley *et al*., 2015; Ngaba *et al*., 2020). Hence, understanding the *SOC* storage dynamics and the factors that control this process in forest ecosystems is critical for better C budget management and climate change mitigation options.

To date, studies on *SOC* content or storage following afforestation and stand age have been widely carried out worldwide, and showed contradictory results. Some scholars presented that the *SOC* decreased in the early stage of afforestation and then gradually increased with stand age (Pregitzer and Euskirchen, 2004; Zhaodi *et al*., 2018). Whereas others showed an increasing *SOC* in the early period after afforestation followed by a gradual decrease (Ali *et al*., 2019; Zhang *et al*., 2019), a stable *SOC* after afforestation (Simon *et al*., 2012), or no significant increase with stand development (Matthias and Arain, 2006; Yue *et al*., 2018). Nonetheless, according to most researches, *SOC* significantly increased with forest age (Cheng *et al*., 2015; Deng *et al*., 2017; Zhang *et al*., 2018). One possible interpretation to this discrepancy is that, in addition to stand age, several other factors impact *SOC* accumulation, such as tree species, forest types, climate conditions, soil physicochemical characteristics, and former land use (Smal and Olszewska, 2008; Noh *et al*., 2010).

Acacia mangium Willd. is one of the most principal afforestation tree species in some of the eight important forestry-ecological regions and Southeastern region in Vietnam (MARD, 2018), where it has been planted on more than 800,000 ha and comprises approximately 19% of all forested plantation areas in Vietnam (MARD, 2020). Its wood is suitable for the production of pulps, timbers, and household furniture (MARD, 2018). Besides producing woods for industries, *A. mangium* plantations also have a crucial role in providing environmental services such as C uptake and storage given by its high growth rate. Thus, a better knowledge of *SOC* dynamics of *A. mangium* plantations is of great importance in the accurate prediction of soil C storage and its influence on future climate change and forest management. Although there is abundant studies in *A. mangium* forests; growth and yield prediction (Shah Newaz and Millat-e-Mustafa, 2004), biomass accumulation and C storage (Hai *et al*., 2009; Lee *et al*., 2015; Cuong *et al*., 2020), wood properties (Jusoh *et al*. 2014), soil nutrients (Lee *et al*. 2015, Matali and Metali, 2015), biological N fixation (Lydie-Stella *et al*., 2017), and benefits and threats on biodiversity (Koutika and Richardson, 2019). Nevertheless, existing knowledge and studies have offered limited information on the distribution of *SOC* and its influencing factors in an age-sequence of *A. mangium* plantation forests, particularly in the Southeastern region of Vietnam. Therefore, the present study was designed to examine the *SOC* content and storage in an age-sequence of three *A. mangium* plantation stands (4-, 7-, and 11-years-old) in Southeastern region, Vietnam. The specific purposes of the study were to: (i) quantify the *SOC* content and stocks; and (ii) identify the controlling parameters of *SOC* variation in *A. mangium* plantations across three different ages in the Southeastern region. Our findings can strengthen understanding of C sink management in *A. mangium* forest soils and provide new insight into the unique relationship between *SOC* and influential environmental factors (i.e. plant biomass and soil physicochemical properties).

MATERIAL AND METHODS

Study site description

The study was conducted at the Chang Riec Historical - Cultural Forest (11°00′30″ to 11°35′13″N and 106°00′00″ to 106°07′10″E), located in Tay Ninh Province, Southeastern region, Vietnam (Figure 1). The study area has two distinct seasons: the dry season (December to April) and the rainy season (May to November). The annual mean temperature is 26.9°C with a yearly range of 25.2°C to 28.8°C. The annual mean precipitation is 1967 mm with average rainy days of 155 days (IBST, 2009). This study area terrain is relatively flat, with an altitude of 29-67 m a.s.l. and slopes of 3-5°. Soil type in this region is mainly grey-brown, developed on ancient alluvium, and soil depth over 100 cm. Soil's texture is loam (Cuong *et al*., 2020). The dominant tree species of the area consist of *A. mangium* Willd., *Acacia hybrid (Acacia auriculiformis* A. Cunn. ex Benth. × *A. mangium* Willd.*)*, *Dipterocarpus obtusifolius* Teijsm. ex Miq., *Tectona grandis* L.f., *Hopea* spp., and *Khaya senegalensis* (Desv.) A.Juss.. The plantation forests are composed of about 40% of the total forest area. *A. mangium* amounts to approximately 20% of the total plantations in this region and plays an important role in pulp and timber production. In this study, we selected three differently aged (4-, 7-, 11-years) *A. mangium* plantations, which were all covered by previous Cassava (*Manihot esculenta* Crantz) before afforestation. Additionally, no fertilization was applied after afforestation. The initial density of the experimental stands were 1000 trees·ha^{-1} (initial spacing, 4 m × 2.5 m), and thinning operations were carried out once, twice, and three times for the 4-, 7-, and 11-year-old stands, respectively. The diversity, healthy, and abundance of understory vegetation in the *A. mangium* plantations were found, particularly in the 7- and 11-year-old stands. The dominant species of understory vegetation in the *A. mangium* plantations include *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 perlarius* (Lour.) Merr., *Lygodium microphyllum* (Cav.) R. Br., *Dryopteris parasitica* (L.) Kuntze, *Helicteres angustifolia* var. *obtusa* (Wall. ex Kurz) Pierre, and *Cynodon dactylon* (L.) Pers (Cuong *et al*. 2020).

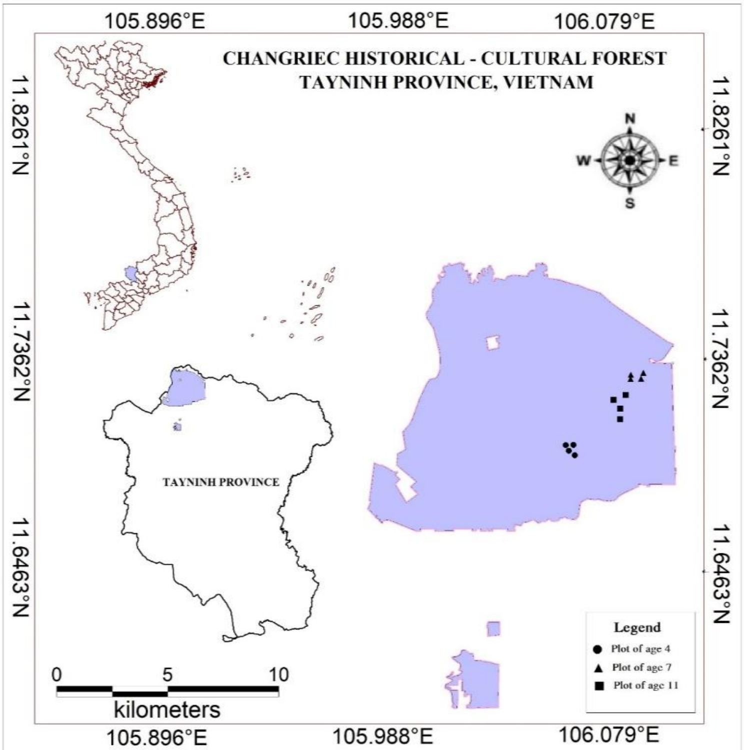

Figure 1. Map of experimental plots in Changriec Historical - Cultural Forest (Tayninh Province, Southeastern region, Vietnam)

Biomass estimation

Four plots of 40 m × 25 m were established in each *A. mangium* stands in February to April 2019 (Figure 1). The detailed descriptions of the study site and biomass estimation were given by Cuong *et al*. (2020) and is reproduced in Table 1.

