Article

Variation in soil organic carbon stocks in three tropical dry deciduous forests of Madhya Pradesh, India

Debojyoti Raha[1], **Javid Ahmad Dar**[1,2], **Subashree Kothandaraman**[1], **Mohammed Latif Khan**[1]
[1]Forest Ecology and Ecosystems Laboratory, Department of Botany, Dr. Harisingh Gour Vishwavidyalaya (A Central University), Sagar, Madhya Pradesh, 470003 India
[2]Department of Environmental Science, School of Engineering and Applied Sciences, SRM University, Andhra Pradesh, 522502 India
E-mail: khanml61@gmail.com, javidahmad.d@srmap.edu.in

Received 14 October 2021; Accepted 20 November 2021; Published 1 March 2022

Abstract

Assessment of soil organic carbon (SOC) dynamics in tropical dry deciduous forests is imperative to know their contribution in regulating the regional and global carbon (C) cycles. In the present study, three forest types: dry deciduous teak (DDTF), dry deciduous mixed (DDMF) and *Boswellia* (BF) forests were selected to assess the variation in SOC and the factors influencing it. The SOC stocks (0-50 cm) varied significantly within and among the forest types and ranged from 48.7 (BF) to 89.1 (DDTF) Mg C/ha (mean: 64.6 ± 9.7 Mg C/ha). The differences observed could be due to variations in organic matter input, quality and quantity of litter produced, topography, vegetation composition, soil bulk density, soil moisture and soil depth. The total mean SOC stocks at 0-10, 10.1-30 and 30.1-50 cm depths were 19.2, 24.4 and 21.0 Mg C/ha, respectively. The SOC showed significant positive relationships with soil organic matter ($r = 0.79$, $P < 0.01$), soil moisture ($r = 0.41$, $P < 0.01$), aspect ($r = 0.52$, $P < 0.01$) and dominance ($r = 0.53$, $P < 0.01$), which accounted for 66.8, 15.7, 8.4 and 5.6% of variance. This study provided an understanding of the SOC stock variation among three tropical dry deciduous forest types in the Central Indian landscape and identified the roles of different drivers in SOC storage.

Keywords soil carbon; driving factors; topography; moisture; tropical dry deciduous forests; Central India.

Proceedings of the International Academy of Ecology and Environmental Sciences
ISSN 2220-8860
URL: http://www.iaees.org/publications/journals/piaees/online-version.asp
RSS: http://www.iaees.org/publications/journals/piaees/rss.xml
E-mail: piaees@iaees.org
Editor-in-Chief: WenJun Zhang
Publisher: International Academy of Ecology and Environmental Sciences

1 Introduction

Assessment of the dynamics of soil organic carbon (SOC) stocks in tropical dry forest ecosystems is essential to understand their contribution in regional and global carbon (C) cycles. In tropical forests, SOC pool is a large terrestrial C reservoir (Lal, 2004a; Piao et al., 2009). It represents the balance between C inputs and C outputs and is a continuum of intact plant parts to highly oxidized forms of C (Araujo et al., 2017). The present estimated C stock in the world's forests is 861 ± 66 Pg C, of which 383 ± 30 Pg C (44%) is stored in soil to a depth of 1 metre, with the highest contribution from tropical forest soils (~32%; Jobbágy and Jackson, 2000; Pan et al., 2011). An advantage of forest soils than those in other land uses is the constant availability of litter that would enrich the SOC stock (Debasish-Saha et al., 2014). As SOC has the potential to store twice the collective amount of C contained in the atmosphere and biosphere, loss of C from soils can have a significant impact on atmospheric carbon dioxide (CO_2) levels, and thereby on climate (Lal et al., 2007; Singh et al., 2011). The potential of a forest to sequester and store SOC is dependent largely on the tree species composition and community structure as well as their interactions with microclimate and other soil characteristics (Osei et al., 2021). It is therefore important to estimate the variation and distribution of SOC stocks in different vegetation types to understand their role in the regional and global C sequestration.

Soil organic carbon is the vital constituent of the global C sequestration (Doetterl et al., 2016; Gandhi and Sundarapandian, 2017), which determines the soil quality and productivity (Krishan et al., 2009). The SOC sequestration is a highly advisable mitigation option that is synergistic with climate change adaptation, contributing to water and food security (Lal, 2004b; Lal et al., 2007). In soils up to 100 cm, nearly 50% of SOC is locked in top 30 cm (Batjes, 1996). The estimated SOC values at 30 cm soil depth on a global level are 699 Pg C and 1417 Pg C at a depth of 1 m as per Food and Agricultural Organization (FAO, 2009; Hiederer and Kochy, 2012). Vegetation characteristics, soil characteristics, terrain features and climate are the principal factors governing SOC sequestration (Lal, 2021). Different factors drive the SOC stocks of top soil in forest ecosystems such as forest type, soil, litter input, topography, climate, elevation, soil fertility, disturbance regime, invasion and fire regime (Aragao and Shimabukuro, 2010; Dieleman et al., 2013; Dar et al., 2015; Sundarapandian et al., 2016; Dar et al., 2019; Lone et al., 2019). Litter chemistry and litter C quality has a great impact on litter decomposition, which in turn have a pronounced effect on nutrient cycling and SOC sequestration (Berg, 2014; Wang et al., 2021). Soil characteristics (like soil pH, soil temperature, soil moisture, etc.) are affected by climate, which in turn have an effect on SOC stocks (Zhang et al., 2017; Tong et al., 2021).

Tropical dry forests comprise almost half of the world's tropical and subtropical ecosystems. They experience a dry period of 5-8 months, rains in summer and annual rainfall of 500 to 1500 mm, and are the most threatened and least studied forest types (Murphy and Lugo, 1986; Janzen, 1988; Blackie et al., 2014). Most of the studies have focussed only on the aboveground biomass stocks in tropical dry forests (Salunkhe et al., 2018). However, the information on SOC storage and dynamics is required for better understanding of C stocks and cycling in these forests, and to support regulatory frameworks such as the United Nations Reducing Emissions from Deforestation and Forest Degradation (REDD+) programme in developing countries.

The SOC stock assessment in tropical forest ecosystems is a key strategy to mitigate the climate warming, through C sequestration and management programmes. Although several studies on SOC stocks of tropical forests have been reported, there is a paucity of SOC stock estimates at forest-type level from tropical dry deciduous forests of India. In the present scenario, the SOC stocking potential of different forest types in Central India is essential to understand their contribution to the regional and global soil C stocks. Hence, the present study has been undertaken (i) to assess the SOC storage in three tropical dry deciduous forest types of Sagar, Madhya Pradesh, and (ii) to analyze the relationships between SOC stocks and different factors.

