



Soil organic carbon stocks in the forests of different continents

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Abstract

Carbon stocks in soil vary substantially across the globe depending on the type of forests, their locations, and soil depths. We applied meta-analysis to 64 relevant published data with no restriction of published date, country, and journals. However, it was always kept in mind to include high impacted journals. The aim of this review was to evaluate whether soil organic carbon (SOC) varies with forest types, soil depths, and altitudes. Globally, the SOC stocks in the forests were found in the order of Boreal forest (BF) > Subalpine forest (SAF) > Temperate forest (TeF) > Afromontane forest (AfMF) > Montane forest (MF) > Subtropical forest (SF) > Alpine forest (AF) > Tropical forest (TF) ranging from 64.3 t/ha to 206.6 t/ha, the minimum is in tropical forest and maximum in the boreal forest. The SOC stocks were also found varied with soil depths and forests of different continents too. The maximum value of SOC stocks was 366.94 t/ha in 0-40 cm soil depth and the minimum value was 20.16 t/ha in the 80-100 cm soil depth. Linear relationship of SOC stocks was obtained with altitudes, the value increases along the increasing elevations. In conclusion, SOC stocks varied as forests, soil depths, and elevations.

Keywords: Elevation, forest types, soil depth, soil organic carbon, SOC stocks

DOI: <https://doi.org/10.3126/on.v20i1.45219>

Manuscript details: Received: 21.01.2022 / Accepted: 11.05.2022

Citation: Gachhadar, P., C.B. Baniya and T. Mandal 2022. Soil organic carbon stocks in the forests of different continents. *Our Nature* 20(1): 57-69. DOI: <https://doi.org/10.3126/on.v20i1.45219>

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Introduction

Soil is the largest sink of organic carbon on the earth. It has the ability to stock 1.5-3 times more amount of carbon than the plants in the forest ecosystem (Lal, 2004; Stockmann *et al.*, 2013; Ciais *et al.*, 2014). It is a key component in the global carbon cycle and an important indicator of sustainable forestry (Davidson and Janssens, 2006; Bangroo *et al.*, 2017). Minor changes in the stock of soil organic carbon (SOC) in terrestrial ecosystems may affect the global carbon cycle (Lal, 2005; Nave *et al.*, 2010; Li *et al.*, 2013).

Soil organic carbon is influenced by climate (Davidson and Janssens, 2006), soil physical properties, disturbance regimes such as fire (Harden *et al.*, 2015), deforestation (Tolessa and

Senbeta, 2018), and landslides (Błońska *et al.*, 2018). Climate affects both plant growth and yields, and it mediates decomposition rates thus impacting the quantity and rate of carbon cycling. Nevertheless, there are several other controlling factors such as topography (Cardinael *et al.*, 2017), soil type (Albaladejo *et al.*, 2013; Zhang *et al.*, 2020), soil depth (Li *et al.*, 2013; Niu *et al.*, 2015; Lozano-García *et al.*, 2016; Pandey and Bhusal, 2016), soil biota (Zhang *et al.*, 2020), forest types (Tewksbury and Van Miegroet, 2007; Baishya and Barik, 2011), altitudes (Bangroo *et al.*, 2017) and aspects (Lozano-García *et al.*, 2016). However, altitude is not directly influencing the ecosystem but it influences climatic factors mainly temperature and moisture to a great extent (Dar and Somaiah, 2015) that

governs the nature of the vegetation and process of soil formation (Chaudhari *et al.*, 2013). SOC increases with precipitation and clay content gradients and decreases with temperature gradient (Jobbágy and Jackson, 2000; Bhattacharyya *et al.*, 2008), which has been confirmed on regional and global scales (Yang and Feng, 2007). Temperate forests show increasing trend in SOC stocks with increasing altitude (Zhu *et al.*, 2010). Sometimes surface soil is not strongly related with altitude (Dieleman *et al.*, 2013).

