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Soil organic carbon storage by shaded and unshaded coffee systems and its implications for climate change mitigation in China

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Abstract

Shaded coffee systems can mitigate climate change by fixation of atmospheric carbon dioxide (CO_2) in soil. Understanding soil organic carbon (SOC) storage and the factors influencing SOC in coffee plantations are necessary for the development of sound land management practices to prevent land degradation and minimize SOC losses. This study was conducted in the main coffee-growing regions of Yunnan; SOC concentrations and storage of shaded and unshaded coffee systems were assessed in the top 40 cm of soil. Relationships between SOC concentration and factors affecting SOC were analysed using multiple linear regression based on the forward and backward stepwise regression method. Factors analysed were soil bulk density (ρ_b), soil pH, total nitrogen of soil (N), mean annual temperature (MAT), mean annual moisture (MAM), mean annual precipitation (MAP) and elevations (E). Akaike's information criterion (AIC), coefficient of determination (R^2), root mean square error (RMSE) and residual sum of squares (RSS) were used to describe the accuracy of multiple linear regression models. Results showed that mean SOC concentration and storage decreased significantly with depth under unshaded coffee systems. Mean SOC concentration and storage were higher in shaded than unshaded coffee systems at 20–40 cm depth. The correlations between SOC concentration and ρ_b, pH and N were significant. Evidence from the multiple linear regression model showed that soil bulk density (ρ_b), soil pH, total nitrogen of soil (N) and climatic variables had the greatest impact on soil carbon storage in the coffee system.

Introduction

Coffee was first introduced to Yunnan province in southwest China more than 100 years ago. The mountainous landscape (altitude 800–2000 metres) and mild climate in south and southwest Yunnan are very suitable for coffee production (ICO, 2015). In recent years, the area of unshaded coffee plantations using similar management practices is rapidly expanding in Yunnan. At present, 1.24×10^5 ha have been planted with Arabica coffee in these regions (Liu *et al*., 2016), which accounts for over 95% of China's coffee production (ICO, 2015). Coffee has been the fourth biggest agricultural commodity in Yunnan after tobacco, sugar cane and tea (Chen, 2015). In order to increase greater yields, large quantities of unshaded coffee have been planted in Yunnan. However, due to physical and social drawbacks in unshaded coffee plantations, nowadays, the shade trees have been planted by farmers in the unshaded coffee plantations. Recent studies have noted that the carbon storage capacity of shaded coffee plantation has gained increasing attention (Méndez *et al*., 2011; Goodall *et al*., 2015). Although Yunnan has a large number of studies on SOC stocks (Blécourt *et al*., 2013; Li *et al*., 2015; Chen *et al*., 2016), there are few researches on SOC reserves assessments in coffee plantations.

The importance of understanding the region pool of carbon in different kinds of soil has been highlighted (Batjes, 1996). Therefore, the utility of coffee plantations in sequestering carbon should be understood to facilitate the development of region policy prescriptions or smaller-scale certification programmes oriented around C-sequestration in Yunnan. Some researchers have pointed out that SOC stock is influenced by numerous variables, including climate factors, soil properties, site variables and management practices (Schimel *et al*., 1994; Tan *et al*., 2004; Cai *et al*., 2016). Furthermore, studying the relationship between SOC concentration and its influencing factors may be useful to predict SOC stock in these coffee plantations. Therefore, the purpose of this study is to investigate how the vertical distribution patterns of SOC concentration in the profiles varied under two different coffee production systems of Yunnan. In addition, this study will also introduce a response equation to combine the relative changes in the SOC concentration of shaded and unshaded coffee systems, soil

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bulk density (ρ_b), soil pH, total nitrogen of soil (N) and climatic variables, so as to provide precise data for certification programmes oriented C-sequestration in this district.

Materials and methods

Study area

This study was conducted in coffee-growing region in southwest Yunnan (98°38′27.481″–102°18′38.372″; 21°59′35.613″–25°49′26.969) namely, Puer, Lingcang, Baoshan, Dehong (Fig. 1). In general, the area has distinct wet and dry seasons. The wet season lasts from June to October, and the pronounced dry season occurs from November until May (Chen, 2001). The climate is the sub-tropical and tropical monsoon climate. The soils in the region are characterized as acidic lateritic red soil and a reddish brown sandy loam soil (Liu *et al.*, 2016; Zhang *et al.*, 2017). The primary coffee varieties are Catimor, S288, Borbón and Caturra, and the age of the plantations ranges from 3 to 15 years. On average, the planting density (plants/ha) in unshaded range from 3500 to 2500. Based on management level and vegetational and structural complexity, two coffee management categories in major coffee-growing regions are characterized as shaded and unshaded plantations. In shaded plantations, the shade trees are rubber (*Hevea brasiliensis*), macadamia (*Macadamia ternifolia*) and longan (*Euphoria longan*). The density of shade trees varies greatly because shade trees are planted by farmer without arranged regime. In addition, many trees are still relatively young (∼5–10 years) in the shaded plantations of Lincang; however, the age of the shades trees are over 10 years in Dehong coffee-growing regions. Two different coffee managements were focused on generating products that were exclusively market-oriented. These coffee-producing systems require high inputs of chemical fertilizers and an intensive work force throughout the year. The main fertilizers were urea and compound fertilizers. The characteristics of coffee plantations are shown in Table 1.

