

ALTITUDINAL GRADIENTS AND FOREST EDGE EFFECT ON SOIL ORGANIC CARBON IN CHINESE FIR (*CUNNINGHAMIA LANCEOLATA*): A STUDY FROM SOUTHEASTERN CHINA

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Abstract. In forest ecosystems, soil organic matter facilitates carbon sequestration and serves as a sink for atmospheric CO₂. Carbon in forest soils plays an important role in mitigating global climate change. Soil carbon density was measured at three depths (0-20, 20-40, and 40-60 cm) in four different elevation classes sites at the forest exterior and forest interior in the sub-tropical forests of southeastern China. Results showed that soil organic carbon (SOC) varied between 46.48 and 83.12 Mg ha⁻¹ at forest exterior and 50.18 and 90.68 Mg ha⁻¹ at forest interior in different elevation classes. A significant increasing trend in soil organic carbon was found with an increase in elevation at both forest exterior and forest interior. Similarly, a positive correlation between soil organic carbon and elevation was observed at forest exterior (R² = 0.87, P = 0.0001) and forest interior (R² = 0.93, P = 0.0001). The percentages of soil carbon at 0-20, 20-40, and 40-60 cm depths at forest exterior and forest interior were 47.24-52.76, 47.23-52.77, and 46.95-53.05% respectively. Soil bulk density was directly related to soil depth and inversely related to elevation at forest exterior and forest interior. Overall the mean SOC at forest exterior and forest interior was 60.83 Mg ha⁻¹ and 68.20 Mg ha⁻¹ respectively. The study showed that there is a 5.7% difference in soil carbon density between forest exterior and forest interior which highlights the fact that ignoring edge effects may lead to overestimation of soil carbon density. Therefore, we suggest the establishment of permanent sample plots sites at the forest exterior and forest interior and recommend regular periodic surveys of soil for accurate forest soil carbon measurement.

Keywords: *forest edge effects, elevation gradients, soil carbon, soil bulk density, sub-tropical forest*

Introduction

At the global scale, the estimated amount of soil organic carbon (SOC) is about three times that of carbon which resides within vegetation and twice that of atmospheric carbon (Li et al., 2016; Smith et al., 2008). Therefore, small fluctuations in SOC pools may influence global carbon budgets and atmospheric CO₂ concentrations (Du et al., 2014; Li et al., 2016). Generally, increases in SOC mostly result from biomass carbon being transferred to the soil through decomposition (Shaheen et al., 2017). Hence, SOC is primarily balance by carbon input from vegetation production and output through decomposition (Singh et al.,

2011). These SOC production and decomposition processes are usually a measure of soil climate, disturbance and texture as well as land use, hydrology, and topography (Singh and Rawat, 2013). Moreover, altitudinal gradients and climatic variables (precipitation and temperature) could also affect the carbon pool (He et al., 2016).

The forest covers are recognized as the largest and most effective carbon sinks among terrestrial ecosystems and help to mitigate global climate change (Amir et al, 2018; Beckline et al., 2018; Dar and Somaiah, 2015; Mannan et al, 2018; Saeed et al., 2016). Among these forest ecosystems, mountain forest ecosystems have an important role in the global carbon cycle (Gower, 2003) and store about 26% of the total terrestrial ecosystem's carbon (Garten Jr and Hanson, 2006). In addition, forests at high altitudes are known to store more SOC compared to similar forests located at lower altitudes (Charan et al., 2012; Wei et al., 2013; Zhu et al., 2010).

Forest logging, including when under legal forest management, can create edge-like conditions inside the forest (Barros and Fearnside, 2016). Forest edge refers to the limit of continuous canopy or boundary in canopy composition and which is substantially different from the corresponding forest interior (Harper et al., 2005; Remy et al., 2016). Forest edges exhibit different microclimatic conditions such as light, temperature, wind, and soil moisture to the corresponding forest interior. These microclimatic differences enable the forest edges to capture relatively more atmospheric carbon than the forest interior (Remy et al., 2016). Several other studies have shown that microclimatic and edaphic conditions are generally different between forest edges and forest interior zones (Burke and Nol, 1998; Camargo and Kapos, 1995; Davies-Colley et al., 2000; Delgado et al., 2007; Didham and Lawton, 1999; Gehlhausen et al., 2000; Jose et al., 1996; Kapos, 1989; Pohlman et al., 2009; Rodrigues, 1998; Williams-Linera et al., 1998). These studies showed that edges experience faster wind speed, higher soil and air temperature, lower soil and air humidity and vapor pressure, than the interior of a forest. Although in a forest ecosystem the effects of an edge on soil carbon have been broadly studied, little literature is available regarding the edge effect on soil carbon along an altitudinal gradients, especially in China.