Rainfall increases with altitude, which characterizes the soil properties, soil processes and its formation (Dahlgran *et al.*, 1997) hence influences biomass production. Soil moisture increases with altitude up to temperate climate and decline thereafter reaching the lowest in upper alpine. Soil temperature will be highest in tropical and subtropical conditions; which declines with the altitude. These probably make soil moisture and soil temperature suitable for the optimum growth, productivity and litter production in temperate forests thereby resulting highest SOC stock build up in the temperate climate (Zhu *et al.*, 2010; Singh *et al.*, 2011; Dar and Sundarapandian, 2016). Intensive sunlight radiation at less dominated by large trees with closed canopy in lower altitude may also facilitate organic matter formation on the soil (Liu *et al.*, 2018). Human and animal interference is also high in lower altitude which may lead to an accumulation of manure and other organic substance which in return might also be resulted in accelerated decomposition of litters. Thus amount of SOC storage depends upon rate of decomposition and carbon input, vegetation types and its net primary productivity, soil properties (Tian *et al.*, 2010). Species variability, type, age, soil and climatic variability, aboveground biomass and belowground biomass, dead wood, litter, herbaceous biomass and soil also affect the change in SOC stocks (Yosef *et al.*, 2019).

Top soil layer found to have lower bulk density that means soil is better for the plant growth as compared to soil at the lower depth (Ali *et al.*, 2017; Ghimire *et al.*, 2018). That means SOC contents is less with the increasing soil depth but bulk density is high. Lower layer of soil contains less fine roots, less SOC stocks, less soil

contents, soil dwelling organisms and high compaction (Bajracharya *et al.*, 2004; Shrestha and Singh, 2008). The soil organic carbon (SOC) stocks decreases with increasing soil depths (Sheikh *et al.*, 2009; Sakin *et al.*, 2011; Chaudhari *et al.*, 2013), while Bulk density (BD) increasing with increase in the depth of soil profile for all the land uses as the soil property remains less. Degraded soil contains low SOC stocks due to lower amount of organic matter (Chaudhari *et al.*, 2013), which happened due to lowering input of leaf litter, low decomposition of fine roots, greater soil disturbances, lower root biomass and loss of vegetation (Rattan Lal, 2014; Ghimire *et al.*, 2018). The review tried to document the average value of SOC stocks in different forests and even SOC stocks by forest types in different continents. It gives an idea that which continent is rich in forest diversity and rich in SOC stocks even in soil properties.

Materials and Methods

Reviewing of literatures focusing on SOC and altitudes, forest types and soil depths was done through online database and search engines. Google scholar, ResearchGate, Nepjol, Agora, Hinari were used to search literature. During search keywords such as “carbon stock”, “soil”, “soil organic carbon”, “forest soil”, “forest”, “forest carbon”, “SOC altitudinal gradient”, “and soil depth” were used in order to include maximum relevant literatures. We crosschecked references of relevant articles centered on SOC. We critically reviewed each searched literature. The steps of literature reviewed are given in the Figure 1. There was no limitation of countries and year of publications. We found a total of 37 journals with impact factor ranging from 0.07 to 4.8 and 8 journals were without impact factors but listed under ISI.

A matrix based on information about forest types, altitude, soil depth and SOC from each literature was prepared. The measurement unit of SOC stocks was made uniform i.e all were converted into ton per hectare (t/ha) unit. The unit of altitudes in feet from the sea level was converted into meter and the unit of soil depth for all literature was made uniform by changing into centimeter (cm), if they were in meter (m) or other

units. The aim of this review is to review the patterns of SOC stocks along varied altitudes along different forest types and the soil depths. Data matrixes were used to analyze response and predictors. Soil organic carbon was the main response and the response variable was analyzed against forest types, countries, soil depth. Each

analyzed result was presented in the form of figure. F-statistics was used in order to compare significant P-value among categorical forest types, depths. Data were analyzed with the help of R software (R Core Team, 2020).