Soil sampling

In 2015–2016, lists of coffee growers within each coffee region were obtained from the Coffee Association of Yunnan (CAYN), from which plantations covering >1 ha and with slopes ranging from 0° to 35° were selected. Another key consideration was that Arabica coffee was grown as the major crop. In total, 50 individual plantations were selected, of which 22 plantations were planted with shade trees and 28 were plantations without shade trees. Data collection at each soil sampling plantation started with semi-structured interviews with farmers to compile data on farm management, fertilizer use, pesticide use, shading, coffee and shade tree densities, and yields (Table 1). In addition, the geographical locations of the soil sampling plantation were obtained using a hand-held GPS (G210). A soil sampling plantation was randomly divided into three plots. In each plot, five randomly distributed soil sampling points were taken and pooled to one composite sample. In order to acquire soil bulk density at 0–10, 10–20 and 20–40 cm, the stainless steel cutter with edge cylinders with a height of 50 mm and a diameter of 50 mm (98.2 cm^3 inner volume) was hammered into the ground at each sampling soil depth. Systematically collected soil samples for SOC analysis were sampled at 20 cm depth intervals in the top 40 cm in the coffee inter-row with a distance of 40–50 cm from the stem of a coffee plant. Previous work indicated that this position provided a spatially integrative measurement of soil properties for the entire coffee plot (Hergoualc'h *et al.*, 2012). After collection, all collected soil samples were transported to the laboratories of Dehong Tropical Agriculture Research Institute of Yunnan (DTARI) for organic carbon, pH and bulk density analysis. In total, 450 soil samples were systematically collected for soil bulk density (ρ_b) analysis, and 300 soil samples were analysed for SOC. According to the coffee plantation management practice, 300 soil samples for SOC were divided into two parts: 132 in shaded coffee plantations and 168 in unshaded coffee plantations.

Laboratory analyses and soil carbon stock calculations

Bulk density samples were sealed in metal collection cans and dried at 105°C. Soil bulk density was calculated by dividing the oven dry mass by the volume of the core. Soil samples for SOC analysis were sampled at 20 cm depth intervals in the top 40 cm. Soil samples collected for SOC analyses were air dried in the laboratory. The coarse roots and stones were extracted by hand and then the soil was passed through a 2 mm sieve. Soil organic carbon concentration was measured using the Walkley-Black method and applying a correction factor of 1.32 to account for the incomplete oxidation of organic carbon that is known to occur with the Walkley-Black method (Mylavarapu, 2014). There are low pH values (<7.0) and negative HCl test in the soil samples. This confirmed absence or insignificant amount of carbonates in the soil. Therefore, all measured soil carbon was considered as SOC. Soil total nitrogen (N) was determined by the Kjeldahl method. Soil pH was determined on air-dried samples with a soil solution ratio of 1 : 2.5. Soil total SOC stock was determined by using the formula (Don *et al.*, 2011):

$$\text{SOC stock } [t/\text{ha}] = \sum_{i=1}^{n} \text{SOC concentration } [t/t] \times \text{bulk density } [t/\text{m}^3] \times \text{soil volume}(\text{m}^3/\text{ha})$$

where n was the number of soil layers. The average soil bulk density of 0–10 and 10–20 cm was used as the soil bulk density of 0–20 cm.

Observational data sets

The daily surface air temperature and precipitation observations came from 22 China Meteorological Administration (CMA) meteorological stations (Fig. 1) in the past 30 years. In this study, the annual average air temperature, moisture and precipitation were selected as climatic variables. Each coffee plantation was paired to a meteorological station with the shortest distance.