2 Materials and Methods

2.1 Study area

The present study was undertaken in three tropical dry deciduous forest types viz., dry deciduous teak forest (DDTF, Site I), dry deciduous mixed forest (DDMF, Site II) and *Boswellia* forest (BF, Site III) in Sagar, Madhya Pradesh (Table 1, Fig. 1) which are a part of lower Vindhyan range of Central India, and is situated at an average height of 420 m a.s.l. The area has a hot dry summer from April to June, followed by a monsoon season from July to September and a cool and relatively dry winter from October to March. The area receives an annual average rainfall of 1187.6 mm of which the rainy months contribute approximately 90%. The mean annual minimum and maximum temperatures vary between 10°C (January) and 42.7°C (May) respectively (WorldClim, 2020). As per Champion and Seth's Classification (Champion and Seth, 1968), the forest in the area belongs to group 4b. Vegetation and soil sampling were done in three forest ranges of Sagar district, viz. Shahgarh, Nanakpur and Heerapur by laying 14 plots of 60 m × 20 m in each study site/forest type following standard methods (Misra, 1968). In each plot, the diameter of all the tree individuals (≥ 10 cm diameter at breast height of 1.37 m (DBH)) were recorded. The predominant tree species in the study sites of the three different forest types are *Tectona grandis*, *Butea monosperma* and *Lagerstroemia parviflora* in DDTF, *Tectona grandis*, *Terminalia tomentosa* and *Lagerstroemia parviflora* in DDMF, and *Boswellia serrata*, *Tectona grandis* and *Lagerstroemia parviflora* in BF. A total of 25 tree species (24 genera, 14 families) were recorded from the above-said three forest types. Diversity indices (Shannon's diversity and Simpson's dominance) were calculated using PAleontological STatistics software (PAST; Hammer et al. 2001; Natural History Museum, University of Oslo).

Table 1 Study site characteristics of the three different forest types (DDTF - dry deciduous teak forest, DDMF - dry deciduous mixed forest and BF - *Boswellia* forest) of Sagar, Madhya Pradesh.

Parameter	**Forest type**		
	DDTF	**DDMF**	**BF**
Latitude (^{o})	24.212-24.226	24.130-24.241	24.240-24.243
Longitude (^{o})	79.111-79.113	79.144-79.145	79.121-79.133
Altitude (m a.s.l.)	401.6	371.8	486.2
Slope (°)	0.26-1.25	0.27-0.84	0.40-1.06
Aspect (°)	262.2-354.3	105.3-187.3	213.8-245.7
No. of plots	14	14	14
Species richness	14	23	15
Genera	14	22	15
Families	9	13	10
Shannon's index (H)	1.14	2.08	1.76
Dominance index (D)	0.46	0.19	0.27
Evenness index	0.22	0.34	0.39
Total tree density	8192	12032	7272
Density (No./ha)	585.1 ± 35.7	859.4 ± 93.1	519.4 ± 35.9
Total tree basal area	287.9	287.1	413.3
Basal area (m^2/ha)	20.6 ± 1.7	20.5 ± 1.4	29.5 ± 1.6
Maximum tree DBH (cm)	60.8	54.1	62.9
Mean tree DBH (cm)	18.9	15.7	24.3

DBH: Diameter at breast height.

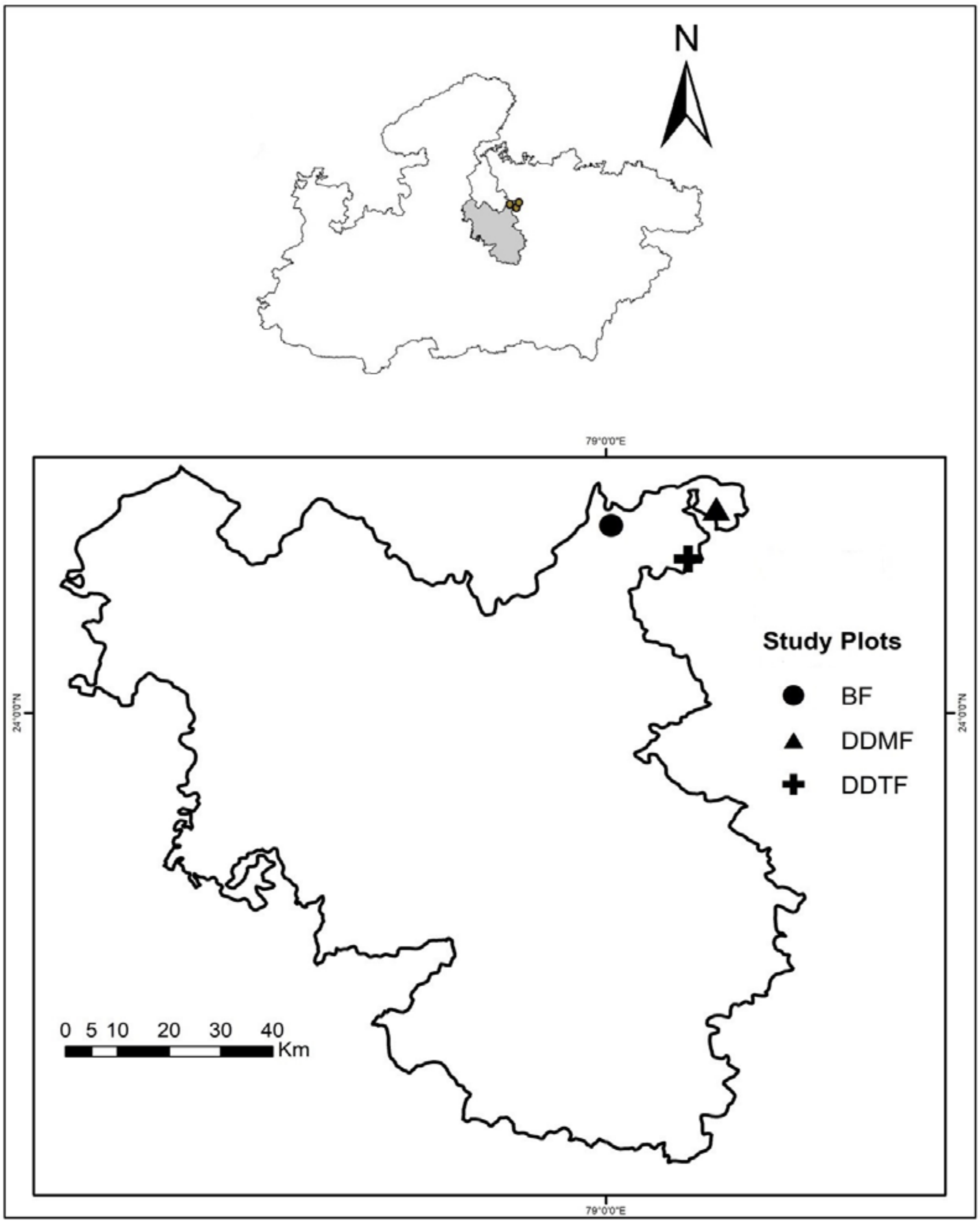

Fig. 1 Location of the study sites in Sagar, Madhya Pradesh.

2.2 Soil sampling and analysis

In the present study, three composite soil samples were collected from each plot at three depths (0-10, 10.1-30 and 30.1-50 cm) with the help of a metallic cylinder of diameter 5 cm. Soil samples were packed in situ in polyethylene bags and brought to the laboratory for further processing. The composite soil samples were air-dried and sieved through a 2 mm stainless steel sieve, and ground using a mortar and pestle. For SOC estimation, Walkley and Black's method (Walkley and Black, 1934) was used, which is a widely used procedure (Pearson et al., 2005). The percent (%) soil organic matter (SOM) was calculated by using the following formula:

$$\%OM = \frac{\text{SOC\%} \times 1.72}{0.58}$$

Another three sets of undisturbed soil samples were collected from each plot at 0-10, 10.1-30 and 30.1-50 cm depths for the measurement of bulk density. Proper care was taken while removing these cores to prevent any soil loss from sampling. The samples were oven-dried at 105 ± 5°C for 72 hours and then weighed. The coarse fragments were separated by a stainless steel mesh sieve and the samples were then re-weighed. Soil bulk density and SOC stocks (Mg C/ha) were then calculated by following Pearson et al. (2005):

$$\text{Bulk density } (g/m^3) = \frac{\text{Oven dry mass } (g/m^3)}{\text{Core volume } (m^3) - (\text{Mass of coarse fragments } (g) \,/\, 2.65\ (g/cm^3)}$$

where 2.65 was taken as a constant for the density of rock fragments (g/cm^3).