China has a unique soil carbon distribution due to its diverse climatic profile ranging from subtropical to alpine, and from humid to arid and desert conditions (Yang et al., 2007). In China, most of the research work has been focused on the evaluation of forest biomass carbon stored in China's forests and storage of other forests ecosystem components, such as SOC, has rarely been reported (Li et al., 2004; Yu et al., 2010). Compared to the periodic National Forest Inventory (NFI), soil surveys are less frequently conducted in the country, hence the lack of national soil carbon data (Peng et al., 2016; Yang et al., 2014). This lack of sufficient soil carbon data limits the accurate evaluation of soil carbon in China (Pan et al., 2011; Yang et al., 2007; Yu et al., 2010). However, based on soil data from field surveys and global data sets from 1980, soil carbon density in the 0-100 cm soil depth in China's forests were estimated at 115.90–193.55 Mg C ha⁻¹ (Li et al., 2004; Xianli et al., 2004; Yang et al., 2007; Yu et al., 2007), while Peng et al. (2016) have estimated 136.11–153.16 Mg C ha⁻¹. These variations in soil carbon reflect a lack of contemporary measurements of forests soil carbon. Similarly, no reliable information is available regarding the effect of edges on soil carbon in China's forest. Therefore, this study estimates SOC and bulk density along forest edges and forest interior, at different altitudes in the sub-tropical forest of China's southeast Fujian province. The results show there is a variation in soil carbon and bulk density at forest edges and forest interior at different elevations.

Materials and methods

Study area

The field surveys were conducted in the Jiangle county in China's southeastern Fujian Province, 117° 05'–117° 40'E and 26° 26'–27° 04'N. The area exhibits a humid tropical climate and the frost-free period usually spreads over 287 days. The area receives an average 1699 mm precipitation annually, while the average yearly temperature is 18.7 °C. The soil type is red, fertile, moist and loamy. The woodland cover of the forest farm is 1887 km², making-up over 83.9% of its geographical area. The main tree species are Chinese Fir (*Cunninghamia lanceolata*), Moso bamboo (*Phyllostachys pubescens*), and Masson pine (*Pinus massoniana*) with the most dominant being Chinese Fir. (Guangyi et al., 2017; Hao et al., 2015; Liping et al., 2018). The shrub layer includes species such as Chinese fringe flower (*Loropetalum chinense*), Rough pellionia (*Pellionia scabra*), Chinese sweetspire (*Itea chinensis*) and Rubus (*Rubus reflexus*) while the herb layer mostly comprises Chinese hicropteris (*Diplazium chinense*), Herba sarcandrae (*Sarcandra glabra*), Parasitic Cyclosorus (*Cyclosorus parasiticus*), and Common lophatherum (*Lophatherum gracile*).

Soil sample treatment and analysis

Field surveys were carried out between April and July 2017 in the study area to collect soil samples covering elevations gradient ranging from 40 m to 1203 m above sea level (a.s.l) (Fig. 1).