Statistical analyses

The data were divided into two main groups: shaded plantation and unshaded plantation. Each plantation was set as independent replicate. Statistical analysis was performed using the software SPSS 24, with a probability level of 5% to test the significance of the treatment effects. The effect of shaded trees on SOC concentration, SOC stock, and soil bulk density was analysed using one-way ANOVA. Since the Levene's Test for equality of variances is significant, the data were analysed with Tamhane'ST2. The Mann–Whitney test was used when the data were not normally distributed. Multiple linear regression combined with forward

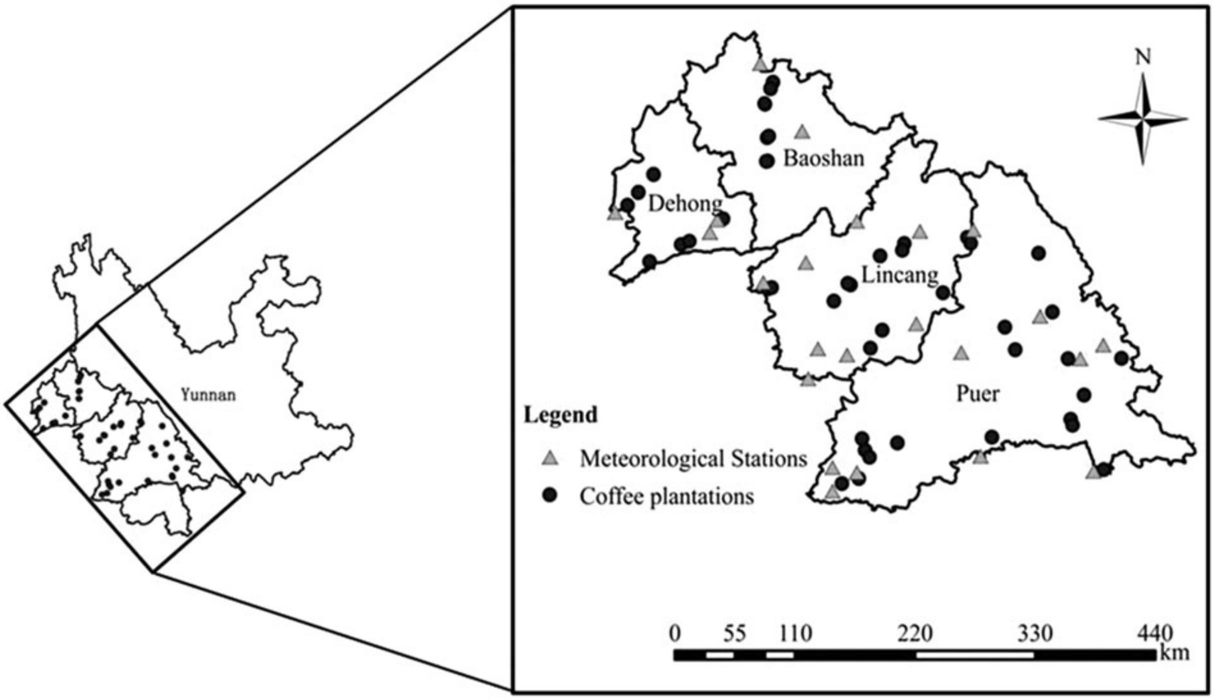

Fig. 1. Distribution of coffee plantations surveyed in this study.

Table 1. The characteristics of the coffee system

	Coffee trees		Shade trees				
Plantation	Tree spacing (m)	Row spacing (m)	Tree spacing (m)	Row spacing (m)	Age (years)	Fertilizer (times/year)	Fresh fruit yield (t/ha)[a]
Coffee	1–2	2–3	–	–	3–7	2–3	10–18
Coffee + rubber	1–2	2–3	3–5	12–2	3–10	2–3	10–18
Coffee + macadamia	1–2	2–3	4–5	4–8	2–6	2–3	9–19
Coffee + longan	1–2	2–3	4–5	5–8	>10	2	14

[a]Fruit = coffee berry.

and backward stepwise regression method to quantify the relationship between a dependent variable (SOC concentration) and multiple independent variables (Meersmans *et al.*, 2012), such as average soil bulk density (ρ_b), soil pH, total nitrogen of soil (N), mean annual temperature (MAT), mean annual moisture (MAM), mean annual precipitation (MAP) and elevation (E). The coefficient of determination (R^2), root mean square error (RMSE) and residual sum of squares (RSS) were used to evaluate the goodness of fit, while the performance relative to the number of model parameters was evaluated through the Akaike information criterion (AIC). The AIC can be expressed as (Meersmans *et al.*, 2012):

$$\text{AIC} = \ln(\text{RSS}/N) + 2k$$

RSS is the residual sum of squares, N is the number of observations, and k is the number of parameters in the model. The model with the lowest AIC is considered the best model.

Results

Soil bulk density was significantly ($P < 0.05$) smaller under shaded coffee system than unshaded coffee system in 20–40 cm depth (Table 2). Similarly, soil total nitrogen (N) concentrations of shaded coffee system were significantly ($P < 0.05$) greater in the upper 40 cm of soil as compared to unshaded coffee system. Soil pH was not significantly different between coffee systems (5.4–5.6) (Table 2). The mean C/N ratio of unshaded coffee system ranged from 12.6 in 0–20 cm to 9.5 in 20–40 cm, and C/N ratio under shaded coffee system changed little from 0–20 cm (11.4) to 20–40 cm (11.5). However, there was no significant difference ($P > 0.05$) between shaded and unshaded coffee system.

