Altitudinal variation of soil organic carbon stock in tropical forest of Courtallam hills, Southern Western Ghats of India

E. Pandian* and P. Ravichandran

Department of Plant Science, Manonmaniam Sundaranar University, Tirunelveli-627012, Tamil Nadu, India

*Corresponding Author: pandianmaha111@gmail.com

[Accepted: 20 December 2020]

Abstract: The climate change and carbon mitigation through forest ecosystems play an important role in the global perspective. Soil is a huge carbon reservoir and its storage capacity varied greatly with forest type and altitude. The mountain ecosystem varies in soil organic carbon stock (SOC) due to variations in soil types, climatic conditions, vegetation patterns and elevational gradients. Soil organic carbon stockswere measured at three depths (0–10, 10–20, and 20–30 cm) in five different forest elevation (200, 400, 600, 800, and 1000 m asl) on Courtallam hills, Southern Western Ghats, India. SOC stocks increased significantly with the increase in altitude (P<0.05) at all the three layers (0–10, 10–20 and 20–30 cm). A total of SOC stocks ranged from 42.79 mg ha\(^{-1}\) at 0–30 cm depth were observed in lower altitude (200 m) and the highest value of 50.25 mg ha\(^{-1}\) at 0–30 cm depth was observed in mid-elevation 600 m, while in other elevational showed 46.45, 48.49 and 45.05 mg ha\(^{-1}\) in 400, 800 and 1000 m respectively. SOC ranged from 17.89 to 22.37 mg ha\(^{-1}\) in soil surface layer (0–10 cm), 14.00 to 16.573 mg ha\(^{-1}\) in middle layer (10–20 cm) and 9.08 to 11.35 mg ha\(^{-1}\) in the bottom layer (20–30 cm). These results would also enhance our ability to assesses the role of these forest types in soil carbon sequestration and for developing and validating the SOC models for tropical forest ecosystems.

Keywords: Soil organic carbon -Courtallam hills - Altitudinal variation - carbon storage - Southern Western Ghats.

INTRODUCTION

It is obvious that soil is important for all living organisms in the terrestrial ecosystem and soil is the huge reservoir of organic carbon and plays an important role in the global carbon cycle (Gebrehiwot et al. 2018). Accumulates of soils carbon four times higher than vegetation and thrice than the atmosphere (Jobbgy & Jackson 2000, Lal 2004a). A small change in soil carbon consequently large changes occur in atmospheric concentration (Raich & Schlesinger 1992, IPCC 2000). Carbon contribution is about 32% in soil and 56% in the vegetation of tropical forests (Pan et al. 2011). Tropical forest soils are exchanging higher carbon with atmosphere than terrestrial ecosystem (Raich & Schlesinger 1992, Beer et al. 2010, Amundson et al. 2015). The carbon loss was estimated 1.6±0.8 Pg year\(^{-1}\), mainly in the tropics (Smith 2008). Moreover, Crowther et al. (2016) evaluated that carbon stock loss from the upper soil horizon is estimated 55±50 Pg by 2050, which is about 17% of the predictable anthropogenic emissions over this period (Ballantyne et al. 2015), and the concentration of SOC is used as an indicator of soil productivity and quality (Waring et al. 2014). The concentration of carbon dioxide (CO\(_2\)) in the atmosphere has increased from approximately 277 ppm (Joos & Spahni 2008) to 406.42 ppm (NOAA 2017), consequently increasing global warming and forest ecosystems play an important role in the climate change and mitigation of CO\(_2\) from the atmosphere (Pandian & Parthasarathy 2016a, Pandian & Parthasarathy 2017, Gandhi & Sundarapandian 2017).

SOC estimated on a global level and have got the values of 699 Pg C in the top layer of 30 cm and 1417 Pg C for 1 m depth of the soil profile (Hiederer & Kochy 2012). SOC is evaluated to be more than 2000 Pg of carbon in the upper layer (100 cm) of soil depth (Batjes 1996) which is by far greater than the cumulative soil organic carbon stock of the atmosphere and vegetation (Lal 2004b). In the top layer of 100 cm of the soil profile,
nearly 50% of SOC are locked up in top layer of 30 cm (Batjes 1996, Hiederer 2009, Wang et al. 2014). SOC accumulation rate on the top soil (0–30 cm) ranged from 11.5 to 43.2 gm² yr⁻¹, of which 70–90 % accumulation was in 0–15 cm (Boutton et al. 2009). The top layer of 0–30 cm soil profile is more dynamic and plays an important role in the carbon cycle due to the input of organic matter and associated surface fine root dynamics, which is susceptible to human activities and natural processes. SOC storage in the soil surface of forests is larger due to the rate of low decomposition of forest floor litter. Therefore, assessment of SOC up to 30 cm of depth is of enormous importance. For example, decreasing temperatures with increasing elevation in the Sierra Nevada of California have been shown to limit SOC turnover, consequential in increased SOC accumulation at higher altitude (Trumbore et al. 1996). In general, several studies have been reported on the SOC stock in different forest types of India and elsewhere (Ravindranath et al. 1997, Chhabra et al. 2003, Jobbagy & Jackson 2000, Lal 2004a, 2004b, Ramachandran et al. 2007, Neumann-Cosel et al. 2011, Sheikh et al. 2011, Throop et al. 2012, Sundarapandian et al. 2013, Tsui et al. 2013, Venkanna et al. 2014, Gray et al. 2015, Santos et al. 2015, Gurmesa et al. 2016, Paz et al. 2016, Subashree et al. 2019). Yet, some tropical forests still remain unexplored. The literature survey showed that a study on soil organic carbon stock assessment in the tropical forest of Western Ghats is very limited and in particular, published information on the tropical forest of the Courtallam hills, is not available. A better understanding of carbon stocking potential in different forest ecosystems in the Western Ghats is essential in the current scenario. Therefore, the present study has been undertaken to estimate the SOC stocks in the tropical forest ecosystem of Courtallam hills along altitudinal gradient.