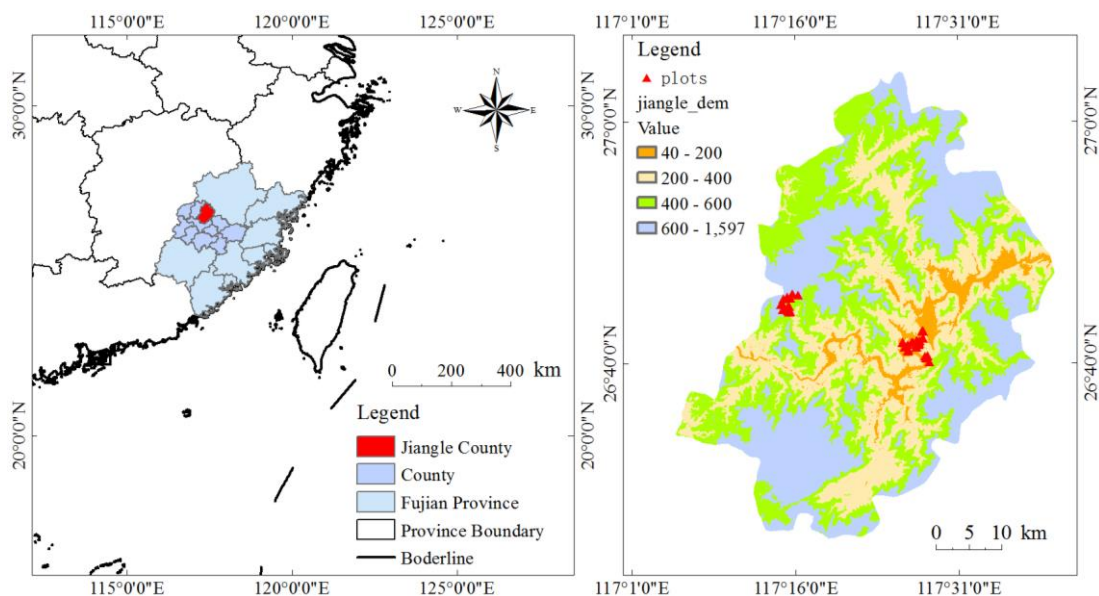


Figure 1. The map and location of the study site

The site characteristics of *Cunninghamia lanceolata* forest at different elevation are given in Table 1. The area was divided into 4 elevation classes (EC) and the elevation difference of each class was 200 m (a.s.l). In each EC, 4 sample plots were taken at forest edges and 4 at forest interior. The forest interior plots were laid out at 60 m distance from the forest edges. The sizes of sample plots ranged between 400 and 600 m². The soil samples were collected from three sub plots of (1 × 1 m) within each

plot of 400 to 600 m² at varying depths. The samples were collected at three depth increments in the center of the subplot (that is, of 0-20, 20-40 and 40-60 cm, respectively). The soil samples were collected using a soil auger (Soil auger, Shangyu Hongguanf instrument and Equipment Co., Ltd., China) and soil core of an identified volume of 100 cm³.

Table 1. Characteristics of the *Cunninghamia lanceolata* forest at different elevation classes in Jiangle County, Fujian Province. Different super scripts in each column represent significant difference ($n = 8, p \leq 0.0001, \text{Alpha} = 0.05$. TTB = total tree biomass)

Classes	Diameter range (cm)	Stem density (Mg ha ⁻¹)	Basal area (m ² ha ⁻¹)	TTB (Mg ha ⁻¹)
1	4-44	1683.33±249.76 ^a	40.09±11.17 ^d	180.94±68.18 ^d
2	4-38	1716.67±232.99 ^a	64.83±12.57 ^c	319.77±80.62 ^c
3	6-42	1447.92±239.78 ^b	94.58±15.39 ^b	511.43±108.73 ^b
4	8-50	1289.58±265.61 ^b	127.69±5.86 ^a	732.13±55.15 ^a
Mean	27	1534.38±294.88	81.80±35.13	436.07±224.16

The collected samples were weighed and packed in labeled bags. Then the samples were transferred to the Southern Forest, Experimental Base of Beijing Forestry University Sanming Jiangle for further analysis. The samples were first air-dried (Shel Lab Gravity Convection Laboratory Oven SGO3) and then the soil bulk density (g cm⁻³) was measured for each soil sample. These air-dried samples were manually ground with a pestle and passed through a 0.50 mm sieve for the determination of SOC as described by (Lu, 1999).

Analysis of soil carbon

To find out the soil carbon of each collected soil sample, the sub samples (1 g) were taken from the labeled sample and analyzed in the laboratory using the oxidizable organic carbon method of (Walkley and Black, 1934). A measure of the soil carbon in Mg ha⁻¹ was obtained by calculating the soil bulk density of each sample according to Equation 1.

$$BD = MS (g)/VC (cm^3) \quad (\text{Eq.1})$$

where BD = Soil bulk density (g cm⁻³), MS = Weight of the soil sample (g) and VC = Volume of the core (cm³)

The soil organic carbon (Mg ha⁻¹) was calculated from the relationship of the soil bulk density, soil organic carbon and depth increment using Equation 2 (Ahmad and Nizami, 2015; Pearson et al., 2007).

$$\text{Soil Carbon (Mg ha}^{-1}\text{)} = BD (g \text{ cm}^{-3}\text{)} \times SOC (\%) \times TH (cm) \times 100 \quad (\text{Eq.2})$$

where TH = Thickness of horizon (cm)

The difference between the soil carbon at the forest interior and forest edges was obtained using Equation 3.

$$SCD = SC (in) - SC (ex) \quad (\text{Eq.3})$$

where SCD = Soil carbon difference (Mg ha^{-1}), SC (in) = Soil carbon at forest interior (Mg ha^{-1}), SC (ex) = Soil carbon at forest exterior (Mg ha^{-1}).

Statistical analysis

MS Excel for Windows 10 was used to analyze soil carbon data. The relationship between SOC and elevation at the forest exterior and forest interior was examined with linear regression (Sigma Plot version 12.5). Similarly, the relationship of soil carbon and bulk density with respect to soil depth was also studied using linear regression (Sigma Plot version 12.5). To test the differences in soil carbon and bulk density at various depths (0–20, 20–40, 40–60), an Analysis of Variance (ANOVA) and Least significant difference (LSD) were performed on the data from forest edges and forest interior. The differences were considered statistically significant at $P < 0.05$. Statistix version 8.1 (Analytical Software, 2005) was used for these analyses. Sigma Plot version 12.5 was used to analyze the relationship between bulk density and elevation at forest exterior and forest interior at various depths.