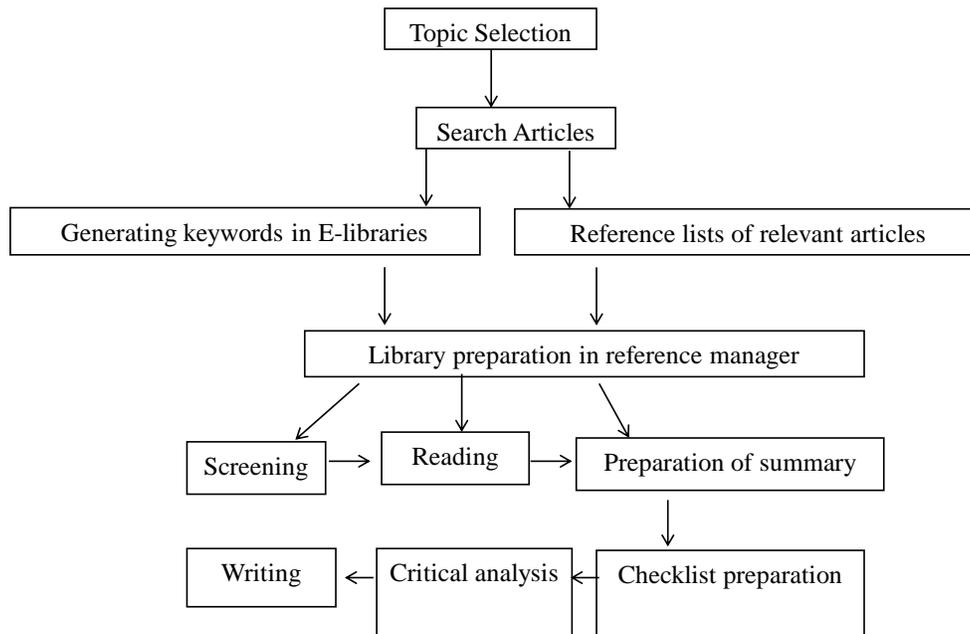


Figure 1. Flow chart of conceptual framework.

Results and Discussion

Soil organic carbon in different forest types

Soil organic carbon varied significantly in various forests types. Averaging the value of all similar forests of different continents the values of SOC stocks were ranging from 64.3 t/ha to 206.6 t/ha from tropical forests to boreal forests (Figure 2). The values of SOC stocks in different forests recorded showed the pattern of increasing trend in the order of BF > SAF > TeF > AfMF > MF > SF > AF > TF. The highest value of SOC stocks was recorded in the boreal forests and the lowest in tropical forests. Soil organic carbon is known to be a very dynamic entity which varies across forest

types. Fascinatingly, different forest types showed different pattern of soil organic carbon stocks, which may be dense to the inclusion of all available data across the globe (various forest plots differing in age, disturbance, regime, climate, species composition, and edaphic conditions etc). Inconsistent to the present result, boreal forests were found to concern high SOC stocks than the temperate forest which may be due to tree species composition (Asase *et al.*, 2012; Chand *et al.*, 2018), edaphic factors (McFarlane *et al.*, 2013), sampling density (Yuan *et al.*, 2013), aspects (Sharma *et al.*, 2011). Tropical forest on the other hand were found to have the lowest SOC stocks which might be due to deforestation (Gurung *et al.*, 2015) as also suggested by Chand *et al.*

(2018). Terai tropical forests (Pandey and Bhusal, 2016; Bhattarai and Mandal, 2018) regenerating forest (Behera and Sahani, 2003), opposite of this the SOC stocks were high in afforested forests with improved soil quality (Nwaogu *et al.*, 2018) and managed forests (Kafle, 2019). The highest SOC stock in boreal forest of Asia perhaps because of lowest decomposition rate and low efflux of CO₂ from the soil (Tewksbury and Van

Miegroet, 2007). While in montane forest of this continent showed lowest SOC stock might be due to effect of high altitude, where litter input is low resulting low carbon accumulation in the soil (Shaheen *et al.*, 2017). SOC stock in the boreal forest of Asia was greater than in the temperate forest (Wei *et al.*, 2013; Zhu *et al.*, 2017). Temperate forests of Africa showed the highest value of SOC stocks than other continents.