MATERIALS AND METHODS

Study area

The present research work was conducted in Courtallam hills of southern Western Ghats in Tirunelveli district of Tamil Nadu, India lies between 08.90211 N, 77.29772 E and 08.91093 N, 77.25842 E (Fig. 1). Elevation range is around 200 m to 1500 m. A total area of Courtallam hills is around 3963 ha and has a diverse geographical and physical features such as hills and low plains, thorn-scrub jungles, rivers and cascades and thick inland forest. The mean daily maximum temperature is 30°C. The weather is quite hot in May and June, and the maximum temperature sometime reaches 39°C. This region enjoys winter (December to March), summer (April to June), Southwest monsoon (June to September) and Northeast monsoon (October to November). The month of November generally receives maximum rainfall. The annual precipitation ranges from 801 mm to 1000 mm. Moreover, Courtallam hills are famous tourist spot where various anthropogenic activities such as forest encroachment for expansion of temple structures, The Western Ghats experience heavy anthropogenic pressures due to visit of tourists illegally the forest area for bathing, forest resource removal (fodder, firewood, medicinal plants, timber, etc.) and the impact of temple visitors by way of cooking inside the forest during festive occasions and solid waste dumping (polythene, glass bottles). The vegetation in this region is mainly dry deciduous and deciduous forests. Nevertheless, evergreen and semi-evergreen forests are also present in the high altitudes. The soil colour was mostly light brown or black colour throughout the study area and soil texture was sandy loam in most of the forest plots while the plots near to the rivulet were sandier than the other study plots.

Methods

Soil samples were collected from all the five 1-ha plots (100 m × 100 m) along the elevational gradient by using soil core sampler (cylindrical corer of diameter 3.5 cm) from November 2017 to February 2018. Dominant tree species for each elevation: Aglaia elaeagnoidea (A. Juss.) Benth. (100–200 m); Glycosmis pentaphylla (Retz.) DC. (200–400 m); Dimocarpus longan Lour. (400–600 m); Schleichera oleosa (Lour.) Oken (600–800 m); and Xanthophyllum flavescens Roxb. (800–1000 m). From each plot, 10 soil samples were randomly collected at three different depths viz., 0–10 cm, 10–20 cm, and 20–30 cm. A total of three composite samples in each plot were prepared by mixing three sets together each for further analysis. Soil samples were first air-dried and sieved through a 2 mm mesh. For organic C estimation, Walkley and Black’s method (Walkley 1947) was used, which is a widely used procedure (Pearson et al. 2005). In Walkley and Black’s method, about 60–86% of soil organic carbon (SOC) is oxidized; therefore, a highly recommended standard correction factor of 1.58 was used to obtain the corrected SOC values (de Vos et al. 2007, Latte et al. 2013). Totally ten undisturbed soil samples were collected from each plot from three depths for measuring the soil pH and soil moisture (five samples each), these five samples were air-dried and sieved through 2 mm sieve for measuring pH of soil was measured through pH meter (Elico LI 615) in a 1:2 (w/v) soil-water ratio. A set of five, fresh soil samples were collected from which gravel, small stones and coarse roots are separate by passing through a 2 mm sieve and...
measured fresh weight in the field itself and the samples were brought to the laboratory. That soil samples were kept in an oven at 105±5°C for 72 h and then re-weighed. Soil moisture content was determined from the difference of initial and final readings.

A total of ten soil samples were collected from each plot from tree depths for measuring bulk density. While taking these cores which was taken to avoid any loss of soil from these samples. The soil samples were weighed, and kept in an oven-dried at 105±5°C for 72 h and then re-weighed. The coarse fragments were removed by sieving and then the samples were weighed. Soil bulk density and SOC stocks were calculated using the formulae of Pearson, Walker, and Brown (2005):

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

Where, 2.65 was taken as a constant for the density of rock fragments (g cm\(^{-3}\))

Total carbon content of 0–30 cm depth was finally assessed by summing up the carbon content of all three surface layers. The total SOC was quantified by following Pearson et al. (2005):

\[
\text{SOC (mg ha}^{-1}\text{)} = [(\text{Soil bulk density (g m}^{-3}\text{) × Soil depth (cm) × C}] × 100
\]

**Statistical analysis**

One-way ANOVA was used to evaluate the differences among SOC stocks by altitude. The relationship between SOC stocks and altitude was examined with linear regression and the relationship between SOC concentration and bulk density was also examined with linear regression using Microsoft Excel.
RESULT AND DISCUSSION

Soil moisture and pH values showed a variation along the elevational gradients. Our results showed that soil pH is slightly acidic (pH ranged 6.2 to 6.9 in five 1-ha plots; Fig. 2) along the elevational gradient, this similar findings are documented in the recreational and natural forest in West Bengal (pH range 5.90 to 7.01; Jana et al. 2010). However, this present study values are greater than the tropical dry deciduous forest in West Bengal (pH range 4.3 to 4.94; Joshi 2012), moist tropical forest of Sunsari district, Nepal (pH range 5.6 to 6.6; Gautam & Mandal 2013), tropical forest stands in Malla wildlife sanctuary, Sri Lanka (pH range 5.78 to 6.19; Kuruppuarachchi et al. 2016) and the tropical dry deciduous forest Sathanur reserve forest, India (pH range 5.9 to 7.1; Gandhi & Sundarapandian 2017). Generally, tropical forest soils are an acidic range due to the organic acid formation from the moderately decomposed organic matter on the upper layers of soil profile (Brouwer & Riezebos 1998). Moreover, the acidic pH could be possibly due to the presence of acidic exudates (Shen et al. 2001).