Results

Soil organic carbon density

The mean soil carbon density up to 0-60 cm depth at the forest exterior and forest interior was 60.83 Mg ha^{-1} and 68.20 Mg ha^{-1} respectively. SOC density increased significantly ($P < 0.05$) with increasing elevation (Fig. 2) and decreased with increasing soil depth in all the EC at both the forest exterior and forest interior. The mean SOC at forest edges and forest interior at 0-20 cm depth was 21.41 and 23.91 Mg ha^{-1} . Similarly, at 20-40 cm and 40-60 cm soil depths the mean SOC at forest exterior and forest interior were 20.24 , 22.61 , and 19.18 , 21.67 Mg ha^{-1} respectively Table 2.

Table 2. Soil organic carbon in different depths at forest exterior and forest interior in Jiangle County, Fujian Province. Different super scripts in each column represent significant difference ($n = 8$, $p \leq 0.0001$, Alpha = 0.05)

Forest exterior (SOC Mg ha^{-1})			
Classes	Depth 1 (0-20 cm)	Depth 2 (20-40 cm)	Depth 3 (40-60 cm)
1	$16.21 \pm 0.20^{\text{no}}$	$15.50 \pm 0.29^{\text{op}}$	$14.77 \pm 0.38^{\text{p}}$
2	$18.42 \pm 0.89^{\text{ijkl}}$	$17.72 \pm 0.70^{\text{klm}}$	$16.84 \pm 0.70^{\text{mn}}$
3	$21.76 \pm 1.11^{\text{g}}$	$20.06 \pm 1.38^{\text{hi}}$	$18.92 \pm 1.43^{\text{ijk}}$
4	$29.25 \pm 1.49^{\text{b}}$	$27.68 \pm 1.68^{\text{c}}$	$26.20 \pm 2.03^{\text{d}}$
Mean	$21.41 \pm 5.70^{\text{e}}$	$20.24 \pm 5.30^{\text{d}}$	$19.18 \pm 4.97^{\text{e}}$
Forest interior (SOC Mg ha^{-1})			
1	$17.65 \pm 0.71^{\text{lm}}$	$16.55 \pm 0.63^{\text{mno}}$	$15.98 \pm 0.59^{\text{nop}}$
2	$20.22 \pm 0.77^{\text{h}}$	$19.27 \pm 0.79^{\text{hij}}$	$18.40 \pm 0.78^{\text{ikl}}$
3	$26.47 \pm 2.28^{\text{cd}}$	$24.45 \pm 2.52^{\text{e}}$	$23.11 \pm 2.25^{\text{f}}$
4	$31.31 \pm 0.31^{\text{a}}$	$30.18 \pm 0.40^{\text{ab}}$	$29.20 \pm 0.63^{\text{b}}$
Mean	$23.91 \pm 6.17^{\text{a}}$	$22.61 \pm 6.01^{\text{b}}$	$21.67 \pm 5.83^{\text{c}}$