Table 1. Biomass characteristics of *Acacia mangium* plantations at different stand ages

Measured variables			Stand age (years)		
			4	7	11
Plants		Stand area (ha)	2.6	2.2	3.6
		Mean *DBH* (cm)	13.78 ± 0.38^a	17.94 ± 0.86^b	21.78 ± 0.85^c
		Mean *H* (m)	14.72 ± 0.17^a	17.29 ± 0.56^b	18.60 ± 0.21^c
		Stand density (tree· ha^{-1})	888 ± 30^a	728 ± 22^b	610 ± 29^c
		Canopy density	0.83 ± 0.01^a	0.81 ± 0.01^b	0.79 ± 0.03^b
		Elevation (m a.s.l.)	38	40	40
		Soil depth (cm)	>100	>100	>100
	Above-ground biomass	Trees (Mg· ha^{-1})	55.08 ± 3.98^a	109.18 ± 4.44^b	175.17 ± 5.11^c
		Understory (Mg· ha^{-1})	4.05 ± 0.05^a	4.31 ± 0.05^b	4.80 ± 0.11^c
		TAGB (Mg· ha^{-1})	59.13 ± 3.98^a	113.49 ± 4.46^b	179.96 ± 5.07^c
	Below-ground biomass	Trees (Mg· ha^{-1})	17.64 ± 0.68^a	34.38 ± 1.43^b	35.40 ± 1.87^b
		Understory (Mg· ha^{-1})	0.82 ± 0.02^a	0.92 ± 0.02^b	1.19 ± 0.02^c
		TBGB (Mg· ha^{-1})	18.46 ± 0.67^a	35.30 ± 1.41^b	36.59 ± 1.87^c
		Litter biomass (Mg· ha^{-1})	11.43 ± 0.91^a	11.90 ± 0.55^{ab}	13.29 ± 1.16^b

Note. Values are means ± standard deviations (SD). *DBH*, diameter at breast height (1.3 m); *H*, tree height; *TAGB*, total above-ground biomass; *TBGB* total below-ground biomass. Means in a row, different lower-case letters are significantly different at $p<0.05$

Soil sampling and laboratory analysis

Five soil profiles were dug to a depth of 50 cm from the four corners and the center of each sample plot, and the samples were taken from four depths (0-10, 10-20, 20-30 and 30-50 cm) using a soil corer (5 cm inner diameter). Soil samples from the same layer in the same plot were mixed in equal volume proportions, air-dried and stored at room temperature. Meanwhile, soil *BD* samples were collected from different soil layers using a stainless-steel cutting ring (volume of 100 cm^3). Soil samples were analyzed at the Centre of Forestry Research and Climate Change laboratory at the Vietnam National University of Forestry (VNUF). Soil *pH* was measured with a *pH* meter at a soil:water ratio of 1:2.5. Soil *BD* was determined by drying the core samples at 105°C until constant weight (Blake and Hartge, 1986), while the pipette method was employed to measure the soil texture and compute the percentage of clay (<0.002 mm), silt (0.002–0.02 mm), and sand content (0.02–2 mm) (Van Reeuwijk, 2002). *SOC* content was analyzed by the potassium dichromate oxidation (external heat applied) method (Nelson and Sommers, 1982). The contents of soil *TN*, *TP*, *TK*, *AN*, *AP*, and *AK* were analyzed according to the Vietnam National Standard methods (TCVN 6498:1999 - ISO 11261:1995; TCVN 8940:2011; TCVN

8660:2011; TCVN 5255:2009; TCVN 5256:2009; TCVN 8662:2011) adopted by Cuong *et al*. (2017) and Thanh & Cuong (2017b). The soil *TN* concentration was determined by the modified Kjeldahl method after digestion with a mixture of $C_7H_6O_3$ and H_2SO_4. The soil *TP* content was determined by the colorimetric method after digestion with $HClO_4$ and H_2SO_4. The soil *TK* concentration was analyzed using the flame photometer method after digestion with $HClO_4$ and HF. The concentration of soil *AN* was measured by the alkaline hydrolysis-diffusion method. The soil *AN* content was reduced to NH_3 after adding a NaOH solution, then the NH_3 was diffused and absorbed by H_3BO_3 solution and titrated using H_2SO_4 to calculate the soil *AN* content. The concentration of soil *AP* was estimated using the Olsen method (the soil *AP* was extracted using $NaHCO_3$ followed by measurement via the molybdenum antimony colorimetric method). The content of soil *AK* was measured using the flame photometer method after extraction with CH_3COONH_4.

Calculation of soil carbon storage

The C storage in each soil layer was computed according to *SOC* content, soil *BD* and sampled depth. Coarse fractions (>2 mm) were very rare in the soil samples. Thus, the following equation was used to calculate *CS* (Deng *et al*. 2017; Thanh and Cuong 2017a; Wang *et al*. 2019):

$$CS_i = SOC_i \times BD_i \times d_i \times 10^{-1} \quad (1)$$

where: CS_i, soil carbon storage in the soil layer i ($Mg \cdot C \cdot ha^{-1}$); *i* represents the 0–10 cm, 10–20 cm, 20–30 cm, and 30–50 cm soil layers; SOC_i, soil organic carbon concentration of the soil layer i ($g \cdot kg^{-1}$); BD_i, soil bulk density of the soil layer i ($g \cdot cm^{-3}$); and d_i, soil thickness of the soil layer i (cm).

Statistical analyses

The effects of plantation age, soil depth and their interactions on *SOC* content and stocks, and soil physicochemical properties in *A. mangium* plantations were analyzed by two-way analysis of variance (ANOVA). Comparisons of *SOC* content and stocks, and soil physicochemical properties among three plantations, and four soil depths were tested by one-way ANOVA followed by Fisher's Least Significant Difference (LSD) test ($p < 0.05$). Before ANOVA analyses, we conducted tests for normality and homogeneity of variance.

Pearson's correlation was applied to understand the relationships between *SOC* contents and environmental factors (e.g., *TAGB*, *TBGB*, litter, *BD*, *pH*, *TN*, *TP*, *TK*, *AN*, *AP*, and *AK*). The environmental factors that had high weighted factor loadings were obtained by reducing the dimension of environmental factors using Principal Component Analysis (PCA); the effect of a possible linear correlation between variables was also eliminated (Fan *et al*., 2018). It should be noted that only principal components (PCs) having eigenvalues greater than 1 and factors having highly weighted factor loading (i.e., those with absolute values for factor loading within 10% of the maximum value) were retained for Stepwise

Multiple Regression Analysis (SMRA) (Tian *et al*., 2016; Fan *et al*., 2018). The SMRA was conducted using the filtered factors as inputs to determine the major factors that influence *SOC*. In the present study, both data processing and statistical analyses were carried out using SPSS 25.0 (IBM Corp, 2017) and R 3.5.2 (R Core Team, 2018) software packages.

RESULTS

C content in the soil layer

The two-way ANOVA analysis revealed the *SOC* was significantly affected by stand age (p<0.001). Besides, soil layer (p<0.001) and the interaction between stand age and soil layer (p<0.001) resulted in a significant effect on *SOC* (Figure 2a). Statistically significant differences were observed among different aged stands of different soil layers for *SOC* values (p<0.05). The *SOC* concentration decreased significantly with an increase in soil depth irrespective of stand age (p<0.05). In 0-10 cm soil layer, *SOC* ranged from 12.70 to 21.90 g· kg^{-1}, which was much greater than that of the other soil depths (10–20, 20–30, and 30–50 cm). *SOC* concentration at all soil depths increased significantly with stand age (p<0.05).

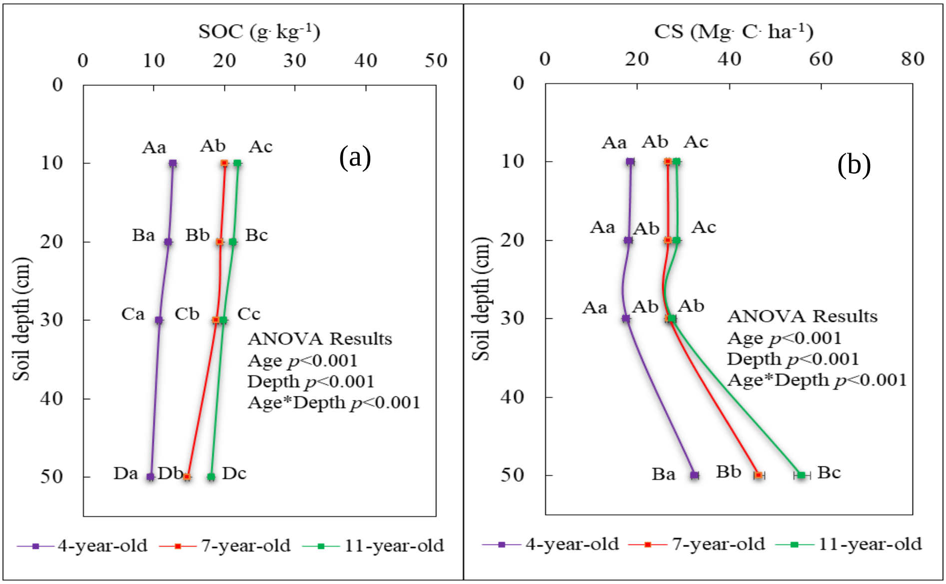

Figure 2. Variation of *SOC* (a) and *CS* (b) with stand age and soil depth. Error bars indicate standard deviation (SD). *Note*. *SOC*, soil organic carbon; *CS*, soil organic carbon stocks. Means with different uppercase and lowercase letters indicate significantly different between soil layers in the same stand ages and between stand ages in the same soil layers (p<0.05), respectively. Results (p-values) of two-way ANOVAs show the effect of stand age, soil depth and the interaction between stand age and soil depth on the *SOC* and *CS*

C storage in the soil layer

Figure 2b represents trends in the soil layer C stocks over an age-sequence of three *A. mangium* stands. Stand age (p<0.001) and soil layer (p<0.001) had significant influences on *CS*. Similarly, the interaction effect between stand age and soil depth demonstrated significant differences in *CS* (p<0.001). The *CS* of the 30-50 cm soil layer followed a significant increasing trend with the increase of stand age (p<0.05). Although the *CS* of the soil at 0–10 cm, 10–20 cm, and 20–30 cm increased with increasing forest age, the relationship was not significant. Summed *CS* from 0 to 50 cm soil depth was 86.86, 126.88, and 140.94 Mg$^{\cdot}$ C$^{\cdot}$ ha^{-1} in the 4-, 7-, and 11-year-old stands, respectively. The uppermost 30 cm of soil stocked a large proportion of C, and the *CS* in the 0–30 cm soil layer occupied 60.37%, 62.53%, and 63.33% of the total soil total C storage in the 0–50 cm soil layer for the three stands.