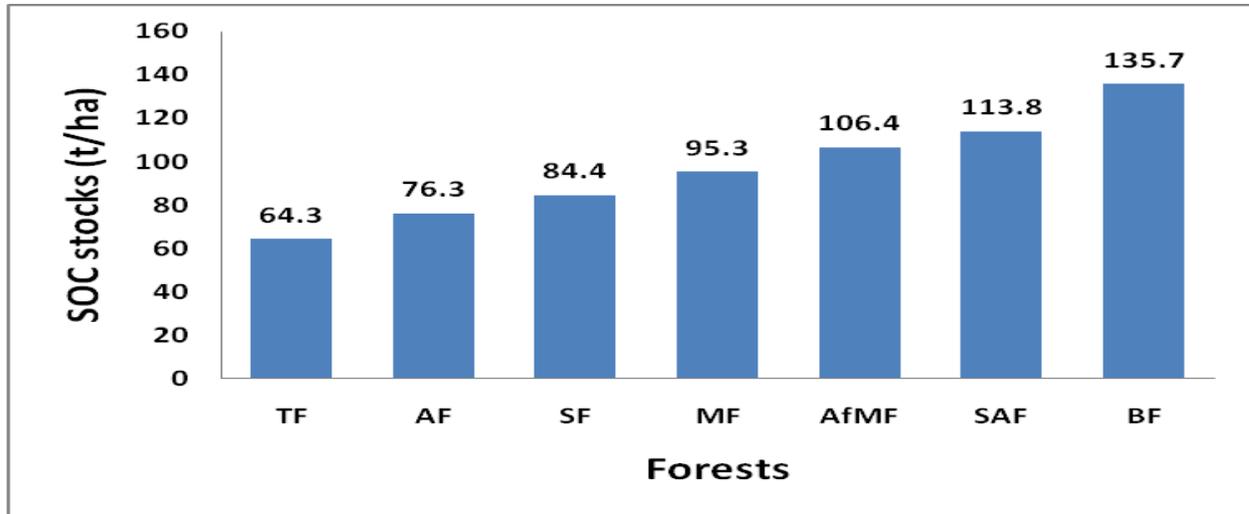


Figure 2. Forest types and their mean SOC stocks.

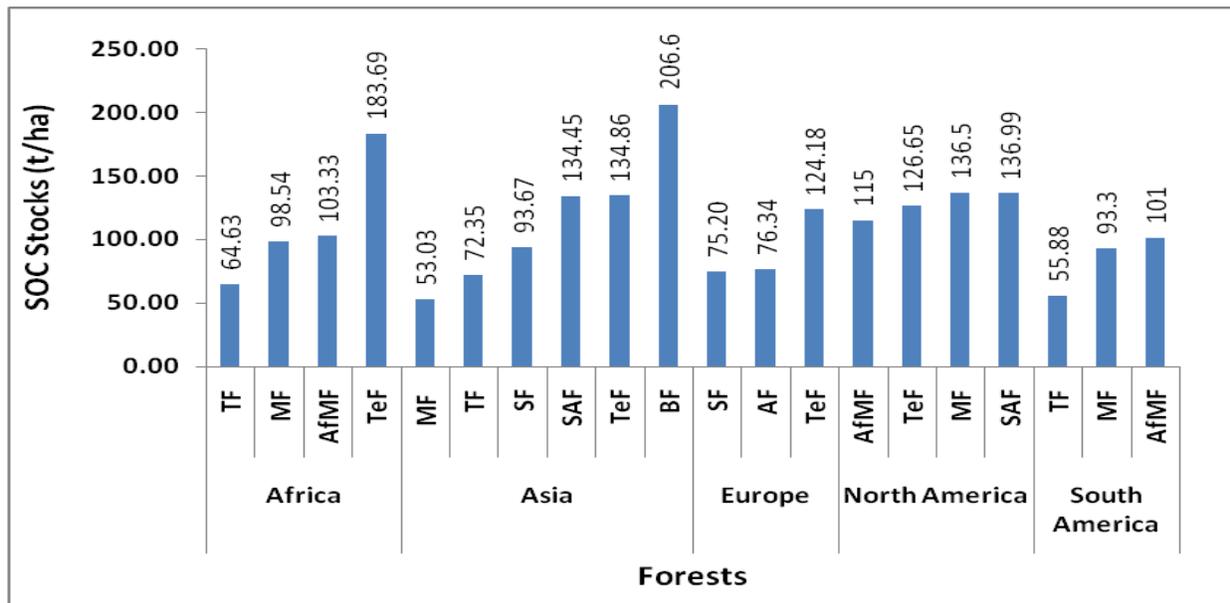


Figure 3. SOC Stocks by forest types in different continents.

