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Review Article

Forest Soil Carbon in Relation to Elevation in Sikkim

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Altitude, which affects tropical, temperate and alpine environs, is an important ecological factor of soil formation. With the variation in altitude, climatic conditions change and as a result contrasting flora can be seen at different altitudes, which in turn influence the development of soils. Vegetation and soils develop with mutual interaction and both are dependent upon external environment. Precipitation and temperature are the major components of climate and change linearly with altitude. The vegetation and litter coverage increase with the elevation and so does the soil organic matter. Forest soils of Sikkim developed from granite-gneiss at different altitudes and supported different vegetations. The latter were studied to find out their relation with the altitude. The soil reaction (pH) of the soils is acidic at the surface and increases towards alkalinity gradually with the increase in soil depth. It bears significant negative correlation with the altitude. Soil organic carbon (SOC) is high at higher altitude and within the profile it is more on the surface and decreases with the increase in soil depth. As a consequence, the bulk density of soil bears significant negative correlation with altitude. The result thus indicates that with the increase in altitude, there is an increase in soil organic carbon pool which virtually reduces the bulk density of soil. The SOC stock is influenced by aspect and vegetation type of the area. The increasing tendency of carbon density with the increase in altitude indicates its better stabilization at cooler temperature, higher precipitation with lesser microbial activity. On the other hand, the lower density of organic carbon at lower hill areas remains as a potential threat for the soils. The carbon stock up to 60 cm soil depth under forest cover of South and West Sikkim combined is 213.39 million tons.

Keywords: Forest Soils; Characteristics; Soil Organic Carbon Stock; Vegetation Type; South and West Sikkim

Introduction

Soil is the largest pool of terrestrial organic carbon in the biosphere, storing more carbon than that in plants and the atmosphere combined (Schlesinger, 1997; FAO, 2006 and Lal, 2008) and containing approximately 2344 Gt (1 gigaton = 1 billion tones) of organic carbon globally (Stockmann, 2013). Worldwide the first 30 cm of soil holds 1500 Peta gram (1 Peta gram, Pg = 10^{15} gram) carbon (Batjes, 1996) and for the soils of India, it is 9 Pg (Bhattacharyya *et al*., 2000). About 40% of the total Soil Organic Carbon (SOC) stock of the global soils resides in forest ecosystem (Eswaran *et al*., 1999). Forests contribute to process of carbon sequestration and act as carbon sink, which is important for reduction of greenhouse gases and global warming. Dhadwal and Nayak, (1993) estimated the total carbon pool of Indian forests as 1994 million tons (Mt) for the year 1985 which was much less than other estimates (Rabindranath and Somashekhar, 1995, Lal and Singh, 2000). Thus, forests are one of the most significant store houses of carbon and play a crucial role in reducing the atmospheric CO_2 levels by sequestering carbon into the growing biomass through the process of photosynthesis and also by increasing the soil organic carbon content which is vital in maintaining carbon balance around the globe. The Himalayan zone, with dense forest vegetation covers nearly 19% of India and contains 33% of SOC reserve of the country (Bhattacharyya *et al*., 2008).

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The most relevant factors that control SOC stock are altitude, climate, vegetation, topography and soil (depth) (Baldock and Nelson, 2000). Altitudinal gradient induces micro-climate which impacts directly on SOC content and rate of mineralization primarily through the effects of temperature and moisture (Banerjee and Prakasham, 2012; Banerjee, 2014). The rate of SOC sequestration and the magnitude and quality of soil C stock depend on the complex interactions between climate, soils, tree species and management, and chemical composition of the litter which is determined by the dominant tree species (Lal, 2005). Temperature is the key factor controlling the rate of decomposition of biomass, as a consequence soils in cooler climate and in moist regime usually contain more organic carbon due to slower mineralization rates (Banerjee, 2014). Vegetation also has a marked influence on SOC concentration (Berg, 2000; Dutta *et al*., 2001; IPCC, 2000) and is the main source of carbon either from the decomposition of aerial plant parts or underground plant parts. Therefore, the sequestration potential of a soil depends on the vegetation it supports (IPCC, 2000; Houghton, 2003; Grace, 2004). Forest ecosystem represents a significant carbon pool to global carbon budget and may significantly contribute to mitigation of global climate change and sustainable agriculture (Lal, 2004; Smith, 2004). In addition, the sequestration potential of a soil also depends on its physical and chemical characteristics, its mineralogical composition, depth of the solum, soil drainage, availability of water and air, and the temperature of the soil (Lal, 2005).