The SOC concentration and stock decreased with soil depth in both coffee systems (Fig. 2). In unshaded coffee system, there was a significantly higher mean SOC concentration (Fig. 2(*a*)) and stock (Fig. 2(*b*)) at 0–20 depth than the 20–40 cm layer ($P <$ 0.05). Total SOC concentration (20 ± 1.4 g/kg) and stock (91 ± 5.3 t/ha) in shaded coffee system was larger than unshaded coffee system (17 ± 1.6 g/kg, 85 ± 7.0 t/ha). Although there was no

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Table 2. Soil dry bulk density, soil pH and nitrogen (N) concentrations at two depth intervals in shaded and unshaded plantations of coffee systems

	0–20 cm		20–40 cm		Total	
Depth	Mean	S.E.	Mean	S.E.	Mean	S.E.
Soil bulk density (g/cm^3)						
Unshaded coffee system	1.25a	0.034	1.33a	0.039	1.29a	0.035
Shaded coffee system	1.14a	0.043	1.20b	0.041	1.17b	0.041
Soil pH						
Unshaded coffee system	5.2a	0.14	5.5a	0.12	5.5a	0.11
Shaded coffee system	5.40a	0.15	5.4a	0.13	5.4a	0.13
Soil N concentration (g/kg)						
Unshaded coffee system	1.71a	0.15	1.46a	0.090	1.62a	0.046
Shaded coffee system	2.00b	0.090	1.81b	0.098	1.84b	0.084
Soil carbon (C)/N ratio						
Unshaded coffee system	13a	1.1	9.5a	0.90	10.1a	0.93
Shaded coffee system	11.4a	0.66	12a	1.2	11.3a	0.84

Notes: For a given soil property, the means followed by the same letter are not significantly different between shaded and unshaded coffee systems at $P = 0.05$.

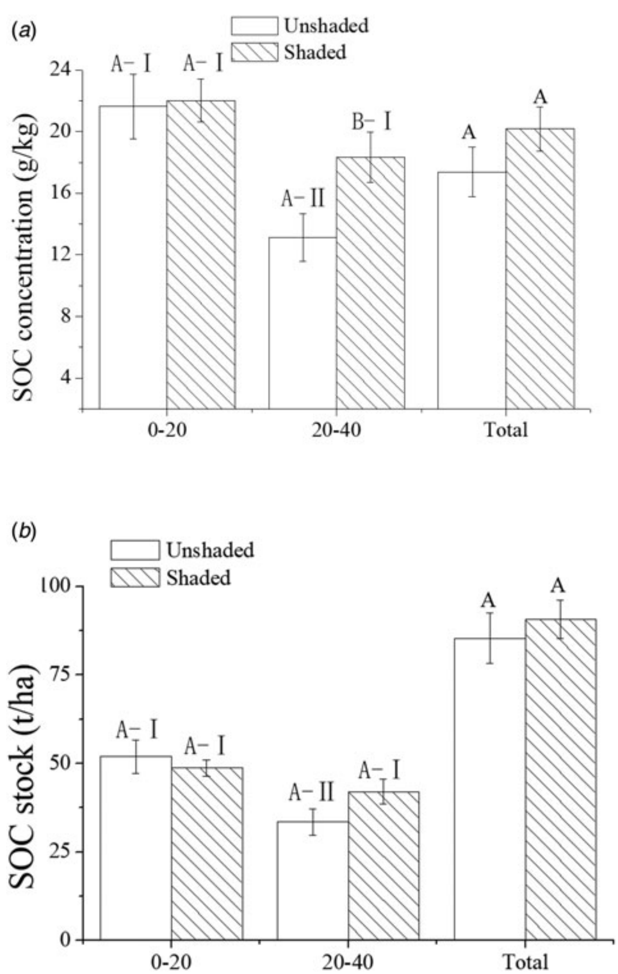

Fig. 2. (a) The soil organic carbon (SOC) concentration and (b) stock at different depths in shaded and unshaded coffee system. Note: Different capital letters indicate significant* differences between the shaded and unshaded coffee system at the same depth and different Roman numerals indicate significant* differences between 0–20 and 20–40 cm at a coffee system (*$P < 0.05$). Error bars represent standard error of the mean. Description of coffee system is presented in Table 1.

significant difference in the total SOC concentration and stock at 0–20 depth between shaded coffee system and unshaded coffee system ($P > 0.05$), the 20–40 cm layer of shaded coffee system showed significantly greater SOC concentration ($P < 0.05$) compared to unshaded coffee system (Fig. 2(*a*)).