The result showed low value of SOC stocks in tropical forest in different continents. SOC depends upon the quantity of litter in the floor and

biomass (Tashi *et al.*, 2016). While tropical forests of India contained larger canopy tree like *Pinus smithiana* and *Abies pindrowand* forests

(Gupta and Sharma, 2011; Bohra *et al.*, 2015) and higher SOC stocks in lower altitudes that might be due to increase in tree species diversity, changes in species composition and soil microbial and micro fungal biomass (Behera and Sahani, 2003). The estimates of SOC stocks of temperate forests significantly higher in Africa, Temperate forests have experienced low human and natural disturbances and relatively low temperature and moderately high precipitation, which slow down the decomposition process (Zhu *et al.*, 2010).

The climatic conditions in the temperate forests are suitable for growth, productivity and litter production. Suitable temperature and moisture possibly favour production of larger fine particles in soil along with high amount of litter that forms the organo-mineral complexes, ultimately producing highest SOC stocks in the temperate forests (Singh *et al.*, 2011). Climate change and forest management systems also play role to increase of soil organic carbon, such as harvested forests revealed higher SOC stock (Suberi *et al.*, 2016). Higher accumulation of SOC stock in temperate forests might be because of forest temperature, composition, forest basal area as well as quantity of leaf litter (Tashi *et al.*, 2016). Temperate forest encountered relatively high SOC stocks that might be because of soil under mixed species (Maraseni and Pandey, 2014), presence of iron, clay and less disturbance in temperate forests (Limbu *et al.*, 2013).

Soil type and lithology play important role for accumulation of soil organic carbon (Albaladejo *et al.*, 2013). Annual precipitation and texture are known as predictors in forest lands. In contradiction of the present review SOC stock decreases with decreasing rainfall in humid climatic conditions where there is less vegetation cover (Sinoga *et al.*, 2012). Soil organic carbon (SOC) stocks generally increases with forest age, cool temperature combined with high precipitation. The soil organic carbon (SOC) stocks distribution pattern is closely similar in the Afro-Montane forests of America and Africa which may be due to similar environmental conditions (temperature and precipitation conditions) and rate of decomposition (Eshetu and Hailu, 2020; Dahlgren *et al.*, 1997; Twongyirwe *et al.*, 2013). Alpine forests showed moderately

lower SOC stocks among the other forests that may be due to climatic condition and land use change (Martín *et al.*, 2016). And they also reported as topsoil had higher SOC stocks, indicates higher biomass production in the north Spain in the alpine region.

SOC stocks along soil depths

Mostly, soil carbon is available in the form of organic carbon obtained from the living organisms stored in deep soil layers (below 20 cm) over long period of time (Fontaine *et al.*, 2007).

In the upper 10 cm soil thickness, the highest SOC stocks i.e. 94.95 t/ha was recorded in the upper layer which gradually decreased to SOC stocks value, 37.21 t/ha in lower layer of 20-30 cm soil depth (Figure 4a) due to litter decomposition and forest types and species, resulting low organic matter in the inner layer (Wei *et al.*, 2013; Albaladejo *et al.*, 2013; Ali *et al.*, 2017; Adhikari and Ghimire, 2019; Pandey *et al.*, 2019). High value of SOC stocks might be due to effect of vegetations (Ranabhat *et al.*, 1997, Sinoga *et al.*, 2012; Mahato *et al.*, 2016). Interestingly, the SOC stocks at 20 cm thickness of soil, the SOC stocks value showed more or less dumbbell shaped curve, where high value were revealed in the 30-50cm of soil depth (Figure 4b). In contrast, in the 30 cm thickness of soil, the value of SOC stocks showed in dumbbell shaped curve and the lowest value of SOC stocks was in the middle in 10-40 cm soil depth (Figure 4c).