The total C content of 0-50 cm soil depth was estimated by summing up the C content of the three layers (0-10 cm + 10.1-30 cm + 30.1-50 cm). The total SOC was calculated by following the formula of Pearson et al. (2005):

$$\text{SOC (Mg C/ha)} = [(\text{soil bulk density } (g/m^3) \times \text{soil depth (cm)} \times C)] \times 100$$

Soil moisture (%) was measured at three different depths (0–10, 10.1–30, and 30.1–50 cm) by the gravimetric method. Soil pH (1:2.5 ratio of soil:water) was measured with a dynamic digital pH meter.

2.3 Forest floor litter sampling

Forest floor litter was collected during March and April 2019 from five 1 m × 1 m sub-quadrats in each plot. Samples were oven-dried at 65°C for 48 hours to a constant mass and weighed. The dry weight was used for the estimation of C concentration as per Coleman (1973):

$$\text{Forest floor litter carbon C} = (\text{Dry weight of litter}) \times 0.45$$

2.4 Statistical analyses

All statistical analyses were computed using Statistical Package for the Social Sciences (SPSS 20.0; Chicago, IL). Pearson correlation (*r*) and Analysis of Variance (ANOVA) were performed to test for significance ($P \leq 0.05$) in SOC stocks, C%, bulk density and litter (top floor) of different forest types. Principal Component Analysis (PCA) was done using PAST 3.1 to identify which of the factors (environmental variables: soil moisture, aspect; diversity attributes: species richness, Shannon's diversity index, Simpson's dominance index, species dominance; structural attribute: SOM) mainly account for variation in SOC.

3 Results

3.1 Soil organic carbon (SOC) stock

The SOC stock varied significantly among and within the three different study sites (Fig. 2a). The SOC stock (0-50 cm) ranged from 48.68 (BF) to 89.12 (DDTF) Mg C/ha among the three study sites of Sagar, Madhya Pradesh, with a mean of 64.68 Mg C/ha. Among all the study sites, SOC stocks were highest in the surface layer (0-10 cm) and decreased with increasing depth. The SOC stock ranged from 13.16 (BF) to 28.85 (DDTF), 18.06 (DDMF) to 33.6 (DDTF) and 14.28 (BF) to 27.91 (DDTF) Mg C/ha at 0-10, 10.1-30 and 30.1-50 cm depths respectively. On an average, SOC (%) at 0-10, 10.1-30 and 30.1-50 cm depths were 29.7, 37.7 and 32.6% respectively (Fig. 2b). In total, SOC stock (0-50 cm) were significantly (*F-value* = 22.26; $P < 0.0001$) highest in DDTF, compared with the other two study sites.

The lowest percentage (%) of SOC and SOM values were observed in BF (SOC 0.81%, SOM 2.4%), whereas the highest values were obtained in DDTF (SOC – 1.6%, SOM – 4.75%). The SOC% decreased significantly (*F-value* = 222.14; $P < 0.0001$) with increase in soil depth. The range of SOC% in the three different depths were 1.44 (BF) to 2.11 (DDTF) at 0-10 cm, 0.85 (BF) to 1.13 (DDTF) at 10.1-30 cm and 0.67 (BF) to 0.85 (DDTF) at 30.1-50 cm (Fig. 2b). The mean SOC% in the three depths were 1.76%, 0.95% and

0.74% at 0-10, 10.1-30 and 30.1-50 cm respectively (Fig. 2c). The mean SOM% in the three depths were 5.22%, 2.81% and 2.19% at 0-10, 10.1-30, and 30.1-50 cm (Fig. 2d).

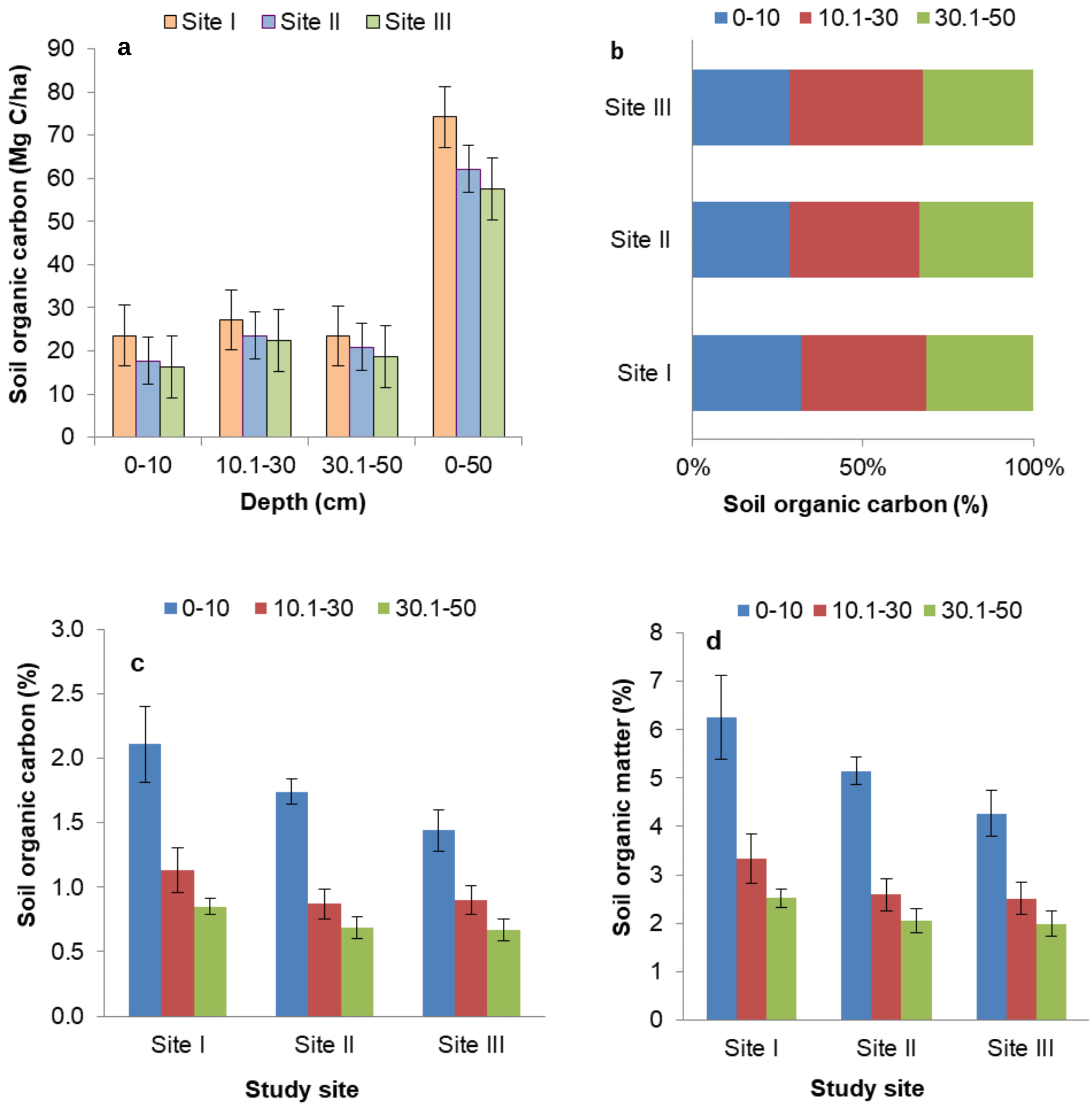

Fig. 2 (a) Soil organic carbon stocks (SOC; Mg C/ha), (b) relative SOC percentage at the three depths, (c) SOC (%), (d) soil organic matter (%) in the three selected study sites (Site I: DDTF; Site II: DDMF; Site III: BF).