Basic soil physicochemical properties

There was a significant interaction between stand age and soil layer on soil physical properties (*BD*, clay, silt, and sand) (p<0.001, Figures 3a-3d). As described in Figure 3a, soil *BD* increased significantly as soil depth increased across all stand ages (p<0.05). The soil *BD* in 4-year-old stand was the highest among all stand ages at four soil depths (i.e., 0–10, 10–20, 20–30, and 30–50 cm) (p<0.05). However, there was no significant difference in soil *BD* between the 11- and 7-year-old stands at the 0–10 and 10–20 cm soil layers (p>0.05). Statistical analysis revealed significant differences in soil clay, silt, and sand contents between the three stand ages at the four soil depths (p<0.05, Figures 3b-3d). The changes of clay, silt, and sand contents showed a trend not obvious along with soil depth in all three stands. There were no significant differences in contents of soil clay, silt, and sand among the four soil depths at the same forest age (p>0.05), except for the clay content at the 11-year-old stand (p<0.05).

Soil chemical properties (*pH*, *TN*, *TP*, *TK*, *AN*, *AP*, and *AK*) were significantly influenced by both stand age and soil depth (p<0.001, Figures 4a-4d, and Figures 5a-5c). Similarly, the interaction among stand age and soil depth also significantly affected the chemical characteristics of the soil (p<0.001, Fig. 4b-4c, and Fig. 5a-5b) except for *pH*, *TK*, and *AK* (p=0.735, Figure 4a, p=0.987, Figure 4d, and p=0.956, Figure 5c, respectively). The soil *pH* value appeared an increasing trend with soil depth in the same forest age but was not significantly different among the four soil depths for any given age stand (p>0.05, Figure 4a). A significant decreasing trend was found as the stand age increased (p<0.05). The respective highest and lowest *pH* values were recorded in the 4- and 11-year-old stands for the four sampled soil depths. The contents of soil *TN*, *TP*, *TK*, *AN*, *AP*, and *AK* decreased significantly with increasing soil depth across the three stands, being higher in the superficial soil depth (0–10 cm) than in the other three deeper soil layers (10–20, 20–30, and 30–50 cm) (p<0.05, Figures 4b-4d, and Figures 5a-5c). Significant differences in soil *TN*, *TP*, *TK*, *AN*, *AP*, and *AK* concentrations were found among the three stand ages at all soil depths ($p<0.05$). These parameter values increased with stand age, being the highest in 11- year-old-stand and the lowest in 4- year-old-stand, and this trend was consistent at the four soil depths.

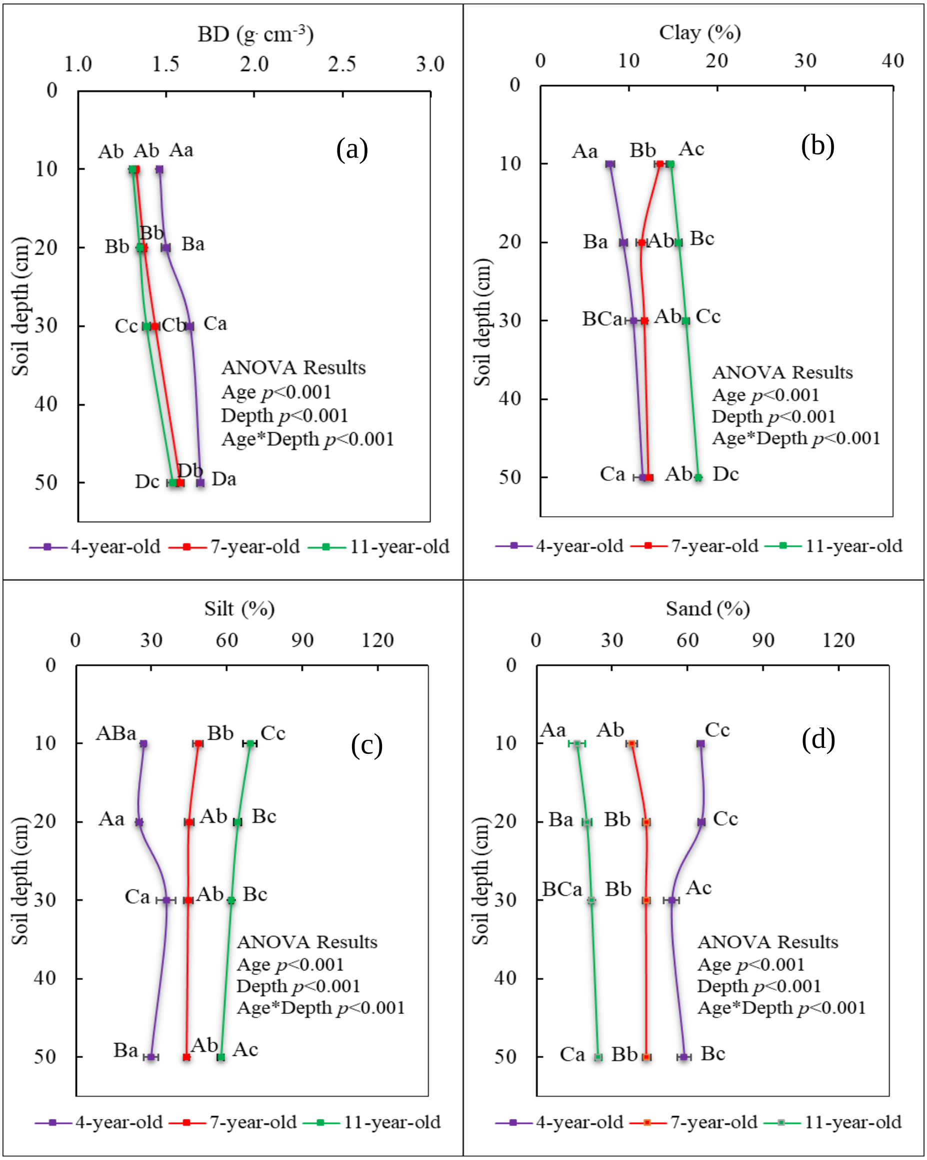

Figure 3. Variation of soil *BD* (a), clay (b), silt (c), and sand (d) with stand age and soil depth. Error bars indicate standard deviation (SD). *Note. BD*, bulk density. Means with different uppercase and lowercase letters indicate significantly different between soil layers in the same stand ages and between stand ages in the same soil layers ($p<0.05$), respectively. Results (*p* values) of two-way ANOVAs indicate the effect of stand age, soil layer, and their interaction on the soil *BD* and particle composition