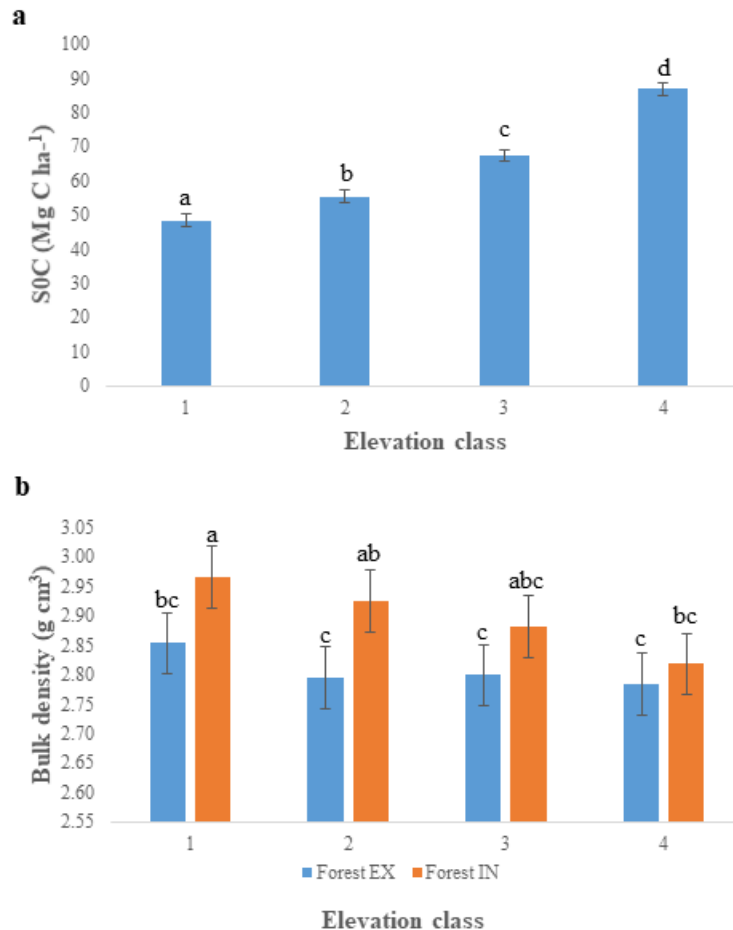


Figure 2. (a) Soil organic carbon in different elevation classes, $p \leq 0.0001$, Alpha = 0.05 (letter on the bars shows significant differences between the soil carbon density across the elevation classes) and (b) Soil bulk density (g/cm^3) in different elevation classes at forest exterior and forest interior, $p \leq 0.0001$, Alpha = 0.05 (letter on the bars shows significant differences between the soil bulk density along the elevation classes at forest exterior and forest interior)

The percentages of soil carbon density at 0-20, 20-40, and 40-60 cm depths at forest exterior and forest interior were 47.24-52.76, 47.23-52.77, and 46.95-53.05% respectively. The highest percentage of soil carbon (34.2%) was observed at 0-20 cm depth in EC 4 at the forest exterior, whereas the lowest (18.5%) was observed in EC 1 at the forest interior. At a depth of 20-40 cm, the highest percentage (34.2%) of soil carbon was observed in EC 4 at the forest exterior, while the lowest (18.3%) was observed in EC 1 at the forest interior. Similarly, at 40-60 cm, the highest soil carbon was in EC 4 (34.1%) at the forest exterior whereas the lowest soil carbon was observed in EC 1 (18.4%) at the forest interior. The correlation analysis highlighted a very positive correlation between elevation between SOC and elevation at the forest exterior ($R^2 = 0.87$, $P = 0.0001$) and forest interior ($R^2 = 0.93$, $P = 0.0001$).

Soil bulk density

The soil bulk densities (BD) at different ECs at forest exterior and forest interior are given in *Figure 2b*. Soil bulk density among the ECs at forest exterior ranged between $2.78 \text{ g}/\text{cm}^3$ at EC 4 to $2.85 \text{ g}/\text{cm}^3$ at EC 1. The mean soil bulk density at forest exterior

was 2.81 g/cm³. The estimated soil BD at the forest interior ranged from 2.82 g/cm³ at EC 4 to 2.96 g/cm³ at EC 1, while the mean soil bulk density at the forest interior was 2.90 g/cm³. The bulk density showed a significant increase ($P < 0.05$) with an increasing in soil depth in all ECs at both the forest exterior and forest interior. Soil bulk density showed significant variation at different depths across all the ECs at forest exterior and forest interior (Fig. 3b). The elevation and soil bulk density were highly negative correlation for different depths. Soil carbon was inversely related to soil bulk density; as soil carbon experienced a decrease with an increase in soil bulk density and vice versa in all ECs at both the forest exterior and forest interior. Similarly, a decreasing trend was observed in the soil bulk density with an increase in elevation.