Correlation coefficients between SOC concentration and explanatory variables in coffee system are given in Table 3. Soil organic carbon concentration had a rather strong negative correlation with soil bulk density (ρ_b) ($P < 0.01$). There were significant negative ($P < 0.05$) relationships between SOC concentration and soil pH. The positive relationship was observed between SOC concentration and soil total nitrogen (N) ($P < 0.01$). There was no significant relationship between SOC and climatic variables in coffee system.

A multiple linear regression model was created using a combined forward and backward stepwise regression method. Using multiple linear regression (Table 4), 19 regression models were set up for the model of coffee system. As the number of variables increased, the R^2 value of multiple linear regression model is increased. In contrast, RSS decreased as the number of variables increased. The best model based on RMSE and AIC values was selected. Soil bulk density (ρ_b), soil pH, soil total nitrogen (N), mean annual temperature (MAT), mean annual moisture (MAM) and mean annual precipitation (MAP) were included in the best model at 0–20 cm depth. This model results showed that six variables could explain 50.5% of SOC concentration variations in 0–20 cm soil depth (Table 3). For the 20–40 cm depth, the multiple linear regression model with the lowest AIC value included all variables. This multiple linear regression with all variables produced the largest R^2 (0.477) and smaller RMSE (6.646%) and RSS (1634) for SOC concentration. The integrated model incorporating six variables was performed better in predicting the total SOC concentration than the other fitted model (Table 4). This model explained 51.9% variations in SOC concentration. All the optimal fitting models showed that ρ_b, pH, N, MAT and MAM were important predictors of SOC concentration. Likewise, MAP was an important predictor of SOC concentration in 0–20 cm soil depth and was present in regression equations.

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Table 3. Correlation coefficients (*r*) between SOC concentration and explanatory variables in coffee system

Variables	0–20 cm	20–40 cm	Total
ρ_b	−0.543 (P < 0.01)	−0.557 (P < 0.01)	−0.616 (P < 0.01)
pH	−0.312 (P < 0.05)	−0.311 (P < 0.05)	−0.351 (P < 0.01)
N	0.500 (P < 0.01)	0.387 (P < 0.01)	0.395 (P < 0.01)
MAT	0.089 (NS)	−0.043 (NS)	0.031 (NS)
MAM	0.140 (NS)	0.230 (NS)	0.204 (NS)
MAP	0.146 (NS)	0.131 (NS)	0.155 (NS)
E	0.039 (NS)	−0.088 (NS)	−0.023 (NS)

SOC, soil organic carbon; ρ_b, average soil bulk density; pH, soil pH; N, total soil nitrogen; MAT, mean annual temperature; MAM, mean annual moisture; MAP, mean annual precipitation; E, elevation; NS, not significant.

Elevation (E) was an influential predictor of SOC concentration in the integrated model.

The measured *v.* predicted values of SOC concentration by the optimal regression models are shown in Fig. 3. Similarly, comparing the predicted SOC concentration values generated by this model with those measured in the field for the soil samples at the different depth indicated that there was a relatively moderate correlation between predicted and measured SOC concentration values. With the increase of soil depth, the correlation (R^2_{adj}) between predicted and measured SOC concentration values increased from 0.280 to 0.426. The R^2_{adj} of 0–40 cm depth SOC concentration was 0.420.

Discussion

In this study, SOC for the shaded coffee plantations was higher than the unshaded coffee plantations. Shade trees not only adverse SOC accumulation, but they may also increase farmers' income. One reason for maintaining shade trees in shaded plantations provided a more stable income due to cash income supplement provided by fruits or timber from the shelter trees (Damatta, 2004). In addition, studies have shown that the commercial polyculture coffee plantation can increase the coffee production in Yunnan (Peng *et al.*, 2012). In a coffee + rubber plantation studied by Zhang *et al.* (2002*b*), the rubber yield increased by 1.88 kg per plant and the yield of coffee green beans could also be stabilized at 3000 kg/ha in a well-managed coffee plantation (Zhang et al., 2002*b*). In addition, a combined coffee-macadamia plantation also significantly increased the yield of coffee per unit area (Long and Wang, 1996). Moreover, coffee white stem borer (*Xylotrechus quadripes*) has become a major problem in Yunnan coffee-growing region. Therefore, it is recommended that coffee plants are planted under a good stand of permanent shading trees as a key strategy to control the white stem borer (Zhang et al., 2002*a*, *b*). This has stimulated many unshaded coffee plantations to convert into shaded coffee plantations in Yunnan.

Land cover by perennial plants will have the greatest impact on soil carbon accumulation increase (Luo *et al.*, 2010). Organic inputs from litter, pruned biomass and roots decay and exudation of the trees contribute to maintain or increase SOC content (Montagnini and Nair, 2004). In the monoculture, carbon inputs from litterfall were much smaller, and the loss cannot be compensated via mineralization (Hergoualc'h *et al.*, 2012). The result of this study has shown that total SOC stock in shaded coffee system was larger than unshaded coffee system. This result suggests that the inclusion of shade trees in shaded coffee system could increase SOC accumulation.