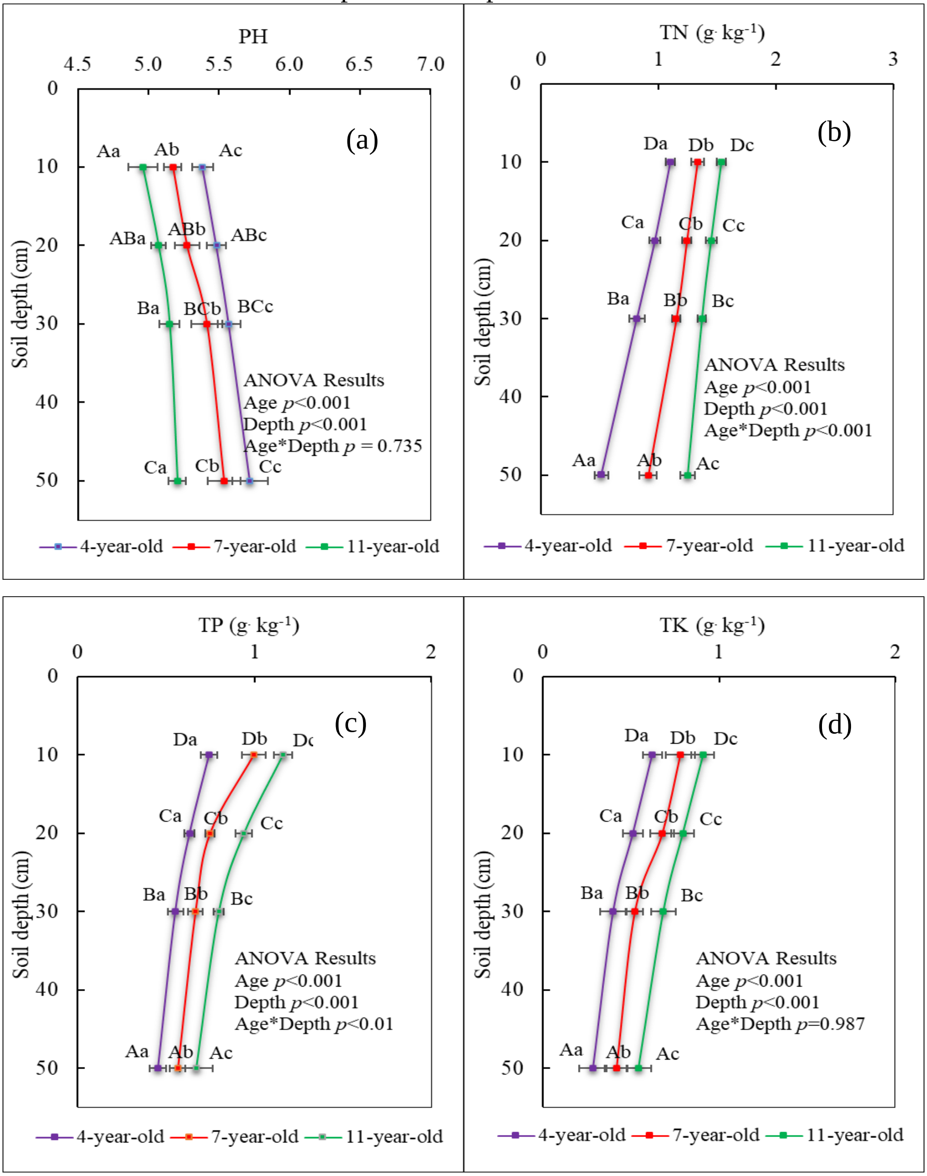

Figure 4. Variation of soil *pH* (a), *TN* (b), *TP* (c), and *TK* (d) with stand age and soil depth. Error bars indicate standard deviation (SD). *Note*. *TN*, total nitrogen; *TP*, total phosphorus; and *TK*, total potassium. Means with different uppercase and lowercase letters indicate significantly different between soil layers in the same stand ages and between stand ages in the same soil layers ($p<0.05$), respectively. Results (*p* values) of two-way ANOVAs indicate the effect of stand age, soil layer, and their interaction on the *pH*, *TN*, *TP*, and *TK*

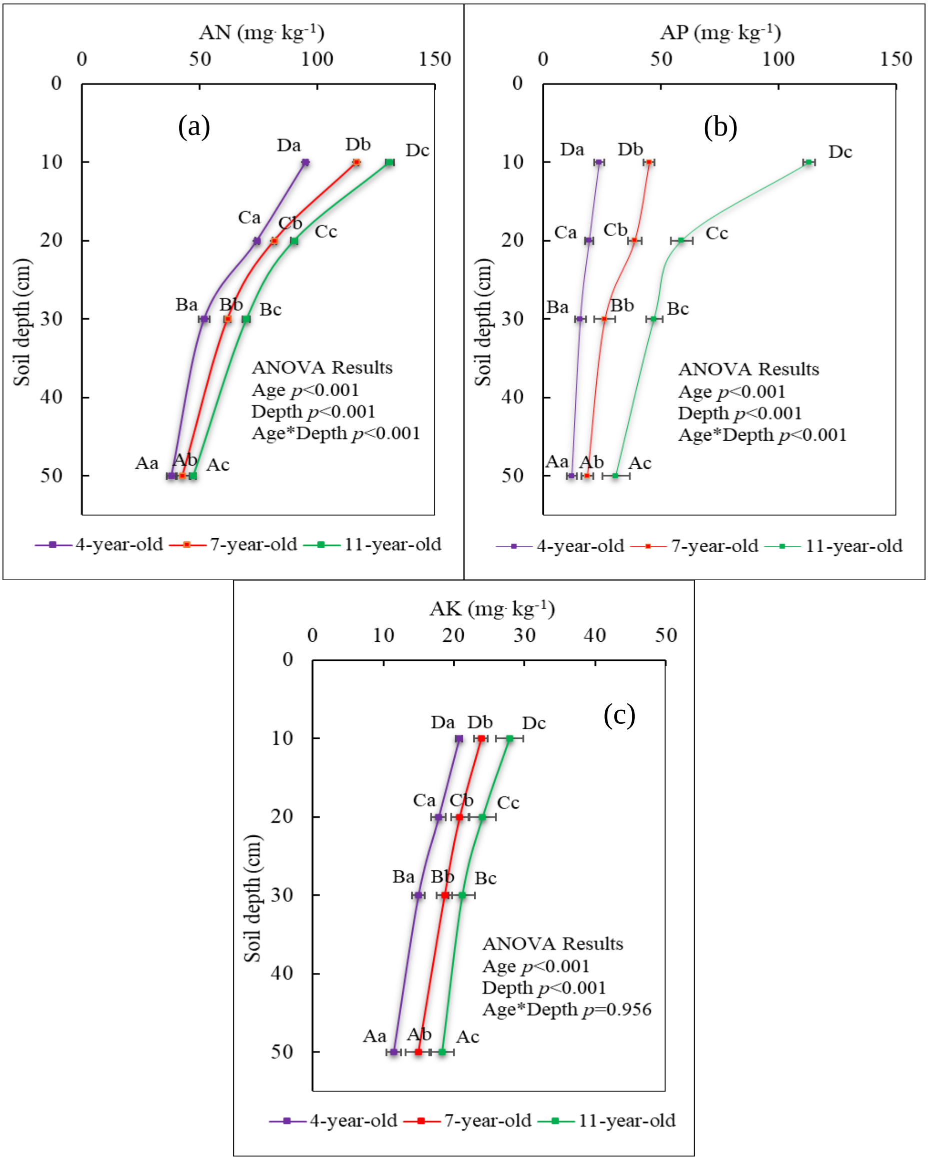

Figure 5. Variation of *AN* (a), *AP* (b), and *AK* (c) with stand age and soil depth. Error bars indicate standard deviation (SD). *Note*. *AN*, available nitrogen; *AP*, available phosphorus; and *AK*, available potassium. Means with different uppercase and lowercase letters indicate significantly different between soil layers in the same stand ages and between stand ages in the same soil layers ($p<0.05$), respectively. Results (p values) of two-way ANOVAs indicate the effect of stand age, soil layer, and their interaction on the *AN*, *AP*, and *AK*

Major factors controlling *SOC*

The correlation analysis showed that *SOC* was strongly and positively correlated with clay, silt, *TN*, *TP*, *TK*, *AN*, *AP*, and *AK* but significantly negatively correlated with *BD*, *pH*, and sand (p<0.01) (Table 2). Plant biomass factors including *TAGB*, *TBGB*, and litter were also significantly positively correlated with *SOC* (p<0.01).

Table 2. Pearson Correlation Coefficient Values (r) between soil organic carbon content and environmental variables at different stand ages of *Acacia mangium* forests

Environmental variables	*SOC* (g· kg^{-1})
TAGB (Mg· ha^{-1})	0.86**
TBGB (Mg· ha^{-1})	0.90**
Litter (Mg· ha^{-1})	0.53**
Clay (%)	0.68**
Silt (%)	0.87**
Sand (%)	-0.86**
BD (g· cm^{-3})	-0.86**
pH	-0.86**
TN (g· kg^{-1})	0.92**
TP (g· kg^{-1})	0.79**
TK (g· kg^{-1})	0.81**
AN (mg· kg^{-1})	0.58**
AP (mg· kg^{-1})	0.75**
AK (mg· kg^{-1})	0.80**

Note. *SOC*, soil organic carbon; *TAGB*, total above-ground biomass; *TBGB* total below-ground biomass; *BD*, bulk density; *TN*, total nitrogen; *TP*, total phosphorus; *TK*, total potassium; *AN*, available nitrogen; *AP*, available phosphorus; and *AK*, available potassium. ** indicates significant effects at p < 0.01

The PCA results revealed that the first principal component (PC1) explained 71.21% of the total variance of data obtained in the 12 study plots, whereas the second principal component (PC2) interpreted 17.19% (Figure 6). These results illustrated that the first two principal components contributed 88.40% of the standardized variance. The first principal component was mainly associated with variation in *TN*, *pH*, and silt, and the second was primarily related to *AN* and clay.

To find the best predictive variables that influence *SOC*, we conducted SMRA with PC1 (*TN*, *pH*, and silt), and PC2 (*AN*, and clay) as independent variables and *SOC* as the dependent variable. The regression model suggested that the soil *TN* and silt were the two most important factors controlling *SOC* and these factors exerted a significant positive effect (Table 3).