3.2 Soil properties and standing crop litter

The soil bulk density (0-50 cm) ranged from 1.14 (BF) to 1.53 (DDMF) g/cm^3. The soil bulk density increased significantly with increase in soil depth (*F-value* = 79.7; $P < 0.0001$) in all the three study sites (Fig. 3a). The bulk density varied significantly (*F-value* = 4.58; $P < 0.01$) across all the study sites. Among the three study sites, the highest value of mean soil bulk density was observed in DDMF (1.33 g/cm^3) and the lowest value was observed in DDTF (1.24 g/cm^3).

The soil pH ranged from 6.1 to 7.4. The soil pH increased significantly with increase in soil depth (*F-value* = 88.82; $P < 0.0001$) in all the three study sites (Fig. 3b). The soil pH also varied across all the study sites, but did not show any statistical significance. Among the three study sites, the highest value of mean pH (0-50 cm) was recorded in DDMF (6.9) and lowest value was recorded in BF (6.7).

The soil moisture ranged from 11.7% (BF) to 17.9% (DDTF). The soil moisture decreased significantly with increase in soil depth (*F-value* = 175.16; $P < 0.0001$) in all the three study sites (Fig. 3c). The soil moisture also varied significantly (*F-value* = 7.04; $P < 0.001$) across all the study sites. The highest mean value of soil moisture (0-50 cm) was recorded in DDTF (15.7%) and the lowest value was recorded in BF (14.1%).

The standing crop litter C ranged from 3.07 Mg C/ha (DDMF) to 4.8 Mg C/ha (DDTF) and varied significantly (*F-value* = 12.93; $P < 0.001$) across all the study sites. The highest mean value of standing crop litter C stock was recorded in DDTF (4 Mg C/ha) and the lowest value was recorded in DDMF (3.29 Mg C/ha, Fig. 3d).

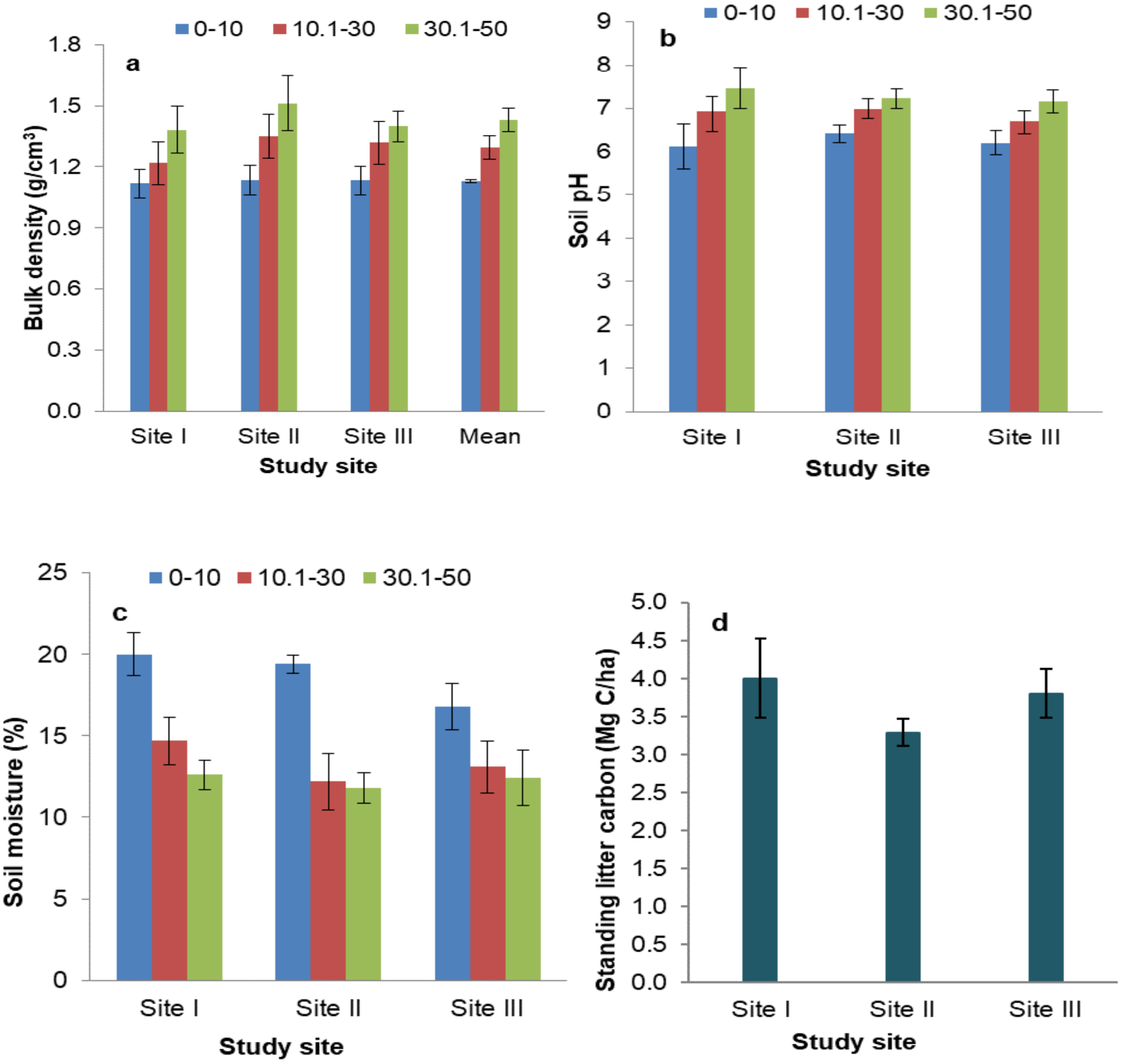

Fig. 3 (a) Bulk density (g/cm^3), (b) soil pH, (c) soil moisture (%), (d) standing litter carbon stock (Mg C/ha) in the three selected study sites (Site I: DDTF; Site II: DDMF; Site III: BF).

3.3 Correlation of SOC stock with different variables

Pearson correlation (r) analysis revealed that different variables could produce either positive or negative effects on SOC stocks (Table 2).The SOC showed significant ($P < 0.01$) positive correlations with SOM ($r = 0.79$), soil moisture ($r = 0.41$), aspect ($r = 0.52$) and dominance ($r = 0.53$). Similarly, the litter ($r = 0.29$) and mean annual temperature ($r = 0.28$, MAT) showed a positive correlation with SOC stocks, but was non-significant, while it showed a significant ($P < 0.01$) negative relationship with diversity indices {Shannon ($r = -0.58$), Simpson ($r = -0.53$), Fisher's alpha ($r = -0.51$) and tree species richness ($r = -0.54$)}.