The finer soil particles play an important determinant of the SOC storage capacity, as higher finer soil particles fractions promoted the formation of organic mineral complexes (Lemma, 2018). High bulk density in unshaded coffee could be due to both soil compaction and soil textural differences. Soil bulk density was higher in unshaded coffee system than shaded coffee system. Thus, this partly supports soil compaction in unshaded coffee. Likewise, there was higher SOC stock in unshaded coffee system in the upper 20 cm as compared with shaded coffee system, although SOC concentration of shaded coffee system was higher than unshaded coffee system. The soil's organic matter (SOM) was one of the dominating factors that changed soil bulk density (Ruehlmann and Körschens, 2009), which negatively correlated with SOC at lower depths (Devi and Kumar, 2009). A similar result was also found in this study. The relationship between SOC concentration and soil bulk density was significantly negative. This relationship maybe a factor that accounted for SOC concentration declined with the increased depth. In the optimal linear regression model, soil bulk density was an important factor explaining the variation of SOC concentration.

It is known that soil pH is one of the factors affecting the turnover of C stocks in soils (Cinzia *et al.*, 2010; Kirk *et al.*, 2010). Since changes in soil pH will affect plant growth and microbial activity, these processes may have a direct impact on SOC stock (Parfitt *et al.*, 2014). Consistent with these findings, a significant negative relationship between soil pH and SOC concentration in coffee system was observed. This result partly indicated that soil pH was a factor that affected SOC concentration in both coffee systems.

Although the decomposition of soil organic matter is often limited by nitrogen availability to microbes (Schimel and Weintraub, 2003; Allison *et al.*, 2010), the effect of N on carbon stock depends on ecosystem type and soil organic matter quality (Allison *et al.*, 2010). There was also a significant positive relationship between SOC concentration and soil total nitrogen (N) in both coffee systems, and it was an influential predictor of SOC concentration in the stepwise regression. The coffee plant's fine roots are found at the surface of the soil (0–30 cm) (Wintgens, 2004). The potential loss of N in the first 0–20 cm soil depth can be reduced by complementing with litter and fine root of shade trees (Lemma, 2018). N uplift by shade trees can partially explain the lower C/N ratio at the surface of the soil (0–20 cm) in the shaded coffee plantations. The decrease of SOC concentration with depth was greater for the unshaded coffee plantations by 8.501 and 3.680 g/kg as compared to the SOC concentration of shaded coffee plantations. However, there was a small variation of total N concentration with depth in the shaded coffee plantations (0.251 g/kg) and unshaded coffee plantations (0.188 g/kg). This may be a result of the lower C/N ratio in unshaded coffee plantations than in shaded coffee plantations.

There were several factors that affected the SOC stock in coffee plantations. Unrevealing the relation between SOC and various site factors in a multidimensional context can be a useful tool for optimizing sustainable soil management at larger administrative levels (Meersmans *et al.*, 2012). In order to compare the best performing algorithms, the AIC was a useful method that can

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Table 4. The multiple linear regression analysis for influencing factors of soil organic carbon concentration in coffee system