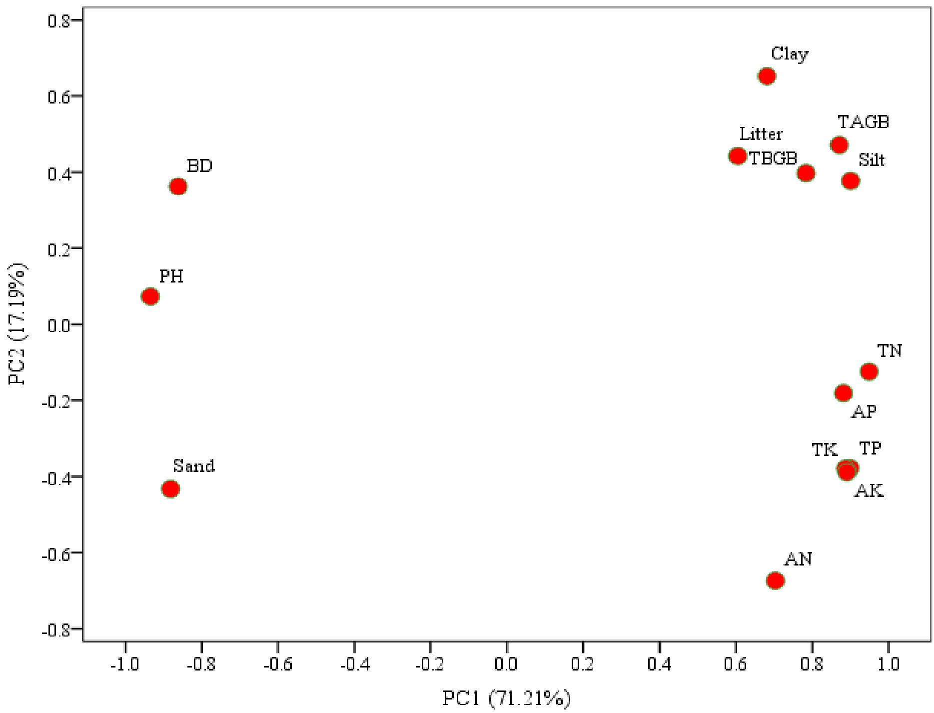

Figure 6. Principle component analysis (PCA) of the environmental variables

Table 3. Results of stepwise multiple linear regression analyses showing the dependence of soil organic carbon on environmental variables

Dependent variable	Explanatory variable	Coefficient estimate	*SE*	*t-value*	*p*-value	R^2
	Constant	1.103	0.804	1.371	0.177	
SOC	*TN*	9.077	1.114	8.149	<0.001	0.898
	Silt	0.113	0.022	5.122	<0.001	

Note. *SOC*, soil organic carbon; *TN*, total nitrogen; *SE*, standard error of the coefficient estimate

DISCUSSION

Soil organic carbon content and storage in *A. mangium* plantations

In the three age-sequence *A. mangium* stands of this study, the *SOC* concentration was the highest in the surface 0–10 cm soil layer and revealed a decreasing trend with increasing depth (Figure 2a). The *SOC* produced from the decomposition of root system and litter near the ground surface will get into the topsoil first, this could be responsible for the significant higher *SOC* content in the upper soil layer (Zhong and Qiguo, 2001; He *et al*., 2009; Laik *et al*., 2009; Thanh and Cuong, 2017a; Zhang *et al*., 2018). The concentration of C stored in the top three soil layers (0–10 cm, 10-20 cm, and 20–30 cm) and the deepest layer (30–50 cm) significantly increased with increased age of *A. mangium* plantations, probably due to the increase of litter productivity and slow decomposition in older stands (Herdiyanti and Sulistyawati, 2009; Ming *et al*., 2014).

Changes in *CS* following afforestation and stand age have been widely carried out in earlier studies. Interestingly, there were varied conclusions concerning the changes in *CS* after afforestation among former studies in the literature. Some researchers found no change in *CS* after afforestation (Zhang *et al*., 2017; Yue *et al*., 2018). Some researchers observed an increasing trend of *CS* in the plantations in the early stages after afforestation followed by a gradual decrease (Noh *et al*., 2010; Ali *et al*., 2019). Some researchers showed that there was an initial decline in *CS* after afforestation followed by a gradual increase (Li *et al*., 2011; Zhaodi *et al*., 2018). Some important factors, such as the choice of plant species used for plantation, forest type, soil cultivation method, soil properties, earlier land use and climate could explain the contradictory results reported in various studies. All these factors, independently or in combination could overshadow the effect of stand age on the accumulation of soil organic C (Noh *et al*., 2010; Zhang *et al*., 2019). In the current study, carbon storage in the mineral soil layer always increased significantly along with *A. mangium* stand development (Figure 2b). Hence, our study results demonstrate that afforestation with *A. mangium* resulted in a remarkable increase in soil organic C storage in Southeastern region. These findings may be attributed, at least in part, to the larger accumulation of soil organic matter (litter and roots) with the forest stand development (Thanh and Cuong, 2017a) and the annual soil respiration was far lower (Yang *et al*., 2007). Similar results were obtained by Hai *et al*. (2009), He *et al*. (2009), Zhao *et al*. (2014), Abaker *et al*. (2016), and Zhang *et al*. (2018), who also observed an increase of organic C in soil following afforestation. Furthermore, in terms of vertical distribution of *CS*, the results of our study illustrated that a large quantity of the *CS* was sequestrated in upper 0-30 cm of the mineral soil horizon in all stands, showing that greater amounts of *CS* were stoked in the topsoil layer. Approximately 60.37% to 63.33% of *CS* in the 0–50 cm range of soil was found in the 0–30 cm range (Figure 2b), where soils can be disturbed by human disturbances and natural erosion. Thus, research the vertical variability of *CS*, and protection of the topsoil from loss is important to promote C sequestration.

Factors influencing *SOC* across stand ages

Our findings revealed that soil *TN* and *AN* were strongly correlated with *SOC* (Table 2). In many ecosystems, it is well known that soil *C* and *N* are two closely associated biogeochemical processes (Hagedorn *et al*., 2003; Abaker *et al*., 2018). As one of the most essential nutrients for plant healthy growth, the quality and quantity of available *N* could impact the biomass productivity and the amount of plant litter, which is the dominant source of organic *C* (Bronson *et al*. 2004; Sam *et al*. 2006). *A. mangium* has a very high biological N-fixation capacity because of its symbiotic association with nodule-forming bacteria (Yang *et al*., 2009; Matali and Metali, 2015), it probably maintains the *N* inputs at our sites, and indirectly increase *SOC*. Partly due to their contribution, the increasing of the soil *N* contents likely affects the accumulation of *SOC (*Zhang *et al*., 2018), including *SOC* variation in the *A. mangium* forest land (Table 3).

In the present study, soil texture could play a crucial role in determining *SOC* accumulation. The variation in *SOC* in different age stands was positively correlated with clay and silt contents, while *SOC* was negatively correlated with sand content (Table 2). Additionally, silt content was the dominant factor influencing *SOC* (Table 3). Therefore, the present results corroborated previous empirical studies demonstrating that soil clay and silt contents contribute to *SOC* formation and preservation (Six *et al*., 2002a; Zhou *et al*., 2019). Fine particle proportions (clay and silt) and microaggregates can protect soil organic matter by stabilizing them against microbial mineralization (Paul, 1984; Baldock and Skjemstad, 2000). Moreover, fine soil particles can enhance water retention in soil and promote biomass production, increase litter input to soils (Burke *et al*., 1989; Yang *et al*., 2008).

Soil *pH* was the environment factor with high factor loading, which could interpret *SOC* variability to certain extents (Figure 6). As depicted in Table 2, *SOC* was significantly negatively correlated with soil *pH*. This result is congruent with the findings of the previous researches (Zhang *et al*., 2018; Zhaodi *et al*., 2018; Zhou *et al*., 2019). The soil *pH* primarily influences microbial respiration and activity, which directly affects soil organic matter formation and decomposition (Senechkin *et al*., 2014), since most microorganisms prefer to grow and metabolize with *pH* values ranging from 5.5 to 8.5 (Holguin *et al*., 2001; Zhou *et al*., 2005). In such *pH* range, more microorganism activities are available, therefore further contribute to higher *SOC* decomposition. The current research found *SOC* increased with a decrease in soil *pH*. The relatively low *pH* values are often related to low microbial activity that reduces the *SOC* decomposition (Lei *et al*., 2019). Thus, relatively low soil *pH* may enhance soil C accumulation in the *A. mangium* forest land.