High amount of SOC stock in top layer than the lower or inner soil layer is due to high soil organic carbon matter content in the upper layer of soil and favourable conditions for rapid decomposition of forest litter (Sheikh *et al.*, 2009; Dahal and Bajracharya, 2012; Shrestha and Devkota, 2013). SOC gradually decreases in the inner soil depth due to low leaf litter and root litter contents and their decomposition (Zhang and Ding, 2017). Similarly, in the lowest depth, there is low microbial biomass which impacts input and output activities of soil (Sharma *et al.*, 2014). On the other hands, the highest SOC stocks (122.38 t/ha) were revealed in the soil depth 30-50cm. In contradiction of this result, it was also recorded that the lower soil organic carbon in upper layer than the inner layer of the soil, which is surprising (Twongyirwe, *et al.*, 2013; Sharma *et al.*, 2014;

Tashi *et al.*, 2016). It was also observed that low SOC stocks in the upper most layer, 0-30cm than the inner most layer, 30-60cm. In contrast top soil contains more nutrients which is responsible for higher SOC stocks (Niu *et al.*, 2015; Nwaogu *et al.*, 2018). The high SOC stocks in deeper soil (30-100cm) depth is due to fine soil particles and land use factor (Singh *et al.*, 2011), which favours the present review study. Bulk density also responsible for variation in SOC stocks; Soil depth brings variation in bulk density i.e. gradual increase in bulk density with the increase in soil

depth. Top soil layer contains lower bulk density that means soil is better for the plant growth compare to the lower depth of soil. So SOC content is less with the increasing soil depth but bulk density is high (Sheikh *et al.*, 2009; Chaudhari *et al.*, 2013). Lower layer of soil contains less fine roots, less soil contents, soil dwelling organisms, high compaction and less property which consequently resulting in having less SOC stocks (Bajracharya *et al.*, 2004; Shrestha and Singh, 2008).