Depth	Regression equation	R^2	RMSE	RSS	AIC
0–20 cm	$V_{SOC} = 56.777 - 29.275V_{\rho b}$	0.368	7.314	2139	17.756
	$V_{SOC} = 33.224 - 29.275V_{\rho b} + 0.303V_{MAM}$	0.397	7.238	2043	17.710
	$V_{SOC} = 6.44 - 27.937V_{\rho b} + 0.386V_{MAM} + 1.032V_{MAT}$	0.425	7.157	1946	17.662
	$V_{SOC} = -12.900 - 20.964V_{\rho b} + 0.382V_{MAM} + 1.192V_{MAT} + 4.582V_N$	0.462	7.019	1832	17.601
	$V_{SOC} = -11.465 - 20.662V_{\rho b} + 0.442V_{MAM} + 1.086V_{MAT} + 5.540V_N - 0.004V_{MAP}$	0.484	6.967	1747	17.554
	$\boldsymbol{V_{SOC} = 5.148 - 17.494V_{\rho b} + 0.341V_{MAM} + 0.998V_{MAT} + 5.990V_N - 0.005V_{MAP} - 2.096V_{pH}}$	**0.505**	**6.921**	**1676**	**17.512**
	$V_{SOC} = 11.245 - 17.592V_{\rho b} + 0.312V_{MAM} + 0.918V_{MAT} + 5.916V_N - 0.004V_{MAP} - 0.240V_{pH} - 0.001V_E$	0.506	7.019	1675	17.512
20–40 cm	$V_{SOC} = 43.104 - 21.648V_{\rho b}$	0.289	7.201	2229	17.797
	$V_{SOC} = 5.268 - 22.004V_{\rho b} + 0.502V_{MAM}$	0.375	6.818	1952	17.665
	$V_{SOC} = 116.216 - 23.707V_{\rho b} - 2.806V_{pH} - 1.826V_{MAT} - 0.016V_E$	0.467	6.447	1662	17.504
	$V_{SOC} = 109.311 - 22.094V_{\rho b} - 3.244V_{pH} - 1.793V_{MAT} - 0.015V_E + 1.356V_N$	0.473	6.496	1645	17.493
	$V_{SOC} = 95.291 - 22.422V_{\rho b} - 2.964V_{pH} - 1.639V_{MAT} - 0.014V_E + 1.356V_N + 0.114V_{MAM}$	0.476	6.562	1636	17.488
	$\boldsymbol{V_{SOC} = 95148 - 22.241V_{\rho_b} - 2.955V_{pH} - 1.613V_{MAT} - 0.014V_E + 1.339V_N + 0.099V_{MAM} - 0.001V_{MAP}}$	**0.477**	**6.646**	**1634**	**17.487**
Total	$V_{SOC} = 49.281 - 24.737V_{\rho b}$	0.388	6.240	1830	17.600
	$V_{SOC} = 20.663 - 25.200V_{\rho b} + 0.381V_{MAM}$	0.445	6.001	1658	17.501
	$V_{SOC} = 51.034 - 18.527V_{\rho b} + 5.023V_N - 3.282V_{pH}$	0.469	5.941	1588	17.458
	$V_{SOC} = 64.253 - 19.471V_{\rho b} + 4.593V_N - 3.627V_{pH} - 0.007V_E$	0.493	5.868	1515	17.411
	$V_{SOC} = 83.058 - 20.878V_{\rho b} + 4.499V_N - 3.877V_{pH} - 0.009V_E - 0.817V_{MAT}$	0.517	5.994	1443	17.362
	$\boldsymbol{V_{SOC} = 70.208 - 20.933V_{\rho b} + 4.388V_N - 3.560V_{pH} - 0.007V_E - 0.675V_{MAT} + 0.095V_{MAM}}$	**0.519**	**5.850**	**1437**	**17.358**
	$V_{SOC} = 70.241 - 21.069V_{\rho b} + 4.177V_N - 3.490V_{pH} - 0.008V_E - 0.658V_{MAT} + 0.082V_{MAM} + 0.001V_{MAP}$	0.520	5.914	1434	17.756

SOC, soil organic carbon; ρ_b, average soil bulk density; pH, soil pH; N, total soil nitrogen; MAT, mean annual temperature; MAM, mean annual moisture; MAP, mean annual precipitation; E, elevation; R^2, the proportion of variation in the measured data explained by the regression equation; RMSE, root mean square error; RSS, residual sum of squares; AIC, Akaike's Information Criteria (AIC).

achieve the most satisfactory compromise between model accuracy and model parsimony, and the model with the smallest AIC was the best (Rossel and Behrens, 2010). To this end, a stepwise linear regression procedure in combination with AIC criteria was used to construct a linear regression model (Meersmans *et al.*, 2012). According to the optimal model, elevation, mean annual temperature (MAT), mean annual moisture (MAM) and mean annual precipitation (MAP) were important factors affecting the SOC in coffee system. Although there was no significant relationship between SOC concentration and climatic variables in both coffee systems, model fit quality (R^2) increased with additional parameters of climatic variables. The coefficient of determination (R^2) for the optimal models (0.48–0.52) corresponds with the predicted power obtained in other studies. Meersmans *et al.* (2012) obtained R^2 values ranging between 0.45 and 0.49 for their predictions of organic carbon for the national scale in France (Meersmans *et al.*, 2012). In the multiple linear regression model, each optimal model contained at least one climate variable. The best model at different soil layers (0–20 cm, 20–40 cm and total) explained 50.5, 47.7 and 51.9% of SOC concentration variations, respectively. This indicated that climate variable may be another important factor affecting SOC concentration in different coffee systems. However, elevation was excluded in optimal multiple linear regression at 0–20 cm depth, indicating that elevation may be a weak predictor of SOC concentration. Similarly, MAP was not in the optimal integrated model, indicating that MAP may have a low affinity for SOC concentration. Other studies have also emphasized the importance of climate variables in predicting SOC concentration. Using stepwise linear regression model, Meersmans *et al.* (2012) identified land use, climate and clay content as the three most important factors explaining the variation of SOC at the national scale (Meersmans *et al.*, 2012). The importance of climate variables for predicting SOC contents was also emphasized in the studies of Martin *et al.* (2011). Their results showed that climate variable is an important factor in explaining the variations of SOC in France (Martin *et al.*, 2011).