![Figure 2. Mean soil moisture and soil pH along the elevational gradient in tropical forest of Courtallam hills, Southern Western Ghats of India.](image)

![Figure 3. Bulk density of soil (mean±SE) in three different depths in tropical forest along the elevation gradients on the Courtallam hills, Southern Western Ghats of India.](image)

The soil bulk density in five 1-ha plots varied along the elevational gradient of the tropical forest (Fig. 3). A significantly (P<0.05) increasing trend was observed in soil bulk density with increasing soil depth in all the study plots (200, 400, 600, 800, 1000 m asl). Soil bulk density ranged from 0.45 to 0.62 gm$^{-3}$ in the surface layer (0–10 cm), 0.63 to 0.69 gm$^{-3}$ in the middle layer (10–20 cm) and 0.78 to 0.83 gm$^{-3}$ in the bottom layer (20–30 cm). The mean bulk density differ from 0.61 to 0.72 gm$^{-3}$ with a mean value of 0.65±0.047 gm$^{-3}$ in Courtallam hills along the elevational gradient and this values are compared with tropical forest reports: dry tropical forest in Jharkhand (1.852 to 1.259 g cm$^{-3}$; Kujur & Patel 2012), tropical dry deciduous forest Sathanur reserve forest, India (1.21 to 1.82 gm$^{-3}$; Gandhi & Sundarapandian 2017), in tropical forests of Kanyakumari Wildlife Sanctuary, Western Ghats, India (1.32 to 1.59 gm$^{-3}$; Subashree et al. 2019) and Achanakmar-Amarkantak Biosphere Reserve of Chhattisgarh (1.02 to 1.19 g cm$^{-3}$; Iqbal & Tiwari 2016). The coarse fragment of fraction
is also one of the important factors influencing the bulk density (Throop et al. 2012). The bulk density of soils is closely connected to total porosity (Singh et al. 2011). Few previous studies also documented that the bulk density of a soil can be altered by the soil type, soil organic matter, texture and mineral composition (Neumann-Cosel et al. 2011, Santos et al. 2015).

Figure 4. Soil organic carbon stocks (mean±SE) at three different depths in tropical forest along the elevation gradients on the Courtallam hills, Southern Western Ghats of India.

The soil organic carbon stock varied across the different forest elevation, increased significantly with increase in altitude (P<0.05) at all the three layers (0–10, 10–20 and 20–30 cm) (Fig. 4). At low altitude, SOC stocks of 42.79 mg ha\(^{-1}\) at 0–30 cm depth was observed in 200 m and the highest value of 50.25 mg ha\(^{-1}\) at 0–30 cm depth was observed in mid-elevation 600 m. The SOC stock values at high altitude 600–800 m and 800–1000 forests have showed almost the similar trend. SOC decreased with increasing soil depth in all the elevations. SOC exhibited a negative trend with an increase in soil depth. SOC ranged from 17.89 mg ha\(^{-1}\) to 22.37 mg ha\(^{-1}\) in soil surface layer (0–10 cm), 14.00 to 16.573 mg ha\(^{-1}\) in middle layer (10–20 cm) and 9.08 to 11.35 mg ha\(^{-1}\) in the bottom layer (20–30 cm) (Fig. 4). In Ecuador, the higher mean SOC was found at higher elevation (169.6±76.9 mg ha\(^{-1}\)) and middle altitudes (110.2±77.3 mg ha\(^{-1}\)) and the lowest mean SOC at low altitude (82.5±48.6 mg ha\(^{-1}\); De la Cruz-Amo et al. 2020). In addition, SOC increase with altitude (Townsend et al. 1995, Schrumpf et al. 2001, Kitayama & Aiba 2002, Raich et al. 2006, Moser et al. 2011, Dieleman et al. 2013), whereas in Garhwal Himalaya, SOC decreased along the altitude gradient (Sheikh et al. 2009), few other studies report no change at all (Soethe et al. 2007, Zimmermann et al. 2010, Phillips et al. 2019). The correlation analyses of SOC with predicting variables are presented (Table 1). Our result revealed that mean SOC stock in all the depth of the tropical forest ranged from 14.26 to 16.75 mg ha\(^{-1}\) with a mean value of 15.54±0.97 mg ha\(^{-1}\), which is lesser value than other reported values in tropical dry deciduous forest Sathanur reserve forest, India (16.92 to 44.65 mg ha\(^{-1}\); Gandhi & Sundarapandian 2017), in Odisha, tropical dry deciduous forests (57.9 mg ha\(^{-1}\), Sahu et al. 2015), in Andhra Pradesh, semiarid tropical forest at Warangal.

Table 1. Correlation (r-value) between soil organic carbon (SOC) and predictor variables along the elevational gradient in tropical forest of Courtallam hills, Southern Western Ghats of India.

| Predictor variables                  | r-Value |
|--------------------------------------|---------|
| Climber species richness             | -0.663  |
| Climber density                      | -0.413  |
| Climber basal area                   | -0.457  |
| Climber above ground biomass         | -0.506  |
| Soil pH                              | -0.055  |
| Soil moisture                        | 0.234   |
| Bulk density                         | 0.88    |
| Bulk density (0–10 cm)               | 0.499   |
| Bulk density (10–20 cm)              | 0.514   |
| Bulk density (20–30 cm)              | -0.316  |