3.4 Principal component analysis of SOC

The PCA was applied at plot-level to identify which of the structural, diversity, and environmental factors cause variation in SOC stocks (Fig. 4). Eigen values of dominant axis, which are closely associated variables for higher SOC were observed as 4.7, 1.1, 0.59 and 0.39 and the corresponding percentage variances were 66.8, 15.7, 8.4 and 5.6 respectively. These values reflect on variations in SOM, moisture (%), aspect (°) and dominance index, which together accounted for 96.5% variation in SOC stock. Structural, diversity and environmental factors accounted for 69.2, 24.9 and 5.8% of variance in SOC stocks.

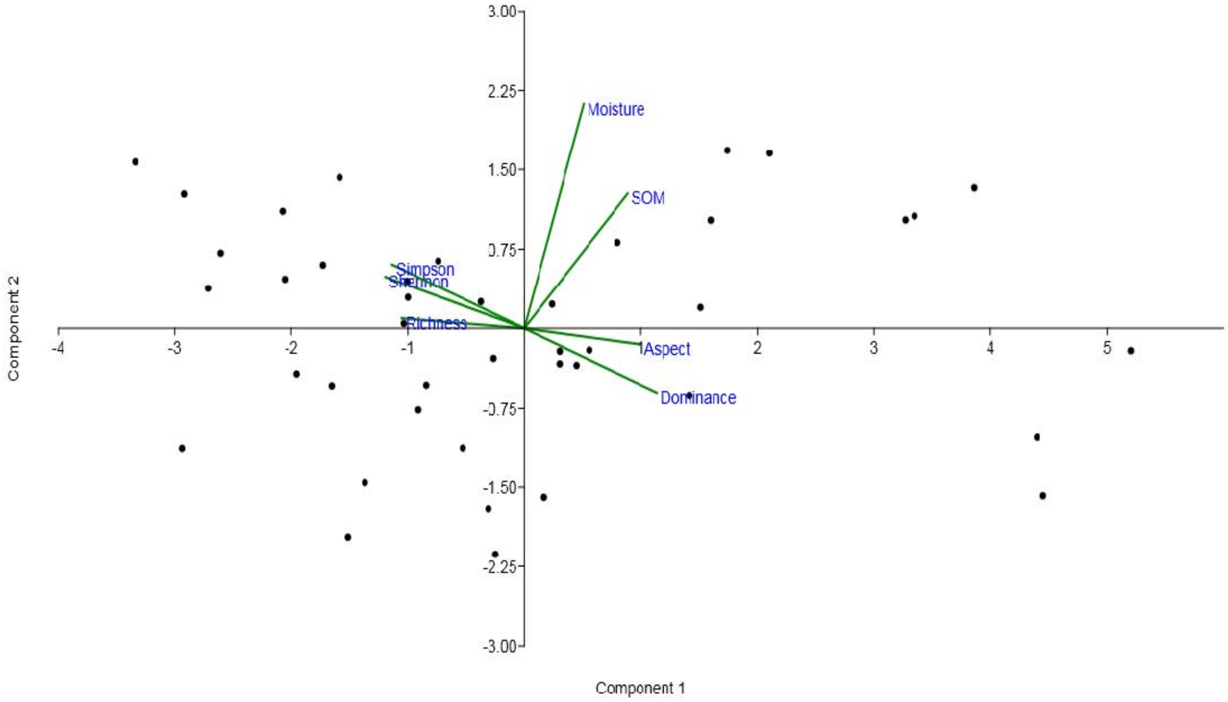

Fig. 4 Principal Component Analysis (PCA) of different variables {environmental variables: soil moisture (moisture), aspect; diversity attributes: species richness (richness), Shannon's diversity index (Shannon), Simpson's dominance index (Simpson), species dominance (dominance); structural attribute: soil organic matter (SOM)} against soil organic carbon stock at plot-level. Each dot represents a plot here.

Table 2 Pearson correlation matrix (r) between soil organic carbon (SOC Mg C/ha) stocks and multiple variables.

Parameter	SOC	D	BA	B	SOM	pH	BD	M %	Litter	Alt.	MAT	MAP	S	A	Shan.	Simp.	E	Domi.	FA	SR
SOC	1																			
Density	.114	1																		
Basal area	-.178	-.073	1																	
Biomass	-.218	-.066	**.978****	1																
SOM	**.793****	.060	-.171	-.180	1															
pH	-.143	.073	-.237	-.192	.075	1														
BD	-.016	-.284	-.057	-.021	.029	.154	1													
M %	**.414****	.170	**-.529****	**-.463****	**.543****	**.415****	.104	1												
Litter	.292	-.252	.169	.110	**.355***	-.284	-.066	-.145	1											
Altitude	-.248	-.271	.193	.167	-.223	-.002	.202	**-.393****	.091	1										
MAT	.289	**.355***	-.156	-.108	**.313***	-.001	**-.308***	**.351***	.017	**-.443****	1									
MAP	.006	-.183	**-.328***	**-.331***	.012	.102	**.369***	.087	-.126	.279	**-.765****	1								
Slope	-.021	**-.457****	-.089	-.122	-.013	.044	**.375***	**-.312***	.121	.190	**-.306***	.274	1							
Aspect	**.523****	**-.316***	-.006	-.092	**.609****	-.176	-.197	.184	**.662****	-.019	-.040	.021	.123	1						
Shannon	**-.583****	-.093	.107	.192	**-.550****	.113	.199	-.275	**-.366***	.220	.004	-.077	.074	**-.721****	1					
Simpson	**-.537****	-.041	.142	.208	**-.510****	.120	.168	-.243	-.292	.132	.058	-.184	.073	**-.631****	**.943****	1				
Evenness	-.120	.074	.114	.123	.016	.165	.011	.109	.090	-.102	**.370***	**-.503****	-.195	-.122	**.363***	**.520****	1			
Dominance	**.537****	.041	-.142	-.208	**.510****	-.120	-.168	.243	.292	-.132	-.058	.184	-.073	**.631****	**-.943****	**-1.000****	**-.520****	1		
FA	**-.512****	-.284	.048	.141	**-.518****	.062	.190	**-.333***	**-.315***	**.370***	-.180	.148	.137	**-.598****	**.817****	**.613****	-.116	**-.613****	1	
SR	**-.541****	-.166	.050	.153	**-.533****	.057	.186	**-.309***	**-.389***	**.314***	-.106	.117	.115	**-.685****	**.863****	**.676****	-.105	**-.676****	**.973****	1

SOC: soil organic carbon (0-50 cm), D: density (No. of stems/ha), BA: basal area (m2/ha), B: biomass (Mg/ha), SOM: soil organic matter, M: moisture (%), Alt.: altitude (m asl.), MAT: Mean annual temperature, MAP: Mean annual precipitation, S: slope, A: aspect, Shan.: Shannon, Simp.: Simpson, E: evenness, Domi.: Dominance, FA: Fisher’s alpha, SR: species richness.