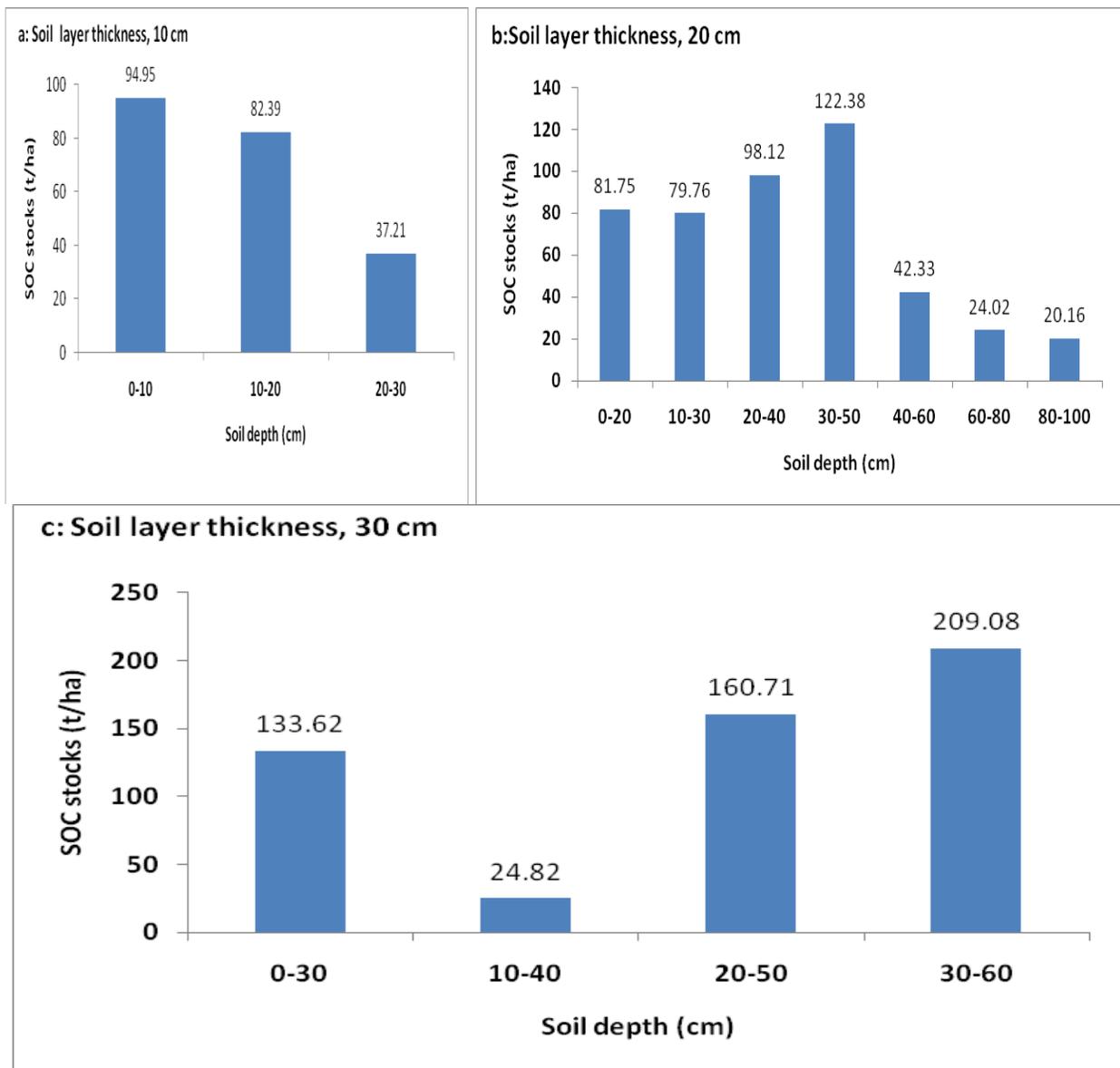


Figure 4. (a,b,c); Soil organic carbon stocks in the forest along different soil depths.