Note. *Bulk density correlated with soil organic carbon (%).
| Location | Forest type | Depth (cm) | C stock (mgha⁻¹) | Source |
|----------|-------------|------------|------------------|--------|
| Andean | Tropical Montane Forests | - | 26.65–268.09 | De la Cruz-Amo et al. (2020) |
| Tamil Nadu (Kanyakumari) | Tropical forests | 0–30 | 58.54–123.6 | Subashree et al. (2019) |
| Andhra Pradesh | Tropical dry forest | 0–30 | 27.59–32.3 | Ramana et al. (2017) |
| Sathanur reserve forest, Eastern Ghats | Tropical dry deciduous forest | 0–30 | 16–47 | Gandhi & Sundarapandian (2017) |
| South India (Kerala, Karnataka & Andhra Pradesh) | Agro forests | 0–100 | 98–156 | Hombegowda et al. (2016) |
| Chhattisgarh | Tropical dry forest | 0–100 | 122.55 | Iqbal & Tiwari (2016) |
| Uttarakhand | Alpine forest | NA | 91.29 | Kumar & Sharma (2016) |
| Gujarath | Tropical forest | 0–30 | 0.9–1.7 (Mean) | Yadav et al. (2015) |
| Andhra Pradesh | Three different land uses | 0–30 | 1.3–9.6 | Mastan et al. (2015) |
| Haryana | Tropical dry forest | 0–30 | 37.6 | Gupta et al. (2014) |
| Haryana | Tropical dry forest | 0–30 | 58.24 | Gupta & Sharma (2014) |
| Maharashtra | Tropical dry forest | 0–30 | 13.5–50.2 | Patil et al. (2014) |
| Barak Valley, Assam | Dipterocarpus Forests | 0–100 | 91.40–141.13 | Debjajit et al. (2014) |
| Haryana | Tropical dry forest | 0–30 | 9.0–14.08 | Singh et al. (2014) |
| Mizoram | Tropical bamboo forests | 0–30 | 50.1–84.23 | Vanlaffakawma et al. (2014) |
| India | Different forest types (entire India) | 0–30 | 22.42–100.33 | Velmurugan et al. (2014) |
| Andhra Pradesh | Different land uses | 0–60 | 87.29 | Venkanna et al. (2014) |
| Himachal Pradesh | Tropical dry forest | 0–30 | 36.04 | Panwar & Gupta (2013) |
| Sivagangai district, Tamil Nadu, | Tropical dry forests | 0–30 | 33.36–48.82 | Sundarapandian et al. (2013) |
| Uttar Pradesh | Tropical dry forest | 0–30 | 21.8 | Chaturvedi et al. (2011) |
| Uttar Pradesh | Agroecosystems | 0–40 | 8.5–15.2 | Singh et al. (2011) |
| Aravally mountain | Tropical forest | NA | 172.84 | Kumar et al. (2010) |
| Kolli hills Tamil Nadu | Tropical dry forest | 0–30 | 175–369 | Mohanraj et al. (2011) |
| Kolli Hills Tamil Nadu | Tropical forest | 0–90 | 63.19–274.06 | Ramachandran et al. (2007) |
| India | Tropical dry deciduous forest | 0–50 | 7.7–85.6 (mean 37.5) | Chhabra et al. (2003) |
| Various climate zones | Europe | 0–10 | 11.3–126.3 | Baritz et al. (2010) |
| Tropical evergreen forests | India/Dadra and Nagar Haveli | 0–50 | 31.6–94.6 | Biswas (1985) |
| Montane temperate forests | India | 0–50 | 12.1–184.3 | Chhabra et al. (2003) |
| Mixed strands | USA | 0–15 | 56 | Compton et al. (1998) |
| Scots pine | Europe | 0–80 | 57 | de Vries et al. (2003) |
| Scot pine | Mediterranean | 0–50 | 35–70 | Diaz-Pines et al. (2011) |
| Permafrost soil | China | 0–30 | 19–193 | Dorfer et al. (2013) |
| Pinus roxburghii | India/Garhwal Himalaya | 0–30 | 62.8 | Gupta & Sharma (2011) |
| Pinus wallichiana | India/Garhwal Himalaya | 0–30 | 102.96 | Gupta & Sharma (2011) |
| Piceasmitichiana and Abies pindrow | India/Garhwal Himalayas | 0–30 | 132 | Gupta & Sharma (2011) |
| Grasslands | India/Uttarakhand | 0–30 | 37.09–142.14 | Gupta & Sharma (2013) |
| Temperate deciduous forests | Eastern US | 0–60 | 55–229 | McFarlane et al. (2013) |
| Coniferous forests | Sweden | 0–50 | 69–73 | Ortiz et al. (2013) |
| Scot pine | Central Spain | 0–8 | 49 | Schindlbacher et al. (2010) |
| Broadleaf and coniferous | Netherlands | 0–10 | 39.5–66 | Schulp et al. (2008) |
| Schima-Castanopsis | Nepal | 0–20 | 52.45 | Shrestha (2009) |
| Norway spruce white-fir | Italy | 0–20 | 53 | Thuille et al. (2000) |
| Moist evergreen and submontane forests | Uganda | 0–30 | 54.6–82.6 | Twongyirwe et al. (2013) |

Mohanraj et al. (2011), and Africa tropical and subtropical region of forests (mean 57 mg ha⁻¹, Kirsten et al. 2016) and followed in table 2. Moreover, our value is closer to several reports (Bhattacharyya et al. 2000, Henry et al. 2009, Panwar & Gupta 2013, Brahim et al. 2014, Gupta et al. 2014, Patil et al. 2014, Gray et al. 2015, Paz et al. 2016), whereas greater than the other reported values in the tropical dry and moist forests of India (8.9 to 177 mg ha⁻¹, Chhabra et al. 2003). Comparison of SOC values are difficult with other studies, because of
different methods used to assess the SOC as well as difficulties in the measurement of bulk density of soils (Throop et al. 2012). Campo & Merino (2016) also stated that large spatial variation in SOC in tropical forest soils are influenced by combined effects on seasonal drought and length, quality and quantity of organic matter, which are determined the level of decomposition and associated sinking ability of the soil.

Figure 5. Soil organic carbon (%) at three different depths (mean±SE) in tropical forest along the elevation gradients on the Courtallam hills, Southern Western Ghats of India.

Figure 6. Relationship between soil organic carbon and A. Climber density; B. Climber species richness; C. Bulk density; D. Soil pH variables along the elevational gradient in tropical forest of Courtallam hills, Southern Western Ghats of India.

The SOC (%) significantly (P < 0.001) decreased with increase in soil depth (Fig. 5). SOC (%) ranged from 0.55 to 0.99% in the surface layer (0–10 cm) with a mean value of 0.72±0.035%, 0.52–0.73% in the middle
layer (10–20 cm) with a mean value of 0.60±0.033% and 0.42–0.69% in the bottom layer (20–30 cm) with a mean value of 0.51±0.026%. About 36.54% of SOC is accumulated in the surface layer followed by the middle layer (34.41%) and bottom layer (29.04%). Gandhi & Sundarapandian (2017) stated that SOC (%) ranged from 0.57 to 1.31% in the surface layer (0–10 cm) with a mean value of 0.83±0.035%, 0.34–1.03% in the middle layer (10–20 cm) with a mean value of 0.626±0.032% and 0.30–0.89% in the bottom layer (20–30 cm) with a mean value of 0.516±0.028%. Higher SOC (%) observed in lower layer of soil (0–10 cm), this could be attributed to maximum litter and plant residues existing on the surface of soil and associated microbial activities. This similarly result was observed by Gray et al. (2015) who reported that vegetation cover is important factors the controlling the SOC stock in the surface layer of soil. The larger organic carbon in the upper layer of soils, this may be due to huge litter accumulation by the processes of decomposition on the forest floor (Gautam & Mandal 2016). In contrast, SOC (%) was greater in plots (11–20 and 21–30 cm depth), this may be due to the prevalence of favorable conditions viz., relatively less anthropogenic activities, high aboveground biomass (Gandhi 2016). Pandian & Parthasarathy (2016b) documented that anthropogenic disturbance not only alters the structure and composition of the forest ecosystem and also one of the main factors responsible for changes in SOC stock between the plots in the study sites (Chiti et al. 2016).