The previous studies showed that *SOC* was significantly positively correlated with plant biomass (He *et al*., 2009; Sun and Guan, 2014), which was confirmed by the current study (Table 2). Other studies reported similar finding for some plantation forests in Vietnam (e.g., *A. mangium, A. auriculiformis, A. hybrid,* and *Eucalyptus urophylla*) (Hai *et al*., 2009). It also demonstrated the increase in biomass accumulated in the above- and below-ground components as the principal source of soil C inputs in forest ecosystems, which play a crucial role in *SOC* dynamics (Kristensen *et al*., 2008). The quantity and quality of aboveground litterfall determine *SOC* accumulation especially for the surface soil layer (Herdiyanti and Sulistyawati, 2009). Belowground root biomass plays a pivotal role in the accumulation of *SOC* across the soil profiles (Bauhus *et al*., 2000; Qu *et al*., 2011). Soil *BD* can be viewed as a key parameter of soil physical health that could affect soil structure, porosity, water-holding capacity, permeability and soil ventilation, and thus further influence the accumulation of *SOC* (Yu *et al*., 2019). In present study, significantly negative correlation between *SOC* and soil *BD* had been found (Table 2), which is in agreement with the results of previous studies (Thanh and Cuong, 2017a; Zhang *et al*., 2018). Plant growth and root penetration with organic matter returning can significantly improve soil structure and porosity and increase *SOC* content and impact soil *BD* (Ruehlmann and Krschens, 2009; Thanh and Cuong, 2017a; Wang *et al*., 2019). Soil *P* is a dominant nutrient that controls plant growth and development (Lei *et al*., 2019). Our results demonstrated that *SOC* was significantly positively correlated with soil *TP* and *AP* contents (Table 2). Lei *et al*. (2012) showed that *P* limitation might restrict *SOC* accumulation. It should be due to the availability of *P* regulating microbial growth and activities. Insufficient *P* supply may influence symbiotic *N* fixation (Augusto *et al*., 2013), and ultimately impact *SOC* accumulation. Another study demonstrated that the decomposition of *SOC* could promote the release of *P*, and the increased *P* availability had a contribution to the *SOC* accumulation (Qian *et al*., 2017). Available *K* could accelerate plant growth and simultaneously provide sufficient nutrient for the healthy root system in plants, increasing the number of plant residuals in the soil and increasing *SOC* (Sam *et al*. 2006). Our research also found a significant positive correlation of soil *K* contents (*TK* and *AK* contents) with *SOC* (Table 2), which might be associated with *K* released by the soil parent material with an increasing rate of weathering. Besides, the stand characteristic parameters such as stand density, canopy closure, mean *DBH*, and *H* may also contribute to interpreting the change of *SOC* in forests at different ages (Table 1).

CONCLUSIONS

The present study results provided an overall view of *SOC* distribution in an age-sequence of *A. mangium* forests (from 4- to 11-year-old plantations). To the best of our knowledge, this is the first report on the dynamics of *SOC* accumulation and the unique relationships between *SOC* and influential environmental variables for *A. mangium* forests in Southeastern region of Vietnam. Soil organic C content increased significantly with forest age. Moreover, *SOC* concentration primarily occurred in the topsoil and declined significantly with depth. Carbon storage in the mineral soil layer increased significantly with stand age. Soil organic C storage indicated obvious surface aggregation, with more than 60% of *CS* being in 0–30 cm depth. Soil *TN* content and soil texture (i.e., soil silt content) were the principal factors regulating the *SOC*. The findings provided by this study revealed that the *SOC* and nutrient regimes were substantially improved by afforestation with *A. mangium*, and provide valuable information for understanding the factors controlling *SOC* in the region.

ACKNOWLEDGEMENTS

This work was funded by the Chinese Government Doctoral Scholarship Foundation (2017GXZ025473) and the Doctoral Scholarship Foundation of Vietnam National University of Forestry (No.1872/QD/DHLN-TCCB). We would like to thank the Chang Riec Historical - Cultural Forest for providing invaluable information on the research site and permitting us to use the forests for this study. We would also like to thank the Dr. Dinh Mai Van and other researchers of the Centre of Forestry Research and Climate Change at VNUF for their support in laboratory analyses and for their comments to improve this manuscript.

REFERENCES

Abaker, W.E., Berninger, F., Saiz, G., Braojos, V., Starr, M. (2016). Contribution of *Acacia senegal* to biomass and soil carbon in plantations of varying age in Sudan. Forest Ecology and Management, 368: 71-80. doi:10.1016/j.foreco.2016.03.003.

Abaker, W.E., Berninger, F., Saiz, G., Pumpanen, J., Starr, M. (2018). Linkages between soil carbon, soil fertility and nitrogen fixation in *Acacia senegal* plantations of varying age in Sudan. PeerJ, 6: e5232. doi:10.7717/peerj.5232.

Albaladejo, J., Ortiz, R., Garcia-Franco, N., Navarro, A.R., Almagro, M., Pintado, J.G., *et al*. (2013). Land use and climate change impacts on soil organic carbon stocks in semi-arid Spain. Journal of Soils and Sediments, 13(2): 265-277. doi:10.1007/s11368-012-0617-7.

Ali, A., Ahmad, A., Akhtar, K., Teng, M., Zeng, W., Yan, Z., *et al*. (2019). Patterns of biomass, carbon, and soil properties in Masson pine (*Pinus massoniana* Lamb) plantations with different stand ages and management practices. Forests, 10(8): 645. doi:10.3390/f10080645.

Augusto, L., Delerue, F., Gallet-Budynek, A., Achat, D.L. (2013). Global assessment of limitation to symbiotic nitrogen fixation by phosphorus availability in terrestrial ecosystems using a meta-analysis approach. Global Biogeochem Cycles, 27(3): 804-815. doi:10.1002/gbc.20069.

Baldock, J.A. & Skjemstad, J.O. (2000). Role of the soil matrix and minerals in protecting natural organic materials against biological attack. Organic Geochemistry, 31(7-8): 697-710. doi:10.1016/S0146-6380(00)00049-8.

Batjes, N.H. (1996). Total carbon and nitrogen in the soils of the world. European Journal of Soil Science, 47(2): 151-163. doi:10.1111/j.1365-2389.1996.tb01386.x.

Bauhus, J., Khanna, P., Menden, N. (2000). Aboveground and belowground interactions in mixed plantations of *Eucalyptus* globulus and *Acacia mearnsii*. Canadian Journal of Forest Research, 30: 1886–1894. doi:10.1139/x00-141.

Blake, G.R. & Hartge, K.H. (1986). Bulk density. In: Klute A (ed) Methods of soil analysis part 1: physical and mineralogical methods, 2nd edn. American Society of Agronomy, Madison. pp. 363-375.

Bronson, K.F., Zobeck, T.M., Chua, T.T., Acosta-Martinez, V., Van Pelt, R.S., Booker, J.D. (2004). Carbon and nitrogen pools of southern high plains cropland and grassland soils. Soil Science Society of America Journal, 68(5): 1695-1704. doi:10.2136/sssaj2004.1695.

Burke, I.C., Yonker, C.M., Parton, W.J., Cole, C.V., Schimel, D.S., Flach, K. (1989). Texture, climate, and cultivation effects on soil organic matter content in U.S.

Grassland soils. Soil Science Society of America Journal, 53: 800-805. doi:10.2136/sssaj1989.03615995005300030029x.

Carvalhais, N., Forkel, M., Khomik, M., Bellarby, J., Jung, M., Migliavacca, M., *et al*. (2014). Global covariation of carbon turnover times with climate in terrestrial ecosystems. Nature, 514(7521): 213-217. doi:10.1038/nature13731.

Chen, CR., Xu, Z.H., Mathers, N.J. (2004). Soil carbon pools in adjacent natural and plantation forests of subtropical Australia. Soil Science Society of America Journal, 68(1): 282-291. doi:10.2136/sssaj2004.2820.

Cheng, J., Lee, X., Theng, B.K.G., Zhang, L., Fang, B., Li, F. (2015). Biomass accumulation and carbon sequestration in an age-sequence of *Zanthoxylum bungeanum* plantations under the Grain for Green Program in Karst regions, Guizhou Province. Agricultural and Forest Meteorology, 203: 88-95. doi:10.1016/j.agrformet.2015.01.004.

Cong, J., Wang, X., Liu, X., Zhang, Y. (2016). The distribution variation and key influencing factors of soil organic carbon of natural deciduous broadleaf forests along the latitudinal gradient. Acta Ecologica Sinica, 36(5): 333-339. doi:10.1016/j.chnaes.2016.06.002.

Cuong, L.V., Thanh, N.M., Long, L.V., Trang, B.T.T., Hieu, N.T. (2017). Some soil physical and chemical properties under natural forest cover in Tanphu protective forest, Dongnai Province. Journal of Forest Science and Technology, 6: 17-24 (in Vietnamese with English abstract)

Cuong, L., Hung, B., Bolanle-Ojo, O.T., Xu, X., Thanh, N., Chai, L., *et al*. (2020). Biomass and carbon storage in an age-sequence of *Acacia mangium* plantation forests in Southeastern region, Vietnam. Forest Systems, 29(2): e009. doi:10.5424/fs/2020292-16685.

Deng, L. & Shangguan, Z. (2017). Afforestation drives soil carbon and nitrogen changes in China. Land Degradation and Development, 28(1): 151-165. doi:10.1002/ldr.2537.