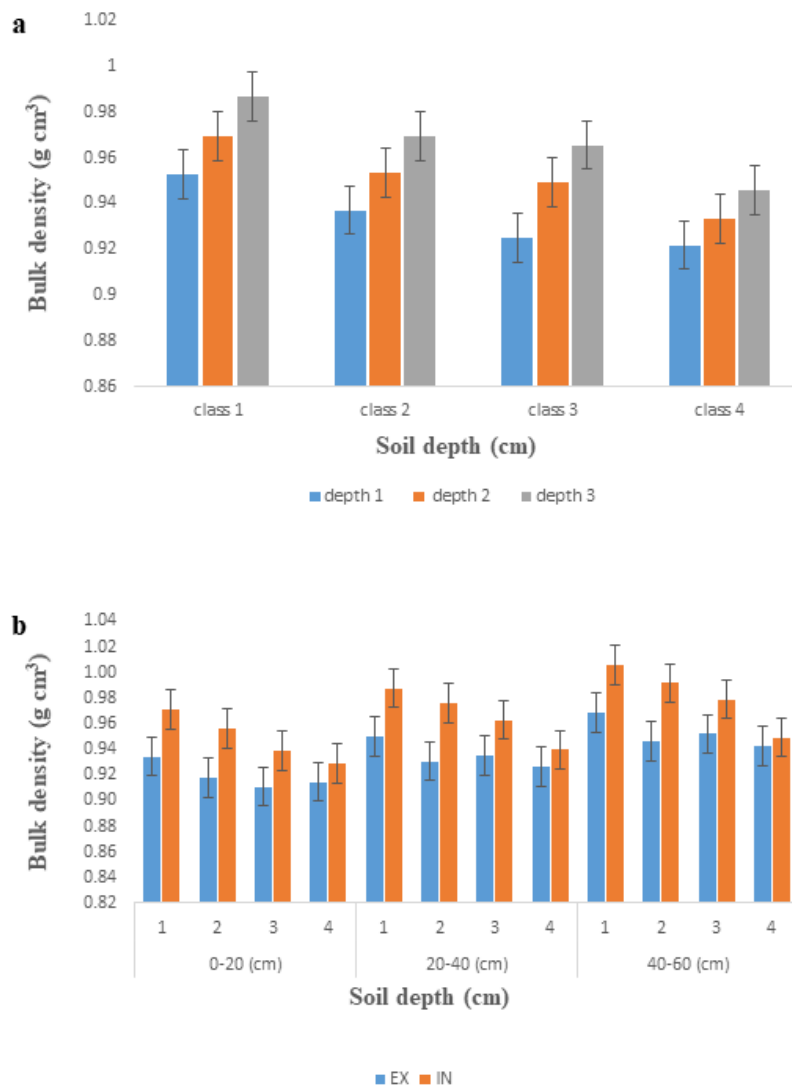


Figure 3. (a) Soil bulk density (g/cm³) in different elevation classes at various depths, $p \leq 0.0001$, Alpha = 0.05 and (b) Soil bulk density (g/cm³) in different depths at forest exterior and forest interior, $p \leq 0.0001$, Alpha = 0.05

Overall the results showed that there are significant ($P < 0.05$) differences in soil carbon in all the EC (Fig. 2). The highest percentage of soil carbon was in EC 4 (33.7%) whereas lowest was in EC 1 (18.7%). Similarly, the percentage of soil carbon

at forest exterior and forest interior in EC 1 was (19.1-18.4%), EC 2 (21.8-21.2%), EC 3 (25-27.1%), and EC 4 (34.2-33.2%), respectively.

Discussion

The present study investigated the variations in the SOC and bulk density at the forest exterior and forest interior across different EC in the Jiangle county of southeastern China. Soil carbon increased with increasing elevation at both forest exterior and forest interior and more SOC was found at the forest interior when compared to the forest exterior. Soil carbon increased with an increase in precipitation and decreased with increasing in temperature (Jobbágy and Jackson, 2000). A significant positive relationship between soil carbon and elevation was observed at both forest exterior ($R^2 = 0.87$, $P = 0.0001$) and forest interior ($R^2 = 0.93$, $P = 0.0001$; Fig. 4).