Many researchers have suggested farmers to develop shaded coffee plantations with commercial trees, such as rubber,

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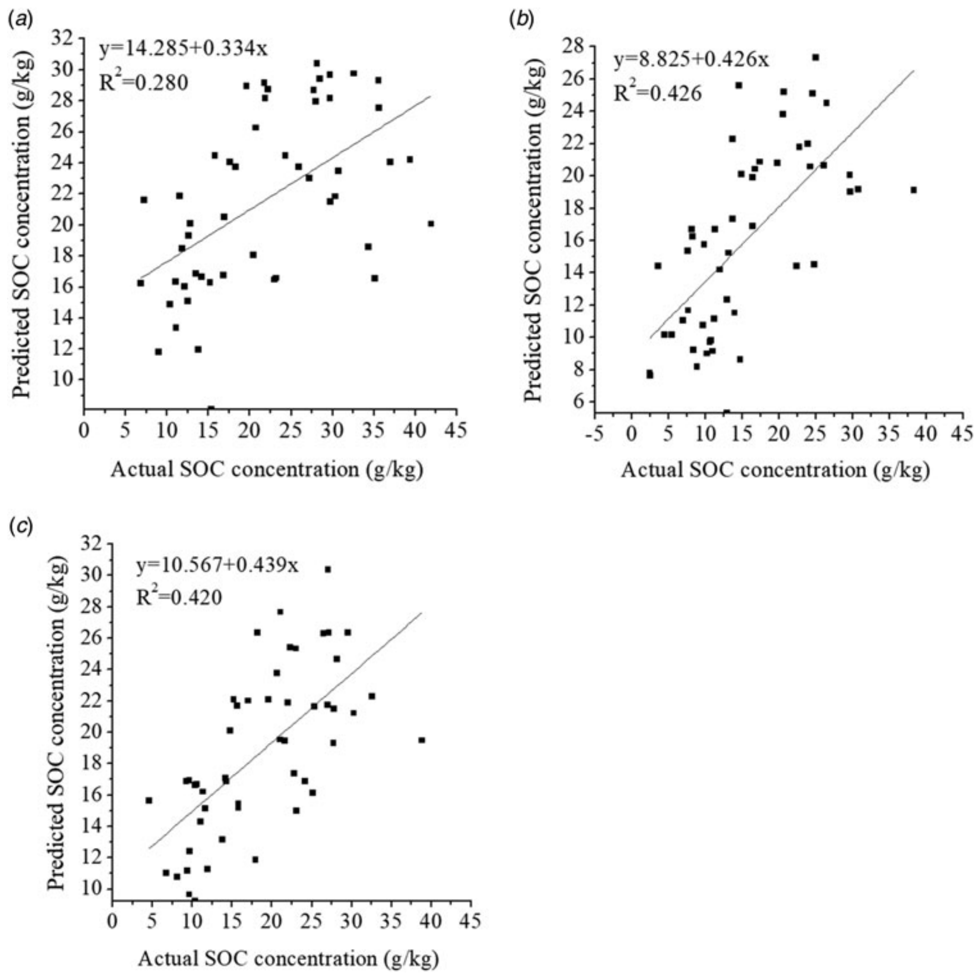

Fig. 3. The relationship between measured soil organic carbon (SOC) concentration and predicted SOC concentration at different depth soil in coffee system. (a) 0–20 cm, (b) 20–40 cm, (c) 0–40 cm.

macadamia, longan (Long et al., 1995*a*, *b*; Li *et al*., 2017). This kind of plantation mixed planting of commercial trees offered a unique opportunity to sequester atmospheric carbon, and simultaneously diversifying incomes by the sale of wood, fruit and rubber (Long et al., 1995*a*, *b*; Li *et al*., 2017). Although the SOC stocks can be increased also under monocultures of trees, polyculture accrued more SOC stocks (Nair *et al*., 2009; Beenhouwer *et al*., 2016). Therefore, it is recommended to plant a commercial polyculture system in coffee-growing regions of Yunnan. An additional pathway would be to included monoculture of coffee system in environmental service reward schemes to provide incentives to coffee farmers for maintaining high C stocks in their coffee plantations. Certification agencies such as the Rainforest Alliance (www.ra.org) are also working to certify the climate-friendly coffee plantation, in the expectation that this may facilitate access to special markets and premiums.

Conclusions

The present study demonstrates that shaded coffee system stored more SOC as compared to unshaded coffee system. This finding has implications for the selection of shaded coffee system suitable for climate change mitigation efforts. There were significant relationships between SOC concentration and soil bulk density, soil pH and soil total nitrogen (N). They are significant factors for the prediction of coffee system SOC concentration at this site. The results from stepwise multivariate regression analyses confirmed the importance of climate variable in explaining the variations of coffee plantation SOC concentration in Yunnan.

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Conflict of interest. None.

Ethical standards. Not applicable.

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