A significant negative correlation was obtained between SOC stocks (mg ha\(^{-1}\)) and some vegetation characteristics viz. climber density, climber species richness and soil pH while a significant positive correlation was observed with bulk density (Fig. 6), this similar find was observed by Jobbagy & Jackson (2000) who documented, a negative relationship of SOC with bulk density. Dinakaran et al. (2014) reported that the climate (temperature, rainfall and soil moisture) is an important factor to affect the accumulation of carbon in soil. Jobbagy & Jackson (2000) also reported that SOC higher with increasing the rainfall, decreasing temperature and evapotranspiration. Similarly, Post et al. (1982) stated that the generally, warm temperate and dry tropical forests had the lowest soil carbon content and near the rivulet where showed low SOC in plots (20–30 cm depth) it may be due to the high rate of organic matter decomposition, consequently leaching due to water runoff (Gandhi & Sundarapandian 2017). The climate is major factor for better understanding of the soil carbon pool changes (Dinakaran et al. 2014).

CONCLUSION

Even though bulk density is the major parameter for estimating the soil organic carbon stock. The SOC stocks increased significantly along the elevation and it decreased with increase in soil depth. Whereas soil bulk density decreased significantly with elevation and it increased in soil depth. Our results showed that the soils of tropical forests of Courtallam hills have a greater potential of soil carbon sequestration particularly at a higher elevation, and this higher elevation of Courtallam hills are more vulnerable to climate change and found greater SOC stocks at a higher elevation than at low elevation, this changes in SOC stocks were mainly the climatic conditions of diminishing the temperature and increasing precipitation with elevation, consequential in reduced litter decomposition rates at high altitudes. Anthropogenic activities such as fuelwood collection, selective felling, grazing, agricultural seepage, this could also modify the certain levels of SOC storage in the long-term. It is the predominant duties to conservation measurements are important to restore the carbon sequestration potential of tropical forests and anthropogenic activities should be minimized for the wealth of the forest, and ultimately enhances the carbon sequestration potential.

ACKNOWLEDGMENTS

This study was supported by DST–SERB–N PDF (PDF/2015/000874) for financial support. We thank the Courtallam forest department for permitting us access to the forests and deep thanks for Range officers and my special thanks to M.P. Senthil Kumar (Ranger), Sankarapandian Sanmugavel (Guard) and field assistant Arun Ajithkumar and Raj Cortallam forest department for his timely help, supports and encouragement throughout the study.

REFERENCE

Amundson R, Berhe AA, Hopmans JW, Olson C, Sztein AE & Sparks DI (2015) Soil and human security in the 21\(^{st}\) century. Science 348: 1261071 [DOI: 10.1126/science.1261071]
Ballantyne AP, Andres R, Houghton R, Stocker BD, Wanninkhof R, Anderegg W & Alden C (2015) Audit of the global carbon budget: estimate errors and their impact on uptake uncertainty. Biogeosciences 12: 2565–2584.

www.tropicalplantresearch.com 709
Baritz R, Seufert G, Montanarella L & Ranst EV (2010) Carbon concentration and stocks in forest soils of Europe. *Forest Ecology and Management* 260: 262–277.

Batjes NH (1996) Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 47: 151–163.

Beer C, Reichstein M, Tomelleri E, Ciais P, Jung M, Carvalhais N & Bondeau A (2010) Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. *Science* 329: 834–838.

Bhattacharyya T, Pal DK, Mandal C & Velayutham M (2000) Organic carbon stock in Indian soils and their geographical distribution. *Current Science* 79: 655–660.

Biswas R (1985) Classification of some typical soils from Dadra and Nagar Haveli. *Journal of Indian Society of Soil Science* 33: 945–947.

Boutron TW, Liao JD, Filley TR & Archer SR (2009) Belowground carbon storage and dynamics accompanying woody plant encroachment in a subtropical savanna. *Soil Science Society of America, Special Publication* 57: 181–205.

Brahim N, Ibrahim H & Hatira A (2014) Tunisian soil organic carbon stock: Spatial and vertical variation. *Procedia Engineering* 69: 1549–1555.

Brouwer L & Riezebos HT (1998) Nutrient dynamics in intact and logged tropical rain forest in Guyana. In Schulte A & Ruhiyat D (eds) *Soils of tropical forest ecosystems: Characteristics, ecology and management*. Springer-Verlag, Berlin, Germany, pp. 73–86.

Campos J & Merino A (2016) Variations in soil carbon sequestration and their determinants along a precipitation gradient in seasonally dry tropical forest ecosystems. *Global Change Biology* 22: 1942–1956.

Chaturvedi RK, Raghubanshi AS & Singh JS (2011) Carbon density and accumulation in woody species of tropical dry forest in India. *Forest Ecology and Management* 262: 1576–1588.

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

Chiti T, Perugini L, Vespertino D & Valentini R (2016) Effect of selective logging on soil organic carbon dynamics in tropical forests in central and western Africa. *Plant and Soil* 399: 283–294.

Compton JE, Boone RD, Motzkin G & Foster DR (1998) Soil carbon and nitrogen in a pine-oak sand plain in central Massachusetts: role of vegetation and land use history. *Oecologia* 116: 536–542.

Crowther TW, Todd-Brown KEO & Rowe CW et al. (2016) Quantifying global soil carbon losses in response to warming. *Nature* 540: 104–108.

De La Cruz L, Bañares-De-Dios G, Cala V, Granzow-De La Cerda Í, Espinosa CI, Ledo A & Cayuela L (2020) Trade-Offs Among Aboveground, belowground, and soil organic carbon stocks along altitudinal gradients in andean tropical montane forests. *Frontiers in Plant Science* 11: 106.