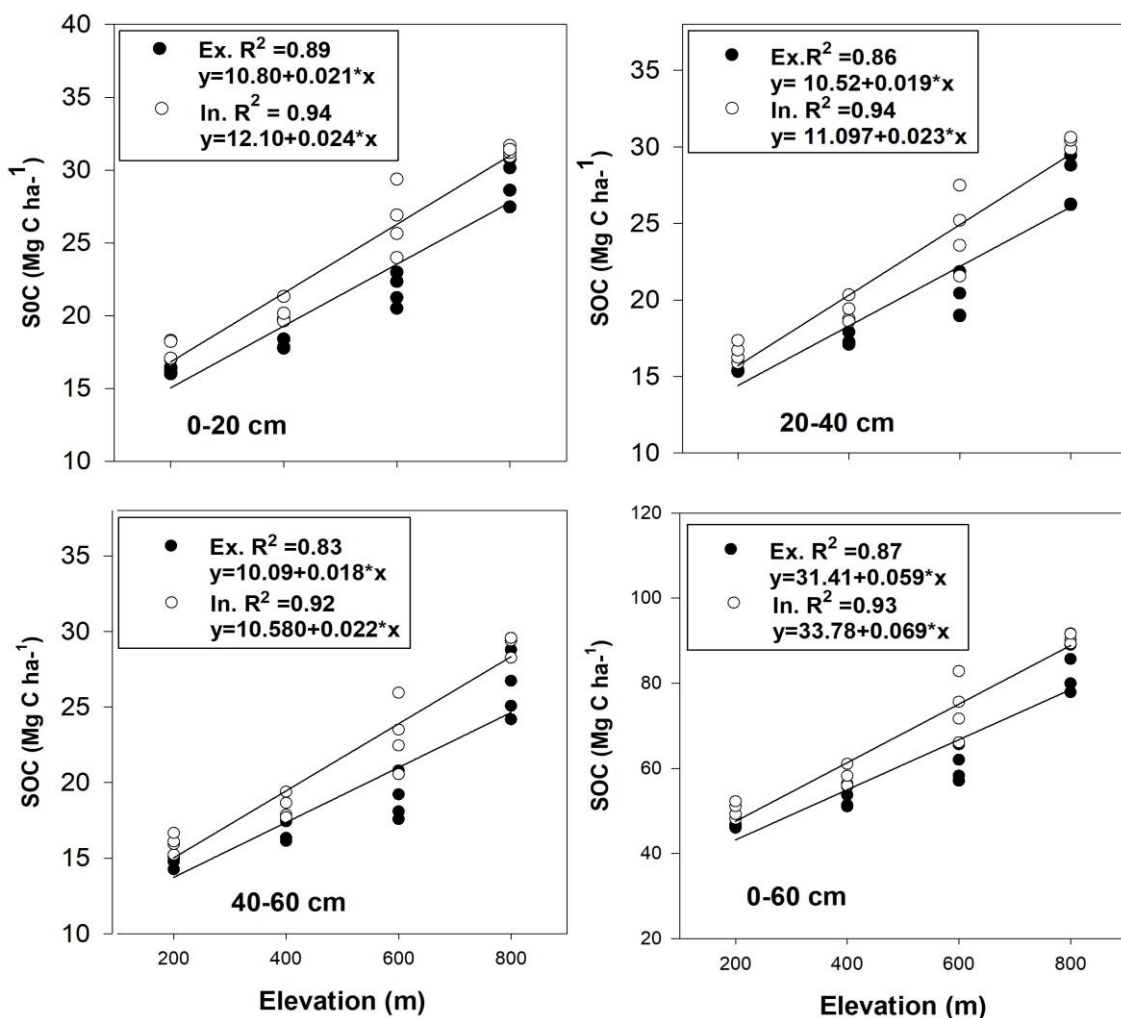


Figure 4. Relationship between elevation and soil organic carbon at forest exterior (Ex) and forest interior (In)

These disparities may be due to the lower temperatures and higher rates of precipitation found at higher elevation. According to Jobbágy and Jackson (2000), Yang et al. (2007)

and Zhu et al. (2010) these differences are due to the distribution of shallower root systems along hilly ecosystems (Jobbágy and Jackson, 2000; Yang et al., 2007; Zhu et al., 2010). Previous research has also reported an increasing trend of soil carbon density with an increase in elevation (Charan et al., 2012; Gupta and Sharma, 2013; Wei et al., 2013; Zhang et al., 2011; Zhu et al., 2010). There was less soil carbon at lower elevations than at higher elevations at both forest exterior and forest interior (*Fig. 4* and *Table 2*). Hence, soils at lower elevations hold significantly lower carbon when compared to soils at higher elevations at both the forest exterior and forest interior. This lower carbon may be attributed to the occurrence of less detritus on the forest floor due to an increase in tree diameter along the elevation gradient. An increase in tree diameter also increases competition among tree species. As a result, there is an increase in the natural shedding of lower branches, hence more deadwood material is present on the forest floor, and consequently more carbon (Charan et al., 2012; Gupta and Sharma, 2013; Wei et al., 2013; Zhang et al., 2011). Furthermore, our results pointed to an overall difference of 5.7% in soil carbon at the forest exterior and forest interior. In comparison, these findings are not consistent with previous findings (Remy et al., 2016), which showed more soil carbon at forest edges as compared to forest interior. However, some of the findings revealed a slight non-significant increase in carbon at forest edges compared to the interior (Barros and Fearnside, 2016). This variation and discrepancy in soil carbon could also be attributed to disturbance and edge-related factors arising from the combined effects of natural and human actions such as winds, floods, farming, roads, streams, and logging (Chaplin-Kramer et al., 2015). In the study area, potentially influential edge related factors include the presence of farmlands, roads, streams, canopy gaps and logging operations. These edge-related factors reduce the soil carbon mainly through soil compaction and soil erosion due to heavy rains and flooding.

A decrease was observed in SOC density with an increase in soil depth in all the ECs at both forest exterior and forest interior *Table 2*. Similar findings were reported by Jobbágy and Jackson (2000) and Dar and Somaiah (2015). This decreasing trend of soil carbon with increasing soil depth may be due to slower soil carbon cycling soil carbon at increased depths and compaction (Dar and Somaiah, 2015; Paul et al., 1997; Trumbore, 2000).