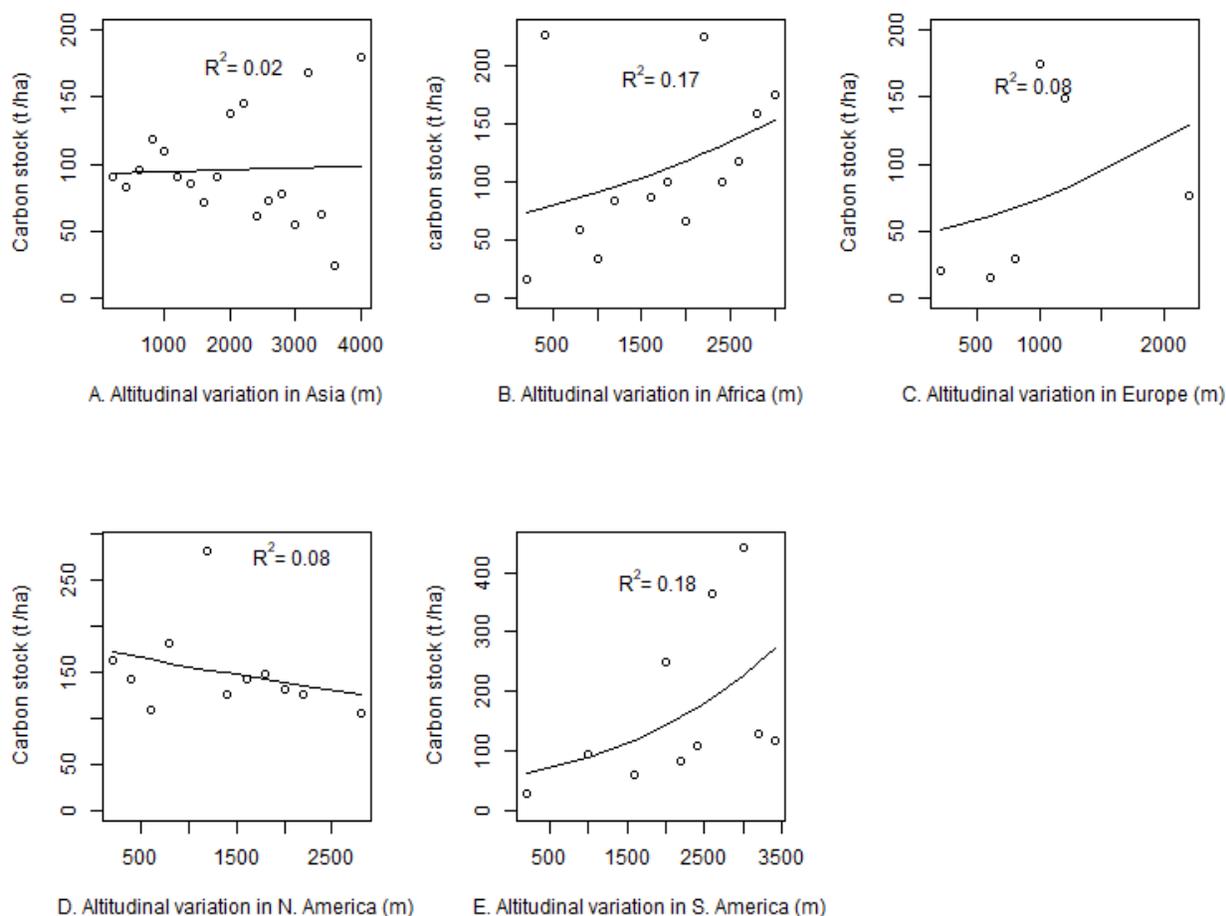


Figure 5. Forest soil organic carbon stocks along varied elevations in different continents.

Soil organic carbon along variation in altitudes

Altitudes play significant role in the variation of SOC stocks (Ji *et al.*, 2015). The soil organic carbon stocks value showed linear relationship with altitude. It means the soil organic carbon stocks increases when the altitude increases in forests of all continents (Figure 5). When altitude increases, temperature decreases and precipitation becomes maximum. Temperature and moisture alter the rate of decomposition SOC stocks showed significantly an increasing trend with increase in altitude (Maraseni and Pandey, 2014; Dar and Somaiah, 2015; Tashi *et al.*, 2016), climatic condition (Chen *et al.*, 2017; Salinas *et al.*, 2011), and age of tree species (Sharma *et al.*, 2009). Altitude was not a variable directly influencing the ecosystem but it influences

climatic factors mainly temperature and moisture to a great extent (Dar and Somaiah, 2015). SOC stocks in temperate climate was higher than the subtropical climate (Singh *et al.*, 2011). SOC stocks in the hill sal forests was high than the tarai sal forests (Bhattarai and Mandal, 2018).

In contrast to the above statement, SOC stocks consistently exhibited decreasing pattern along increasing elevations (Sheikh *et al.*, 2009b; Shaheen *et al.*, 2017; Bangroo *et al.*, 2017), as in higher altitude there was low vegetation which results low accumulation of litter and low input of organic carbon (Bohra *et al.*, 2015). On the other hand no clear trend of SOC stocks with altitude (Ranabhat *et al.*, 1997) which might be due to change in aspects. SOC stocks showed fluctuation

along the altitude (Jiang *et al.*, 2019). The result showed SOC stocks were positively correlated with increasing altitude in the forests of Africa, Europe and South America. High SOC stocks with increasing altitude may be due tree species, species diversity, abundance and richness of species with high liter fall. *Juniperous* species are responsible for high SOC stocks (Manaye *et al.*, 2019). While in North America, forests showed decreasing pattern of SOC stocks with increasing altitude (Leuschner and Moser, 2011; Tewksbury and Miegroet, 2007). Low SOC stocks was reported in temperate forests which might be the effect of soil depths, temperature and precipitation or climatic conditions and boosts up biomass production because of better soil aggregation (Sinoga *et al.*, 2012; Albaladejo *et al.*, 2013). SOC stocks increases with increasing altitudes (Usuga *et al.*, 2010) as total annual rainfall increase with altitude, which controls the soil properties, soil process and development (Dahlgren *et al.*, 1997).

Conclusion

The present review concluded that the total SOC stocks in Africa, Asia, Europe, N america and south America was 450.19 t/ha, 488.36 t/ha, 275.72 t/ha, 515.14 t/ha, 250.18 t/ha respectively. Among them the SOC stocks was highest in north America and lowest in south America. The SOC stocks vary with forest type and soil depths. Globally, the SOC stocks in the forests were found in the order of BF> SAF> TeF> AfMF> SF> MF> AF> TF. This indicates that wood productions is increasingly limited by environmental constraints or assimilate shortage when approaching the uppermost limit of tree growth. Generally, soil organic carbon stocks decreases with increasing soil depths. Altitude alters the soil organic carbon of forests. SOC stocks show linear relationship with altitudes. That means the soil organic carbon stock increases with increasing altitude in the forests of all continents but the relation is not so strong.

Acknowledgements

We grateful to Mr. Baburam Nepali and Mr. Madan Bhattarai for their assistance during data analysis.

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