De Vos B, Lettens S, Muys B & Deckers JA (2007) Walkley-Black analysis of forest soil organic carbon: Recovery, limitations and uncertainty. *Soil Use Management* 23: 221–229.

De Vries W, Reinds GJ, Sanz M, Krause G, Calatayud V, Dupouey J, Sterba H, Gundersen P, Voogd J & Vel E (2003) *Intensive monitoring of forest ecosystems in Europe*. 2003 Technical report in EC, UN/ECE, Brussels, 163 p.

Debajit R, Nepolion B & Das AK (2014) Assessment of aboveground and soil organic carbon stocks in dipterocarpus forests of Barak valley, Assam, northeast India. *International Journal of Ecology and Environmental Sciences* 40: 29–40.

Díaz-Pines E, Rubio A, Miegroet HY, Montes F & Benito M (2011) Does tree species composition control soil organic carbon pools in Mediterranean mountain forests. *Forest Ecology and Management* 262: 1895–1904.

Dieleman WIJ, Venter M, Ramachandra A, Krockenberger AK & Bird MI (2013) Soil carbon stocks vary predictably with altitude in tropical forests: Implications for soil carbon storage. *Geoderma* 204: 59–67.

Dinanakaran J, Hanief M, Meena A & Rao KS (2014) The chronological advancement of soil organic carbon sequestration research: A review. *Proceedings of National Academic Sciences, India, Section B: Biological Sciences* 84: 487–504.

Dorfer C, Kuhn P, Baumann F, He JS & Scholten T (2013) Soil organic pools and stocks in permafrost-affected soils on the Tibetan Plateau. *PLoS ONE* 8(2): e57024. [DOI: 10.1371/journal.pone.0057024]

Gandhi DS & Sundararapandian S (2017) Soil carbon stock assessment in the tropical dry deciduous forest of the Sathnur reserve forest of Eastern Ghats, India. *Journal of Sustainable Forestry* 36: 358–374.

Gandhi S (2016) Large-scale carbon stock assessment in tropical dry deciduous forest of Sathnur reserve forest, Eastern Ghats, India (Doctoral dissertation). Pondicherry University, Puducherry, India, pp. 1–152.
Gautam TP & Mandal TN (2013) Soil characteristics in moist tropical forest of Sunsari district, Nepal. *Nepal Journal of Science and Technology* 14: 35–40.

Gebrehiwot K, Desalegn T, Woldu Z, Demissew S & Teferi E (2018) Soil organic carbon stock in Abune Yosef afroalpine and sub-afroalpine vegetation, northern Ethiopia. *Ecological Processes* 7: 6.

Gray JM, Bishop TFA & Wilson BR (2015) Factors controlling soil organic carbon stocks with depth in eastern Australia. *Soil Science Society of America Journal* 79: 1741–1751.

Gupta MK & Sharma SD (2011) Sequestered carbon: organic carbon pool in the soils under different forest covers and land uses in Garhwal Himalaya region. *International Journal of Agriculture and Forestry* 1: 14–20.

Gupta MK & Sharma SD (2013) Sequestered organic carbon status in the soils under grassland in Uttarakhand State, India. *Applied Ecology and Environmental Sciences* 1: 7–9.

Gupta MK & Sharma SD (2014) Sequestered organic carbon status in the soils under forests land in Haryana state, India. *Octa Journal of Environmental Research* 2: 211–220.

Gupta MK, Sharma SD & Kumar M (2014) Status of sequestered organic carbon in the soils under different land uses in southern region of Haryana. *International Journal of Science, Environment and Technology* 3: 811–826.

Gurmesa B, Demesse A & Lemma B (2016) Dynamics of soil carbon stock, total nitrogen, and associated soil properties since the conversion of Acacia woodland to managed pastureland, parkland agroforestry, and treeless cropland in the Jido Komolcha district, southern Ethiopia. *Journal of Sustainable Forestry* 35: 324–337.

Henry M, Valentini R & Bernoux M (2009) Soil carbon stocks in ecoregions of Africa. *Biogeosciences Discussion* 6: 797–823.

Hiederer R & Kochy M (2012) Global soil organic carbon estimates and the harmonized world soil database (EUR 25225EN). JRC, European Commission, Ispra, Italy, pp. 1–79.

Hiederer R (2009) *Distribution of organic carbon in soil profile data*. JRC, European Commission, Italy. EUR - Scientific and Technical Research Series - (ISSN 1018-5593), pp. 3–4.

Hombegowda HC, Van Straaten O, Köhler M & Hölscher D (2016) On the rebound: soil organic carbon stocks can bounce back to near forest levels when agroforests replace agriculture in southern India. *Soil* 2: 13.

IPCC (2000) *Land use, land-use change and forestry, IPCC Special Report*. Cambridge University Press, United Kingdom.

Iqbal S & Tiwari SC (2016) Soil organic carbon pool under different land uses in Achanakmar Amarkantak biosphere reserve of Chhattisgarh, India. *Current Science* 110: 771–773.

Jana BK, Biswas S, Sonkar S, Majumder M, Roy PK & Mazumdar A (2010) Estimation of soil carbon stock and soil respiration rate of recreational and natural forests in India. In: Jana BK & Majumder M (eds) Impact of climate change on natural resource management. Springer-Verlag, Houten, Netherlands, pp. 329–343.

Jobbagy EG & Jackson RB (2000) The vertical distribution of soil carbon and its relation to climate and vegetation. *Ecological Applications* 10: 423–436.

Joos F & Spahni RE (2008) Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. *Proceedings of the National Academy of Sciences (PNAS)* 105: 1425–1430.

Joshi HG (2012) Vegetation structure, floristic composition and soil nutrient status in three sites of tropical dry deciduous forest of West Bengal, India. *Indian Journal of Fundamental and Applied Life Sciences* 2: 355–364.

Kirsten M, Kaaya A, Klinger T & Feger KH (2016) Stocks of soil organic carbon in forest ecosystems of the eastern Usambara Mountains, Tanzania. *Catena* 137: 651–659.