Soil bulk density

In this study we observed a decrease in the soil bulk density with the increasing in elevation at both the forest exterior and forest interior. A negative correlation was observed between soil bulk density at 0-60 cm depth and elevation at forest exterior ($R^2 = 0.10$, $P = 0.0001$) and forest interior ($R^2 = 0.42$, $P = 0.0001$) in all the ECs (*Fig. 5*). Dar and Somaiah (2015) and Sharma et al. (2010) have also reported the similar relationship between elevation and soil bulk density. The soil organic matter and soil bulk density were inversely proportional. The lower bulk density in soil indicates a higher degree of soil organic matter, good granulation, aeration and higher infiltration (Dar and Somaiah, 2015). Our results also endorse the above explanation.

The present study also indicates that the higher soil bulk density results in lower soil carbon at lower elevation than at higher elevation at both forest exterior and forest interior. In this study, soil bulk density showed an increase with an increased in soil depth in all EC at both the forest exterior and forest interior. This may be due to higher bulk density at greater soil depths in the forest floor, as well as with mixing of minerals in the soil (Schulp et al., 2008).

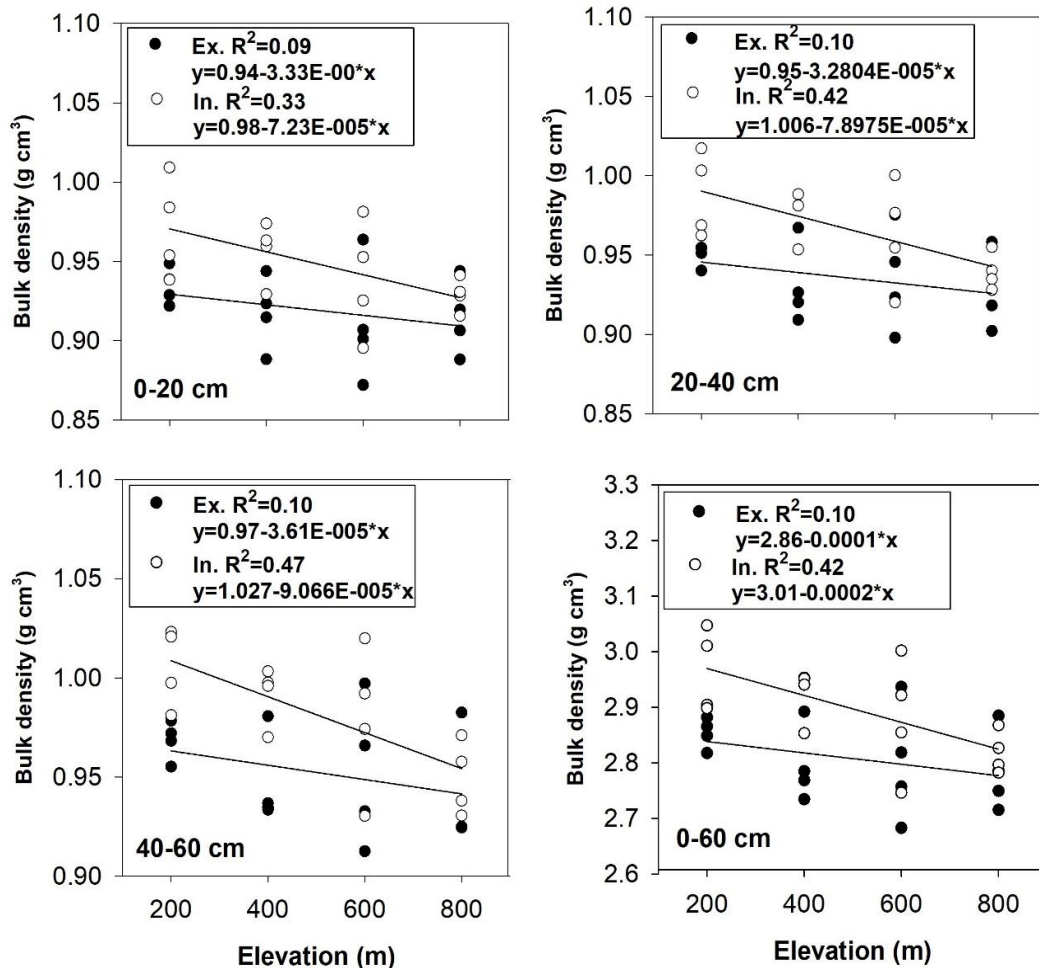


Figure 5. Relationship between soil bulk density and elevation at forest exterior (Ex) and forest interior (In)

Conclusion

Soil carbon density increased significantly with increasing elevation and decreased with increasing soil depth at both forest exterior and forest interior. Forest soil carbon assessment is critical for policy makers when modeling climate scenarios. However, evidence shows that ignoring edge effects may not account for forest soil carbon precisely. Our results showed that the forest interior stored more soil carbon than the forest edge. The magnitude of the edge effect means that ignoring edge effects overestimates carbon stock by 5.7%. These outcomes suggest that edge effects should be given proper consideration during soil carbon accounting.

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