Deng, L., Han, Q.S., Zhang, C., Tang, Z.S., Shangguan, Z.P. (2017). Aboveground and belowground ecosystem biomass accumulation and carbon sequestration with *Caragana korshinskii* Kom plantation development. Land Degradation and Development, 28(3): 906-917. doi:10.1002/ldr.2642.

Fan, H., Zhao, W., Daryanto, S., Fu, B., Wang, S., Wang, Y. (2018). Vertical distributions of soil organic carbon and its influencing factors under different land use types in the desert riparian zone of downstream Heihe River basin, China. Journal of Geophysical Research, 123(14): 7741–7753. doi:10.1029/2018JD028268.

Hagedorn, F., Spinnler, D., Siegwolf, R. (2003). Increased in deposition retards mineralization of old soil organic matter. Soil Biology and Biochemistry, 35(12): 1683–1692. doi:10.1016/j.soilbio.2003.08.015.

Hai, VD., Trieu, D.T., Tiep, N.H., Bich, N.V., Duong, D.T. (2009). *Research on carbon sequestration potential and commercial value of some major types of plantation forests in Vietnam*. Final Project Report No. VAFS2009; Vietnamese Academy of Forest Sciences: Hanoi, Vietnam. 190 pp.

He, B., Liu, Y.H., Yu, H.G., Qin, W.M., Wei, S.H., Cai, S.W. (2009). Carbon density and storage of *Acacia mangium* plantation ecosystem in Nanning, Guangxi, China. Scientla Silvae Sinicae, 45(2): 6-11 (in Chinese with English abstract).

Herdiyanti, I. & Sulistyawati, E. (2009). Carbon stocks in *Acacia mangium* Willd. stands of different ages. In: Kanakaraju D, Kalu M, Ipor I, Lim CK, Lim PT, Roslan HA, Esa Y, Razali A, Ho WS, Mohamad S *et al*., editors. Proceedings of Conference on Natural Resources in the Tropics 3: Harnessing Tropical Natural Resources through Innovation and Technologies, 3–5 August 2009; Sarawak, Malaysia. Kota Samarahan, Malaysia: Universiti Malaysia Sarawak. pp. 679–685.

Hobley, E., Wilson, B., Wilkie, A., Gray, J., Koen, T. (2015). Drivers of soil organic carbon storage and vertical distribution in Eastern Australia. Plant and Soil, 390: 111–127.

Holguin, G., Vazquez, P., Bashan, Y. (2001). The role of sediment microorganisms in the productivity, conservation, and rehabilitation of mangrove ecosystems: an overview. Biology and Fertility of Soils, 33(4): 265-278.

IBM Corp. (2017). IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp.

IBST. (2009). Vietnam Building Code Natural Physical & Climatic Data for Construction. QCVN 02:2009/BXD. Institute for Building Science and Technology (IBST), Vietnam.

Jobbágy, E. & Jackson, R. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications, 10:423-436. doi:10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2.

Jusoh, I., Abu, Zaharin, F., Adam, N.S. (2014). Wood quality of *Acacia hybrid* and second-generation *Acacia mangium*. Bioresources, 9(1): 150-160. doi:10.15376/biores.9.1.150-160.

Koutika, L.S. & Richardson, D.M. (2019). *Acacia mangium* Willd: benefits and threats associated with its increasing use around the world. Forest Ecosystems, 6: 2. doi:10.1186/s40663-019-0159-1.

Kristensen, E., Bouillon, S., Dittmar, T., Marchand, C. (2008). Organic carbon dynamics in mangrove ecosystems: A review. Aquatic Botany, 89(2): 201-219. doi:10.1016/j.aquabot.2007.12.005.

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. Geoderma, 123: 1-22. doi:10.1016/j.geoderma.2004.01.032.

Laik, R., Kumar, K., Das, D.K., Chaturvedi, O.P. (2009): Labile soil organic matter pools in a calciorthent after 18 years of afforestation by different plantations. Applied Soil Ecology, 42(2): 71-78. doi:10.1016/j.apsoil.2009.02.004.

Lee, K.L., Ong, K.H., King, P.J.H., Chubo, J.K., Su, D.S.A. (2015). Stand productivity, carbon content, and soil nutrients in different stand ages of *Acacia mangium* in Sarawak, Malaysia. Turkish Journal of Agriculture and Forestry, 39(1): 154-161. doi:10.3906/tar-1404-20.

Lei, L., Gundersen, P., Zhang, T., Mo, J. (2012). Effects of phosphorus addition on soil microbial biomass and community composition in three forest types in tropical China. Soil Biology and Biochemistry, 44(1): 31-38. doi:10.1016/j.soilbio.2011.08.017.

Lei, Z., Yu, D., Zhou, F., Zhang, Y., Yu, D., Zhou, Y., *et al*. (2019). Changes in soil organic carbon and its influencing factors in the growth of *Pinus sylvestris* var. mongolica plantation in Horqin Sandy Land, Northeast China. Scientific Reports, 9(1): 16453. doi:10.1038/s41598-019-52945-5.

Li, X., Yi, M.J., Son, Y., Park, P.S., Lee, K.H., Son, Y.M., *et al*. (2011). Biomass and carbon storage in an age-sequence of Korea pine (*Pinus koraiensis*) plantation forests in central Korea. Journal of Plant Biology, 54(1): 33–42. doi:10.1007/s12374-010-9140-9.

Liu, Y., Li, S., Sun, X. Yu, X. (2016). Variations of forest soil organic carbon and its influencing factors in East China. Annals of Forest Science, 73(2): 501-511. doi:10.1007/s13595-016-0543-8.

Lydie-Stella, K., Sogni, Viviane, T., Louis, M., Daniel, E. (2017). Nitrogen dynamics in a nutrient-poor soil under mixed-species plantations of Eucalypts and Acacias. Soil Biology and Biochemistry, 108: 84–90. doi:10.1016/j.soilbio.2017.01.023.

MARD. (2018). *Promulgating a list of major forestry tree species, recognition of varieties and seed sources, and management of main forestry tree seed materials*. No. 30/2018/TT-BNNPTNT. Ministry of Agriculture and Rural Development (MARD), Hanoi, Vietnam.

MARD. (2020). *Promulgation of the state of National forests*. No. 1558/QD-BNN-TCLN. Ministry of Agriculture and Rural Development (MARD), Hanoi, Vietnam.

Matali, S. & Metali, F. (2015). Selected soil physico-chemical properties in the *Acacia mangium* plantation and the adjacent heath forest at Andulau Forest Reserve. Malaysian Journal of Soil Science, 19: 45-58.

Matthias, P. & Arain, M.A. (2006). Above- and belowground ecosystem biomass and carbon pools in an age-sequence of *Temperate pine* plantation forests. Agricultural and Forest Meteorology, 140(1-4): 51-63. doi:10.1016/j.agrformet.2006.08.004.

Ming, A., Jia, H., Zhao, J., Tao, Y., Li, Y. (2014). Above- and belowground carbon stocks in an Indigenous tree (*Mytilaria laosensis*) plantation chronosequence in subtropical China. PLoS ONE, 9(10): e109730. doi:10.1371/journal.pone.0109730.

Ngaba, M.J.Y., Ma, X., Hu, Y. (2020). Variability of soil carbon and nitrogen stocks after conversion of natural forest to plantations in Eastern China. PeerJ, 8: e8377. doi:10.7717/peerj.8377.

Nelson, D.W. & Sommers, L.E. (1982). Total carbon, organic carbon and organic matter: In: A.L. Page, R.H. Miller and D.R. Keeney) Methods of soil analysis. Part 2 Chemical and Microbiological Properties. pp. 539-579. doi:10.2134/agronmonogr9.2.2ed.c29.

Noh, N.J., Son, Y., Lee, S.K., Seo, K.W., Heo, S.J., Yi, M.J., *et al*. (2010). Carbon and nitrogen storage in an age-sequence of *Pinus densiflora* stands in Korea. Science China Life sciences, 53(7): 822-830. doi:10.1007/s11427-010-4018-0.

Paul, E.A. (1984). Dynamics of organic matter in soils. Plant and Soil, 76: 275–285. doi:10.1007/978-94-009-6101-2_24.

Pregitzer, K.S. & Euskirchen, E.S. (2004). Carbon cycling and storage in world forests: biome patterns related to forest age. Global Change Biology, 10(12): 2052-2077. doi:10.1111/j.1365-2486.2004.00866.x.

Qian, J., Liu, J., Wang, P., Wang, C., Li, K., Shen, M. (2017). Riparian soil physicochemical properties and correlation with soil organic carbon of an inflowing river of Taihu Lake. IOP Conference Series: Earth and Environmental Science, 59: 012053. doi:10.1088/1755-1315/59/1/012053.