** - Correlation is significant at the 0.01 level; * - Correlation is significant at the 0.05 level.

4 Discussion

Soil is a complex medium that plays a key role in the C dynamics of the biosphere as it is a huge C pool (Moreno et al., 2017). In forest ecosystems, vegetation type plays a crucial role in influencing SOC stocks due to differences in the quality and quantity of litter produced, SOM, species richness, dominance of species, besides other structural, environmental and topographic factors (Subashree et al., 2019; Sun et al., 2019; Wiesmeier et al., 2019). In the current study, SOC stocks varied significantly between and within the forest types. The SOC stock ranged from 48.7 to 89.1 Mg C/ha (mean 64.6 Mg C/ha) between the forest types for a depth of 0–50 cm. The mean SOC stock is well within the ranges reported from different forest types of India (51.9–386 Mg C/ha; Jha et al., 2003) and different sacred groves of Central India (22.4–112.5 Mg C/ha; Dar et al., 2019), but lower than the mean for tropical forests worldwide (162 Mg C/ha; Malhi et al., 1999) and Asian tropical forest soils (148 and 139 Mg C/ha; Brown et al., 1993; Dixon et al., 1994) and higher than that recorded from the dry deciduous forests of India (37.5 Mg C/ha; Chhabra et al., 2003). In the current study, the highest SOC stock were found in the tropical dry deciduous teak forest (DDTF) followed by dry deciduous mixed forest (DDMF), and the lowest was observed in the *Boswellia* forest (BF). The observed differences among these forest types could be due to variations in organic matter input, quality and quantity of litter and its decomposition rates (Jobbágy and Jackson, 2000), moisture content (%), topography, predominant species, stand structure, soil bulk density and microclimate of the study sites (Dar and Sundarapandian, 2015; Hobley and Wilson, 2016; Paz et al., 2016; Sundarapandian et al., 2016; Ma et al., 2017; Kothandaraman et al., 2020; Raha et al., 2020).

In this study, the SOC stock, SOC%, SOM% and soil moisture (%) decreased with increasing soil depth in all the forest types. Organic matter inputs mainly occur in the surface layer and has greater microbial activity and decomposition rate, which decreases with increase in soil depth. However, little variation occurred at depths below 10 cm (Fig. 3c), possibly because the SOC content is primarily determined by the distribution of the root system in deep soil (Jobbágy and Jackson, 2000), soil compaction, weak rate of decomposition and low moisture content (Osuri et al., 2014; Hobley and Wilson, 2016). An increase in soil depth can affect soil structure and permeability negatively, which might have resulted in the decrease in soil moisture (Geng, 2013).

In tropical forest soils, SOC is mostly influenced by site factors. In this study, soil bulk density and pH increased with increasing depth. The mean bulk density varied from 1.24 (DDTF) to 1.33 g/cm^3 (DDMF). This variation in bulk density observed among and between the forest types may be because of variations in soil type, texture, porosity, SOM, mineral composition, disturbance and coarse fragment fractions in the soil (Neumann-Cosel et al., 2011; Throop et al., 2012; Santos et al., 2015). The upper soil layers have low bulk density values compared to other sublayers, as they possess high SOM content and aggregated soil particles (Subashree et al., 2019). Furthermore, it is usually inversely proportional to the SOM, and the higher bulk density in deeper layers is also attributed to less mixing of SOM with the mineral fractions in the soil profile (Schulp et al., 2008). The mean soil pH varied from 6.7 (BF) to 6.9 (DDMF) and it increased significantly with increase in soil depth. Soil pH is often less in the upper soil layer because it is rich in SOM which produces organic acids upon decomposition that lowers the pH (Hong et al., 2019). The litter C acts as a precursor to SOC stock in any forest ecosystem and is an important component of the C cycle. In this study, higher litter C stock have been observed in DDTF type (4.0 Mg C/ha) and the lowest in BF type (3.29 Mg C/ha, Fig. 3d). The highest SOC stock in DDTF could be attributed to the highest litter content, associated with greater moisture content and microbial processes compared to DDMF and BF types, having low forest floor litter and moisture content. Teak forests are known to sequester good amounts of C due to high SOM and good decomposition rates (Hase and Foelster, 1983; Singh et al., 2020).

Correlation analyses reveal potential relationships between variables. Among structural, environmental and diversity attributes, SOM, moisture, aspect and dominance showed significant positive correlations with SOC stock, whereas Shannon's, Simpson, Fisher's alpha and species richness showed significant negative correlations with SOC stocks. The PCA analysis also showed that SOC stocks are positively influenced by SOM, moisture content, species dominance and aspect, while negatively by diversity indices (Shannon, Simpson, Fisher's alpha and tree species richness) as major variables having maximum PCA component matrix. In the present study, the highest SOC stock was observed in DDTF, the forest type with the highest SOM, litter and moisture content (Table 1, Figs. 2 and 3). In tropical forest soils which has a rapid SOC turnover, the association of SOM with other soil minerals stabilizes SOC (Sayer et al., 2019). Soil moisture directly influences SOC dynamics by affecting the rates of root respiration and microbial decomposition, besides changing other soil properties such as pH, bulk density, nutrient availability, weathering, etc. (Schuur et al., 2001; Carvalhais et al., 2014). Indirectly, it controls SOC decomposition by acting as a medium of diffusion for carbon-rich substrates and degradative enzymes (Ramesh et al., 2019; Tarus and Nadir, 2020). In our study, topography (aspect) significantly positively influenced SOC stocks and the highest SOC stocks have been observed along the southern aspect. It could be because of the influence of solar radiation and soil moisture on the southern aspect which favours the growth of plants. Similarly, Gebeyehu et al. (2019) have reported greater SOC stocks along the southern aspect from the dry Afromontane forests of Awi Zone, northwestern Ethiopia. The SOC stocks are known to significantly vary with aspect due to changes in temperatures (Yohannes et al., 2015). This is so because aspect influences the angle of sun rays and due to this, the seasonal climate differs between north-facing and south-facing slopes. Such differences in temperature and climate exert effects on microclimates, soil moisture, tree species composition, photosynthesis, and SOM turnover (Yadav and Gupta, 2006; Yohannes et al., 2015). The SOC stocks are also greatly determined by the dominant tree species composition as they determine the litter quality and quantity, influence rhizodeposition, microbial activity, etc. (Simón et al., 2013). Under natural conditions, soil properties are often shaped by the permanent vegetation cover over a long period of time (Osman, 2013). Forest type is a determinant of SOC storage as it affects both input and decomposition of C (Wiesmeier et al., 2019). The SOC stocks have been reported to vary with differences in the dominant tree species composition in other studies as well: Kooch et al. (2016), Liu et al. (2016a) and Lorenz and Thiele-Bruhn (2019). In tropical forest ecosystems, forest type can alter the SOC stocks through the interacting effects of several factors e.g., climate, topography, structure, temperature, precipitation, forest type, moisture content, SOM, seasonal rainfall, etc. (García-Oliva et al., 2003; Liu et al., 2016b; Pulla et al., 2016; Gebeyehu et al., 2019; Mayer et al., 2020; Yuan et al., 2021; Zhang et al., 2021). In the present study, the highest SOC stock was observed in DDTF type followed by DDMF and BF types. The reason for this could be that DDTF accumulates higher SOM and litter content along with the higher soil moisture and vice versa (Figs. 2 and 3). The SOC stocks are controlled by biomass accumulation, decomposition and transformation of organic matter by influencing soil temperature, precipitation, moisture, topography, litter inputs, etc. Therefore, SOC stocks were highest in the forest type, DDTF with greater SOM and moisture contents, located along the southern aspect having low exposure to solar radiations, and which was dominated by teak.

5 Conclusion

Our results revealed the SOC stock variation among three main tropical dry deciduous forest types in the Central Indian landscape and SOM, moisture, tree dominance and aspect are the predominant drivers. Variations in soil moisture and SOM due to changing climate would bring forth commensurate variations in SOC. The UN-REDD+ programme has called for the assessment of different C pools in developing nations and soil is a major C pool. In the context where there is a dearth of studies on the SOC stocking potential of different tropical dry deciduous forest types of India, our study generated baseline data that could be used for reporting regional and national C inventories, and to develop and validate SOC models. The findings of this study provided important implications for managing SOC reservoir through conservation and enhancement programmes in tropical dry deciduous forests.