Kitayama K & Aiba SI (2002) Ecosystem structure and productivity of tropical rain forests along altitudinal gradients with contrasting soil phosphorus pools on Mount Kinabalu, Borneo. *Journal of Ecology* 90: 37–51.

Kujur M & Patel AK (2012) Quantifying the contribution of different soil properties on microbial biomass carbon, nitrogen and phosphorous in dry tropical ecosystem. *International Journal of Environmental Sciences* 2: 2272–2284.

Kumar A & Sharma MP (2016) Estimation of soil organic carbon in the forest catchment of two hydroelectric reservoirs in Uttarakhand, India. *Human and Ecological Risk Assessment: An International Journal* 22: 991–1001.
Kumar JIN, Kumar RN, Kumar RB & Sajish PR (2010) Tree species diversity and soil nutrient status in three sites of tropical dry deciduous forest of western India. *Tropical Ecology* 51: 273–279.

Kuruppuwarachchi KAJM, Seneviratne G & Madurappperuma DB (2016) Carbon sequestration in tropical forest stands: Its control by plant, soil and climatic factors. *Open Journal of Forestry* 6: 59–71.

Lal R (2004a) Soil carbon sequestration in India. *Climatic Change* 65: 277–296.

Lal R (2004b) Soil carbon sequestration in natural and managed tropical forest ecosystems. *Journal of Sustainable Forestry* 21: 1–30.

Latte N, Colinet G, Fayolle A, Lejeune P, Hebert J, Claessens H & Bauwens S (2013) Description of a new procedure to estimate the carbon stocks of all forest pools and impact assessment of methodological choices on the estimates. *European Journal of Forest Research* 132: 565–577.

Mastan T, Anjali C, Parveen SN & Reddy MS (2015) Assessment of soil organic carbon in three different land use patterns in semi-arid Kadapa district, Andhra Pradesh, India. *International Journal of Current Research in Biosciences and Plant Biology* 2: 38–42.

Mcfarlane KJ, Torn MS, Hanson PJ, Porras RC, Swanson CW, Callaham MA & Guilderson TP (2013) Comparison of soil organic matter dynamics at five temperate deciduous forests with physical fractionation and radiocarbon measurements. *Biogeochemistry* 112: 457–476.

Mohanraj R, Saravanam J & Dhanakumar S (2011) Carbon stock in Kolli forests, Eastern Ghats (India) with emphasis on aboveground biomass, litter, woody debris and soils. *Iforest* 4: 61–65.

Moser G, Leuschner C, Hertel D, Graefe S, Soethe N & Iost S (2011) Elevation effects on the carbon budget of tropical mountain forests (S Ecuador): the role of the belowground compartment. *Global Change Biology* 17: 2211–2226.

Neumann-Cosel L, Zimmermann B, Jefferson S, Van Breugel M & Helmut E (2011) Soil carbon dynamics under young tropical secondary forests on former pastures: A case study from Panama. *Forest Ecology and Management* 261:1625–1633.

NOAA (2017) *Atmospheric CO2 Mauna Loa Observatory, Hawaii* (NOAA-ESRL). Preliminary data released March 6, 2017. Available from: https://www.co2.earth/ (accessed: 10 Mar. 2020).

Ortiz CA, Liski J, Gardenas AI, Lehtonen A, Lundblad M, Stendahl J, Argen GI & Karlton E (2013) Soil organic carbon stock changes in Swedish forest soils - a comparison of uncertainties and their sources through a national inventory and two simulation models. *Ecological Modelling* 251: 221–231.

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA & Hayes D (2011) A large and persistent carbon sink in the world’s forests. *Science* 333: 988–993.

Pandian E & Parthasarathy N (2016a) Decadal (2003–2013) changes in liana diversity, abundance and aboveground biomass in four inland tropical dry evergreen forest sites of peninsular India. *Journal of Forestry Research* 27: 133–146.

Pandian E & Parthasarathy N (2016b) Tree Diversity Changes over a Decade (2003–2013) in Four Inland Tropical Dry Evergreen Forest Sites on the Coromandel Coast of India. *Journal of Forest and Environmental Science* 32: 219–235.

Pandian E & Parthasarathy N (2017) Tree growth, mortality and recruitment in four inland tropical dry evergreen forest sites of Peninsular India. *Biodiversitas: Journal of Biological Diversity* 18: 1646–1656.

Panwar VP & Gupta MK (2013) Soil organic carbon pool under different forest types in Himachal Pradesh. *International Journal of Farm Sciences* 3: 81–89.

Patil SD, Sen TK, Chatterji S, Sarkar D & Handore RM (2014) Changes in soil organic carbon stock as an effect of land use system in Gondia district of Maharashtra. *International Journal of Environmental Sciences* 5: 372–382.

Paz CP, Goosem M, Bird M, Preece N, Goosem S, Fensham R & Laurance S (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 Bio-carbon fund of the World Bank, Arlington, USA, pp. 19–35.

Phillips J, Ramirez S, Wayson C & Duque A (2019) Differences in carbon stocks along an elevational gradient in tropical mountain forests of Colombia. *Biotropica* 51: 490–499.

Post WM, Emmanuel WR, Zinke PJ & Stangenberger AG (1982) Soil carbon pools and world life zones. *Nature* 298: 156–159.
Raich JW & Schlesinger WH (1992) The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus, Series B* 44: 81–99.

Raich JW, Russell AE, Kitayama K, Parton WJ & Vitousek PM (2006) Temperature influences carbon accumulation in moist tropical forests. *Ecology* 87: 76–87.

Ramachandran A, Jayakumar S, Haroon RM, Bhaskaran A & Arockiasamy DI (2007) Carbon sequestration: Estimation of carbon stock in natural forests using geospatial technology in the Eastern Ghats of Tamil Nadu, India. *Current Science* 92: 323–331.

Ramana CV, Raju KN, Basha O & Reddy MS (2017) Estimation of soil organic carbon and soil respiration in a dry forest-Guvalacheruvu Reserve Forest of Kadapa hill ranges. *Proceedings of the International Academy of Ecology and Environmental Sciences* 7: 90.

Ravindranath NH, Somasekhar BS & Gadgi M (1997) Carbon flows in Indian forest. *Climatic Change* 35: 297–320.