Qu, W.D., Chen, Y.M., Wang, L.L., Zhang, F., Zhang, X.W. (2011). Dynamics of soil organic carbon in *Caragana microphylla* forest and its relationships with environment factors in loess hilly region. Science of Soil and Water Conservation, 9(4): 72-77 (in Chinese with English abstract).

R Core Team. (2018). A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Robson, A.D. & Foy, C.D. (1990). Soil Acidity and Plant Growth. Soil Science, 150(6): 903.

Ruehlmann, J. & Körschens, M. (2009). Calculating the effect of soil organic matter concentration on soil bulk density. Soil Science Society of America Journal, 73: 876-885. doi:10.2136/sssaj2007.0149.

Sam, D.D., Que, D.N., Siem, T.N., Binh, N.N. (2006). *Forest soils, nutrition, and management*. Hanoi Agriculture Publishing House, Vietnam.

Shah Newaz, M. & Millat-e-Mustafa, M. (2004). Growth and yield prediction models for *Acacia mangium* grown in the plantations of the central region of Bangladesh. New Forests, 27: 81–88. doi:10.1023/A:1025086920175.

Senechkin, I.V., van Overbeek, L.S., van Bruggen, A.H.C. (2014). Greater fusarium wilt suppression after complex than after simple organic amendments as affected by soil *pH*, total carbon and ammonia-oxidizing bacteria. Applied Soil Ecology, 73: 148-155. doi:10.1016/j.apsoil.2013.09.003.

Simon, G.D., Alberti, G., Delle, Vedove, G., Zerbi, G., Peressotti, A. (2012). Carbon stocks and net ecosystem production changes with time in two Italian forest chronosequences. European Journal of Forest Research, 131(5): 1297-1311. doi:10.1007/s10342-012-0599-4.

Six, J., Conant, R.T., Paul, E.A., Paustian, K. (2002a). Stabilization mechanisms of soil organic matter: implications for c-saturation of soils. Plant and Soil, 24(2): 155-176. doi:10.1023/A:1016125726789.

Six, J., Callewaert, P., Lenders, S., De, Gryze, S., Morris, S.J., Gregorich, E.G., Paul, E.A., Paustian, K. (2002b). Measuring and understanding carbon storage in afforested soils by physical fractionation. Soil Science Society of America Journal, 66(6): 1981-1987. doi:10.2136/sssaj2002.1981.

Smal, H. & Olszewska, M. (2008). The effect of afforestation with Scots pine (*Pinus silvestris* L.) of sandy post-arable soils on their selected properties. II. Reaction, carbon, nitrogen and phosphorus. Plant and Soil, 305(1/2): 171-187. doi:10.1007/s11104-008-9538-z.

Sombroek, W.G., Nachtergaele, F.O., Hebel, A. (1993). Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. Ambio, 22: 417-426.

Sun, L. & Guan, D.S. (2014). Carbon stock of the ecosystem of lower subtropical broadleaved evergreen forests of different ages in Pearl River Delta, China. Journal of Tropical Forest Science 26: 249-258.

Thanh, N.M. & Cuong, L.V. (2017a). Carbon storage in soil under *Acacia mangium* forest cover in Yenbai city, Yenbai Province. Science and Technology Journal of Agriculture & Rural Development, 2: 120-124 (in Vietnamese with English abstract).

Thanh, N.M. & Cuong, L.V. (2017b). Effects of plantation forest types to soil physical and chemical properties in Socson district, Hanoi city. Science and Technology Journal of Agriculture & Rural Development, 2: 133-139 (in Vietnamese with English abstract).

Thomas, G.W. (1996). Soil pH and soil acidity. Methods of Soil Analysis Part 3: Chemical Methods (ed. by DL Sparks). American Society of Agronomy and Soil Science Society of America, Madison. pp. 475-490.

Tian, F.P., Zhang, Z.N., Chang, X.F., Sun, L., Wei, X.H., Wu, G.L. (2016). Effects of biotic and abiotic factors on soil organic carbon in semi-arid grassland. Journal of soil science and plant nutrition, 16(4): 1087-1096. doi:10.4067/S0718-95162016005000080.

Van Reeuwijk, L.P. (2002). Procedures for Soil Analysis. 6th ed. ISRIC, FAO, Wageningen.

Wang, G., Guan, D., Peart, M.R., Chen, Y., Peng, Y. (2013). Ecosystem carbon stocks of mangrove forest in Yingluo Bay, Guangdong Province of South China. Forest Ecology and Management, 310: 539-546. doi:10.1016/j.foreco.2013.08.045.

Wang, Y., Liu, L., Yue, F., Li, D. (2019). Dynamics of carbon and nitrogen storage in two typical plantation ecosystems of different stand ages on the Loess Plateau of China. PeerJ, 7: e7708. doi:10.7717/peerj.7708.

Yang, Y.S., Chen, G.S., Guo, J.F., Xie, J.S., Wang, X.G. (2007). Soil respiration and carbon balance in a subtropical native forest and two managed plantations. Plant Ecology, 193(1): 71-84. doi:10.1007/s11258-006-9249-6.

Yang, Y., Fang, J., Tang, Y., Ji, C., Zheng, C., He, J., Zhu, B. (2008). Storage, patterns and controls of soil organic carbon in the Tibetan grasslands. Global Change Biology, 14(7): 1592-1599. doi:10.1111/j.1365-2486.2008.01591.x.

Yang, L., Liu, N., Ren, H., Wang, J. (2009). Facilitation by two exotic *Acacia*: *Acacia auriculiformis* and *Acacia mangium* as nurse plants in South China. Forest Ecology and Management, 257(8): 1786-1793. doi:10.1016/j.foreco.2009.01.033.

Yu, G., Jian, Z., Liming, W., Jiemin, G., Jianxiang, F., Hao, W., Guanghui, L. (2019). Distribution patterns and controlling factors for the soil organic carbon in four mangrove forests of China. Global Ecology and Conservation, 17: e00575. doi:10.1016/j.gecco.2019.e00575

Yue, J.W., Guan, J.H., Deng, L., Zhang, J.G., Li, G., Du, S. (2018). Allocation pattern and accumulation potential of carbon stock in natural spruce forests in Northwest China. PeerJ, 6: e4859-e4859. doi:10.7717/peerj.4859.

Zhang, L., Zhang, P., Yu, M., Wu, T. (2016). Soil organic carbon content and stocks in an age-sequence of *Metasequoia glyptostroboides* plantations in coastal area, East China. 4th International Conference on Sustainable Energy and Environmental Engineering (ICSEEE). pp. 1004-1012. doi:10.2991/icseee-15.2016.178.

Zhang, H., Wang, K., Zeng, Z., Du, H., Zeng, F. (2017). Biomass and carbon sequestration by *Juglans regia* plantations in the Karst regions of Southwest China. Forests, 8(4): 103. doi:10.3390/f8040103.

Zhang, H., Duan, H., Song, M., Guan, D. (2018). The dynamics of carbon accumulation in *Eucalyptus* and *Acacia* plantations in the Pearl River Delta region. Ann Forest Sci, 75(2):40. doi:10.1007/s13595-018-0717-7.

Zhang, X., Zhang, X., Han, H., Shi, Z., Yang, X. (2019). Biomass accumulation and carbon sequestration in an age-sequence of *Mongolian Pine* plantations in Horqin sandy land, China. Forests, 10(2): 197. doi:org/10.3390/f10020197

Zhao, J., Kang, F., Wang, L., Yu, X., Zhao, W., Song, X., *et al*. (2014). Patterns of biomass and carbon distribution across a chronosequence of Chinese Pine (*Pinus tabulaeformis*) forests. PLoS One, 9(4): e94966. doi:10.1371/journal.pone.0094966.

Zhaodi, W., Xiaodong, Y., Wei, W. (2018). Variation of soil carbon pools in *Pinus sylvestris* plantations of different ages in north China. Acta Ecologica Sinica, 38(3): 248-254. doi:10.1016/j.chnaes.2017.08.004

Zhong, L. & Qiguo, Z. (2001). Organic carbon content and distribution in soils under different land uses in tropical and subtropical China. Plant and Soil, 231(2): 175-185. doi:10.1023/A:1010350020951.

Zhou, L., Li, B.G., Zhou, G.S. (2005). Advances in controlling factors of soil organic carbon. Advances in Earth Science, 20(1): 99-105 (in Chinese with English abstract).

Zhou, W., Han, G., Liu, M., Li, X. (2019). Effects of soil pH and texture on soil carbon and nitrogen in soil profiles under different land uses in Mun River Basin, Northeast Thailand. PeerJ, 7: e7880. doi:10.7717/peerj.7880.

Zu, Y.G., Li, R., Wang, W.J., Su, D.X., Wang, Y., Qiu, L. (2011). Soil organic and inorganic carbon contents in relation to soil physicochemical properties in northeastern China. Acta Ecologica Sinica, 31(18): 5207–5216 (in Chinese with English abstract).