Acknowledgement

We are thankful to the Madhya Pradesh State Forest Department for permission and providing the necessary facilities and staff support during the field work. This study is financially supported by Department of Biotechnology (DBT), Govt. of India (BT/PR12899/NDB/39/506/2015, Dated: 20th June 2017) and Science and Engineering Research Board (SERB), Department of Science and Technology, New Delhi, for funding under National Post-Doctoral Fellowship Scheme (Ref. No.: PDF/2015/000447).

References

Aragao LEOC, Shimabukuro YE. 2010. The incidence of fire in Amazonian forests with implications for REDD. Science, 328: 1275-1278

Araujo MA, Zinn YL, Lal R. 2017. Soil parent material, texture and oxide contents have little effect on soil organic carbon retention in tropical highlands. Geoderma, 300: 1-10

Batjes NH. 1996. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science, 47: 151-163

Berg B. 2014. Decomposition patterns for foliar litter–a theory for influencing factors. Soil Biology and Biochemistry, 78: 222-232

Blackie R, Baldauf C, Gautier D, et al. 2014. Tropical dry forests: a state of global knowledge and recommendations for future research. Center for International Forestry Research (CIFOR), Bogor, Indonesia

Brown S, Iverson LR, Prasad A, et al. 1993. Geographical distributions of carbon in biomass and soils of tropical Asian forests. Geocarto International, 8:45-59

Carvalhais N, Forkel M, Khomik M, et al. 2014. Global covariation of carbon turnover times with climate in terrestrial ecosystems. Nature, 514: 213-217

Champion HG, Seth SK. A revised survey of the forest types of India. Government of India Press, New Delhi, India, 1968

Chhabra A, Palria S, Dadhwal VK. 2003. Soil organic carbon pool in Indian forests. Forest Ecology and Management, 173: 187-199

Coleman DC. 1973. Soil carbon balance in a successional grassland. Oikos, 24: 195-199

Dar JA, Subashree K, Raha D, et al. 2019. Tree diversity, biomass and carbon storage in sacred groves of Central India. Environmental Science and Pollution Research, 26: 37212-37227

Dar JA, Sundarapandian S. 2015. Altitudinal variation of soil organic carbon stocks in temperate forests of Kashmir Himalayas, India. Environmental Monitoring and Assessment, 187: 11

Debasish-Saha, Kukal SS, Bawa SS. 2014. Soil organic carbon stock and fractions in relation to land use and soil depth in the degraded Shiwaliks hills of lower Himalayas. Land Degradation and Development, 25: 407-416

Dieleman WIJ, Venter M, Ramachandra A, et al. 2013. Soil carbon stocks vary predictably with altitude in tropical forests: Implications for soil carbon storage. Geoderma, 204-205: 59-67

Dixon RK, Solomon AM, Brown S, et al. 1994. Carbon pools and flux of global forest ecosystems. Science, 263: 185-190

Doetterl S, Berhe AA, Nadeu E, et al. 2016. Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. Earth-Science Reviews, 154: 102-122

Food and Agricultural Organization. 2009. Harmonized World Soil Database (Vol. 1). IIASA, Laxenburg, Austria and FAO, Rome, Italy

Gandhi DS, Sundarapandian S. 2017. Soil carbon stock assessment in the tropical dry deciduous forest of the Sathanur reserve forest of Eastern Ghats, India. Journal of Sustainable Forestry, 36: 358-374

García-Oliva F, Sveshtarova B, Oliva M. 2003. Seasonal effects on soil organic carbon dynamics in a tropical deciduous forest ecosystem in western Mexico. Journal of Tropical Ecology, 19: 179-188

Gebeyehu G, Soromessa T, Bekele T, et al. 2019. Carbon stocks and factors affecting their storage in dry Afromontane forests of Awi Zone, northwestern Ethiopia. Journalof Ecology and Environment, 43: 7

Geng CH. 2013. Effects of Soil Depth and Soil Tillage Method on the Sweet Potato’s Growth, Yield and Quality in Hilly Region.Ya’an: Sichuan Agricultural University, Sichuan, China

Hammer Ø, Harper DAT, Ryan PD. 2001. PAST: Paleontological statistics software package for education and data analysis. Palaeontologia Electronica, 4: 4-9

Hase H, Foelster H. 1983. Impact of plantation forestry with Teak (*Tectona grandis*) on the nutrient status of young alluvial soil in West Venezuela. Forest Ecology and Management, 6: 33-57

Hiederer R, Kochy M. 2012. Global Soil Organic Carbon Estimates and The Harmonized World Soil Database (EUR 25225EN) JRC. European Commission, Ispra, Italy

Hobley EU, Wilson B. 2016. The depth distribution of organic carbon in the soils of eastern Australia. Ecosphere, 7: e01214

Hong S, Gan P, Chen A. 2019. Environmental controls on soil pH in planted forest and its response to nitrogen deposition. Environmental Research, 2172: 159-165

Janzen DH. 1988. Tropical dry forests: the most endangered major tropical ecosystem. In: Biodiversity (Wilson OE, Peter FM, eds). 130-137, National Academy Press, New York, USA

Jha MN, Gupta MK, Saxena A, et al. 2003. Soil organic carbon store in different forests of India. Indian Forester, 129: 714-724

Jobbágy EG, Jackson RB. 2000. The vertical distribution of soil carbon and its relation to climate and vegetation. Ecological Applications, 10: 423-436

Johnston CA, Groffman P, Breshears DD, et al. 2004. Carbon cycling in soil. Frontiers in Ecology and the Environment, 2: 522-528

Kooch Y, Rostayee F, Hosseini SM. 2016. Effects of tree species on topsoil properties and nitrogen cycling in natural forest and tree plantations of northern Iran. Catena, 144: 65-73

Kothandaraman S, Dar JA, Sundarapandian S, et al. 2020. Ecosystem–level carbon storage and its links to diversity, structural and environmental drivers in tropical forests of Western Ghats, India. Scientific Reports, 10: 13444

Krishan G, Srivastav SK, Kumar S, et al. 2009. Quantifying the underestimation of soil organic carbon by the Walkley and Black technique: Examples from Himalayan and central Indian soils. Current Science, 96: 1133-1136

Lal R, Follett F, Stewart BA, et al. 2007. Soil carbon sequestration to mitigate climate change and advance food security. Soil Science, 172: 943-956

Lal R. 2004a. Soil carbon sequestration in natural and managed tropical forest ecosystems. Journal of Sustainable Forestry, 21: 1-30

Lal R. 2004b. Soil carbon sequestration impacts on global climate change and food security. Science, 304: 1623-1627

Lal R. 2021. Soil management for carbon sequestration. South African Journal of Plant and Soil, 38: 231-237

Liu N, Wang Y, Wang Y, et al. 2016a. Tree species composition rather than biodiversity impacts forest soil organic carbon of Three Gorges, southwestern China. Nature Conservation, 14: 7-24

Liu Y, Li S, Sun X, et al. 2016b. Variations of forest soil organic carbon and its influencing factors in east China. Annals of Forest Science, 73: 501-511

Lone PA, Dar JA, Subashree K, et al. 2019. Impact of plant invasion on physical, chemical and biological aspects of ecosystems: A review. Tropical Plant Research, 6: 528-544