Sahu SC, Sharma J & Ravindranath NH (2015) Carbon stocks and fluxes for forests in Odisha (India). *Tropical Ecology* 56: 77–85.

Santos LTD, Marra DM, Trumbore S, Camargo PB, Chambers JQ, Negron-Juarez RI, . . . Higuchi N et al (2015) Windthrows increase soil carbon stocks in a Central Amazon forest. *Biogeosciences Discussions* 12: 19351–19372.

Schindlbacher A, De Gonzalo C, Diaz-Pines E, Gorria P, Mathews B, Inclan R, Zechmeister-Boltenstern S, Rubio A & Jandl R (2010) Temperature sensitivity of forest soil organic matter decomposition along two elevation gradients. *Journal of Geophysical Research, Biogeosciences* 115: G03018. [DOI: 10.1029/2009JG001191]

Schrumpf M, Guggenberger G, ValarezoManosalvas C & Zech W (2001) Tropical montane rain forest soils. Development and nutrient status along an altitudinal gradient in the south Ecuadorian Andes. *Geographical Society of Berlin (Die Erde)* 132: 43–59.

Schulp CJE, Nabuurs GJ, Verburg PH & De Waal RW (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.

Sheikh AM, Kumar M, Bussman RW & Todari NP (2011) Forest carbon stocks and fluxes in physiographic zones of India. *Carbon Balance and Management* 6: 1–10.

Sheikh MA, Kumar M & Bussmann RW (2009) Altitudinal variation in soil organic carbon stock in coniferous subtropical and broadleaf temperate forests in Garhwal Himalaya. *Carbon Balance Management* 4: 6.

Shen H, Wang XC & Shi WM (2001) Isolation and identification of specific root exudates in elephant grass in response to mobilization of iron- and aluminium phosphates. *Journal of Plant Nutrition* 24: 1117–1130.

Shrestha BP (2009) Carbon sequestration in SchimaCastanopsis forest: a case study from Palpa District. *The Greenery* 7: 34–40.

Singh V, Tewari A, Kushwaha SPS & Dadhwal VK (2011) Formulating allometric equations for estimating biomass and carbon stock in small diameter trees. *Forest Ecology and Management* 261: 1945–1949.

Smith P (2008) Soil organic carbon dynamics and land-use change. In: Braimoh AK & Vlek PLG (eds) *Land use and soil resources*. Springer, New York.

Soethe N, Lehmann J & Engels C (2007) Carbon and nutrient stocks in roots of forests at different altitudes in the Ecuadorian Andes. *Journal of Tropical Ecology* 23: 319–328.

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.

Sundarapandian SM, Dar JA, Gandhi DS, Srinivas K & Subashree K (2013) Estimation of biomass and carbon stocks in tropical dry forests in Sivagangai district, Tamil Nadu, India. *International Journal of Environmental Science and Engineering Research* 4: 66–76.

Throop H, Archer SR, Monger HC & Waltman S (2012) When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. *Journal of Arid Environments* 77: 66–71.

Thuille A, Buchmann N & Schulze ED (2000) Carbon stocks and soil respiration rates during deforestation, grassland use and subsequent Norway spruce afforestation in the Southern Alps, Italy. *Tree Physiology* 20: 849–857.

Townsend AR, Vitousek PM & Trumbore SE (1995) Soil organic matter dynamics along gradients in temperature and land-use on the island of Hawaii. *Ecology* 76: 721–733.
Trumbore SE, Chadwick OA & Amundson R (1996) Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. *Science* 272: 393–396.

Tsui CC & Chen ZS (2013) Soil organic carbon stocks in relation to elevational gradients in volcanic ash soils of Taiwan. *Geoderma* 209: 119–127.

Twongirwe R, Sheil D, Majaliwa JGM, Ebanyat P, Tenywa MM, Van Heist M & Kurmar L (2013) Variability of soil organic carbon stocks under different land uses: a study in an afro-montane landscape in southwestern Uganda. *Geoderma* 193: 282–289.

Tsui CC & Chen ZS (2013) Soil organic carbon stocks in relation to elevational gradients in volcanic ash soils of Taiwan. *Geoderma* 209: 119–127.

Twongirwe R, Sheil D, Majaliwa JGM, Ebanyat P, Tenywa MM, Van Heist M & Kurmar L (2013) Variability of soil organic carbon stocks under different land uses: a study in an afro-montane landscape in southwestern Uganda. *Geoderma* 193: 282–289.

Vanlalfakawma DC, Lalumnawia F & Tripathi SK (2014) Soil carbon pools of bamboo forests of Mizoram, India. *Science Vision* 14: 46–50.

Velmurugan A, Suresh K, Dadhwal VK & Gupta MK (2014) Soil organic carbon status of Indian forests. *Indian Forester* 140: 468–477.

Venkanna K, Mandal UK, Raju AJS, Sharma KL, Ravikant VA, Pushpanjali B, Reddy BS, Masane RN, Venkatravamma K & Babu BP (2014) Carbon stocks in major soil types and land-use systems in semiarid tropical region of southern India. *Current Science* 106: 604–611.

Walkley A (1947) An estimation of methods for determining organic carbon and nitrogen in soil. *Journal of Agriculture and Science* 25: 598–609.

Wang M, Su Y & Yang X (2014) Spatial distribution of soil organic carbon and its influencing factors in desert grasslands of the Hexi corridor, Northwest China. *Plos ONE* 9: 94652. [DOI: 10.1371/journal.pone.0094652]

Waring C, Stockmann U, Malone BP, Whelan B & McBratney AB (2014) Is percent “projected natural vegetation soil carbon” a useful indicator of soil condition? In: Hartemink AE & Mcsweeney K (eds) *Soil Carbon*. Springer, New York, pp. 219–227.

Yadav RS, Pandya IY & Jangid MS (2015) Estimating status of soil organic carbon in tropical forests of Narmada Forest Division, Gujarat, India. *International Research Journal of Environment Sciences* 4: 19–23.

Zimmermann M, Meir P, Silman MR, Fedders A, Gibbon A, Malhi Y, et al. (2010) No differences in soil carbon stocks across the tree line in the Peruvian Andes. *Ecosystems* 13: 62–74.