Lorenz M, Thiele–Bruhn S. 2019. Tree species affect soil organic matter stocks and stoichiometry in interaction with soil microbiota. Geoderma, 353: 35-46

Ma L, Shen C, Lou D, et al. 2017. Patterns of ecosystem carbon density in edge–affected fengshui forests. Ecological Engineering, 107: 216-223

Malhi YA, Baldocchi DD, Jarvis PG. 1999. The carbon balance of tropical, temperate and boreal forests. Plant, Cell and Environment, 22: 715-740

Mayer M, Prescott CE, Abaker WEA, et al. 2020. Tamm review: Influence of forest management activities on soil organic carbon stocks: A knowledge synthesis. Forest Ecology and Management, 466: 118127

Misra R. 1968. Ecology Workbook. Oxford and IBH Publications, New Delhi, India

Moreno F, Oberbauer SF, Lara W. 2017. Soil Organic Carbon Sequestration Under Different Tropical Cover Types in Colombia. In: Managing Forest Ecosystems: The Challenge of Climate Change (Bravo F, LeMay V, Jandl R, eds). 367-383, Springer International Publishing, Switzerland

Murphy P, Lugo A. 1986. Ecology of tropical dry forest. Annual Review of Ecology, Evolution, and Systematics, 17: 67-88

Neumann-Cosel L, Zimmermann B, Jefferson S, et al. 2011. Soil carbon dynamics under young tropical secondary forests on former pastures: A case study from Panama. Forest Ecology and Management, 261: 1625-1633

Osei R, Titeux H, Bielak K, et al. 2021. Tree species identity drives soil organic carbon storage more than species mixing in major two–species mixtures (pine, oak, beech) in Europe. Forest Ecology and Management, 481: 118752

Osman KT. 2013. Physical Properties of Forest Soils. Springer International Publishing, Switzerland

Osuri AM, Kumar VS, Sankaran M. 2014. Altered stand structure and tree allometry reduce carbon storage in evergreen forest fragments in India’s Western Ghats. Forest Ecology and Management, 329: 375-383

Pan Y, Birdsey RA, Fang J, et al. 2011. A large and persistent carbon sink in the world’s forests. Science, 333: 988-993

Paz CP, Goosem M, Bird M, et al. 2016. Soil types influence predictions of soil carbon stock recovery in tropical secondary forests. Forest Ecology and Management, 376: 74-83

Pearson T, Walker S, Brown S. 2005. Sourcebook for land use, land–use change and forestry projects. Winrock International and the BioCarbon Fund of the World Bank, USA

Piao S, Fang J, Ciais P. 2009. The carbon balance of terrestrial ecosystems in China. Nature, 458: 1009-1013

Pulla S, Riotte J, Suresh HS, et al. 2016. Controls of soil spatial variability in a dry tropical forest. PLoS One, 11: 0153212

Raha D, Dar JA, Pandey PK, et al. 2020. Variation in tree biomass and carbon stocks in three tropical dry deciduous forest types of Madhya Pradesh, India. Carbon Management, 11: 109-120

Ramesh T, Bolan NS, Kirkham MB, et al. 2020. Soil organic carbon dynamics: Impact of land use changes and management practices: A review. Advances in Agronomy, 156: 1-107

Salunkhe O, Khare PK, Kumari R, et al. 2018. A systematic review on the aboveground biomass and carbon stocks of Indian forest ecosystems. Ecological Processes, 7: 17

Santos LTD, Marra DM, Trumbore S, et al. 2015. Windthrows increase soil carbon stocks in a Central Amazon forest. Biogeosciences Discussions, 12: 19351-19372

Sayer EJ, Lopez-Sangil L, Crawford JA, et al. 2019.Tropical forest soil carbon stocks do not increase despite 15 years of doubled litter inputs. Scientific Reports, 9: 18030

Schulp CJ, Nabuurs GJ, Verburg PH, et al. 2008. Effect of tree species on carbon stocks in forest floor and mineral soil and implications for soil carbon inventories. Forest Ecology and Management, 256: 482-490

Schuur EA, Chadwick OA, Matson PA. 2001. Carbon cycling and soil carbon storage in mesic to wet Hawaiian montane forests. Ecology, 82: 3182-3196

Simón N, Montes F, Díaz–Pinés E, et al. 2013. Spatial distribution of the soil organic carbon pool in a Holm oak dehesa in Spain. Plant and Soil, 366: 537-549

Singh AK, Sahu C, Sahu SK. 2020. Carbon sequestration potential of a teak plantation forest in the Eastern Ghats of India. Journal of Environmental Biology, 41: 770-775

Singh H, Pathak P, Kumar M, et al. 2011. Carbon sequestration potential of Indo-Gangetic agro-ecosystem soils. Tropical Ecology, 52: 223-228

Subashree K, Dar JA, Sundarapandian S. 2019. Variation in soil organic carbon stock with forest type in tropical forests of Kanyakumari Wildlife Sanctuary, Western Ghats, India. Environmental Monitoring and Assessment, 191: 690

Sun X, Tang Z, Ryan MG, et al. 2019. Changes in soil organic carbon contents and fractionations of forests along a climatic gradient in China. Forest Ecosystems, 6: 1

Sundarapandian SM, Amritha S, Gowsalya L, et al. 2016. Soil organic carbon stocks in different land uses in Pondicherry university campus, Puducherry, India. Tropical Plant Research, 3: 10-17

Tarus GK, Nadir SW. 2020. Effect of Forest Management Types on Soil Carbon Stocks in Montane Forests: A Case Study of Eastern Mau Forest in Kenya. International Journal of Forestry Research, 2020: 8862813

Throop H, Archer SR, Monger HC, et al. 2012. When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. Journal of Arid Environment, 77: 66-71

Tong R, Zhou B, Jiang L, et al. 2021. Leaf litter carbon, nitrogen and phosphorus stoichiometry of Chinese fir (Cunninghamia lanceolata) across China. Global Ecology and Conservation, 27: e01542

Walkley A, Black IA. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science, 37: 29-38

Wang L, Chen Y, Zhou Y, et al. 2021. Litter chemical traits strongly drove the carbon fractions loss during decomposition across an alpine treeline ecotone. Science of the Total Environment, 753: 142287

Wiesmeier M, Urbanski L, Hobley E, et al. 2019. Soil organic carbon storage as a key function of soils – A review of drivers and indicators at various scales. Geoderma, 333: 149-162

WorldClim Global Climate Data. 2020. Free climate data for ecological modelling and GIS. http://www.worldclim.org/

Yadav AS, Gupta SK. 2006. Effect of micro–environment and human disturbance on the diversity of woody species in the Sariska Tiger Project in India. Forest Ecology and Management, 225: 178-189

Yohannes H, Soromessa T, Argaw M. 2015. Carbon Stock Analysis along Slope and Slope Aspect Gradient in Gedo Forest: Implications for Climate Change Mitigation. Journal of Earth Science and Climatic Change, 6: 305

Yuan J, Zhang Y, You C, et al. 2021. The three–dimension zonal pattern of soil organic carbon density in China’s forests. Catena, 196: 104950

Zhang G, Zhang P, Peng S, et al. 2017. The coupling of leaf, litter, and soil nutrients in warm temperate forests in northwestern China. Scientific Reports, 7: 11754

Zhang Y, Ai J, Sun Q, et al. 2021. Soil organic carbon and total nitrogen stocks as affected by vegetation types and altitude across the mountainous regions in the Yunnan Province, south–western China. Catena, 196: 104872