The influence of Land Use Land Cover (LULC) type, altitude and aspect direction on SOC density and its vertical distribution in the soil profile in the northern part of Wang watershed in Western Bhutan was studied by Dorji *et al*. (2014). They observed that the north facing slopes at 3500 to 4000 m zone stored the largest SOC density in comparison to other LULC Types, altitudinal zones and aspect directions with different LULC types. The study reveals that vegetation and soil moisture as influenced by altitudinal variation of precipitation are the main factors controlling the distribution of SOC density in the soil profile.

The influence of forest type, altitude as well as climate change on SOC stock in the Temperate mountains of Kashmir Himalayas under *Betulautilis forests* and *Juglansregia* forests were studied at three depths (0-10, 10-20, and 20-30 cm respectively) by Ahmad Dar and Somaiah (2015). They observed an increasing trend of SOC stock and decreasing trend of Bulk density with increase in altitude. The results suggest that SOC stocks in temperate forests of Kashmir Himalaya vary greatly with forest type and altitude as well as the climate change influencing the carbon sequestration potential.

Sheikh *et al*. (2009) studied the stocks of SOC along altitudinal gradients in the coniferous subtropical and broadleaf temperate forests of Garhwal Himalayas. The SOC stocks were found to decrease with decrease in altitude from 185.6 to160.8 t Cha^{-1} and from 141.6 to 124.8 t Cha^{-1} in temperate (*Quercus leucotrichophora*) and subtropical (*Pinus roxburghii*) forests, respectively.

The variation of organic matter content in different forest types at two different soil depths (0-50 cm and 0-100 cm) were studied by Chhabra *et al*. (2003) and they estimated total soil organic pool in Indian forests as 4.13 Pg C in top 50 cm and 6.81 Pg C in top 100 cm of soil. The estimated soil organic carbon densities by forest types can be used in the form of models for estimation of C release from forest by deforestation as well as the historic loss in soil organic C from Indian forests.

Sikkim, the smallest state in north-eastern India developed from granite-gniess on Eastern Himalayas, enjoys a wide range of climate, physiography, and vegetations influencing the formation of different kinds of soil. Over 81% of the total geographical area of the state is under forest with a variety of natural flora and fauna. The addition of organic matter on the forest floor through litterfall and its subsequent decomposition in this state has got a profound effect on the nature of the soil being formed. Soil organic carbon (SOC) in the forests of the Eastern Himalayas is important to estimate their contribution to regional, national and global carbon stocks. This information is poor and scanty for the SOC stock of the Eastern Himalayas. No published information is available for the Sikkim Himalayas. Keeping the foregoing observations in mind, an attempt has been made to develop the SOC stock of forest soils of Sikkim and also to study its variability pattern with respect to land use, physiography and climate.

Study Site

Sikkim is a small state of India in the Eastern Himalayas with steep mountains and deep valleys. It lies between latitudes 27°52 N to 20°92 N and longitudes 87°592 E to 88°562 E. It is bound by Nepal in the west and Bhutan in the east and China in the north and north-east. In the south it shares its border with the state of West Bengal. Sikkim has four districts – East Sikkim, West Sikkim, North Sikkim and South Sikkim. The study was undertaken in the South and West Sikkim districts.

The horse shoe area viz., the Chola ridge towards the East, the Singalila ridge towards the west and the mighty Himalayan axis at the north enclose Sikkim, which traps the moisture-laden winds from Bay of Bengal. Consequently, Sikkim receives plenty of rain round the year. Within the altitude ranging from 280m to 8585m, Sikkim has a diverse climate ranging from tropical to high alpine. In the foot hills and lower valleys, almost tropical conditions prevail. With the rise in altitude, temperature decreases and rainfall increases. Average annual rainfall of Sikkim is 3208mm. Maximum average temperature is 39°C during July-August and minimum of 7°C in December.

Sikkim is a botanical paradise due to the existence of dense forests with new and phyto-geographically interesting taxa. The forest vegetation in the study area is mostly evergreen, semi-evergreen with coniferous and deciduous forests in patches. Generally, deciduous species are mostly found in the lower hill areas whereas coniferous species are mostly found in the middle and upper hill ranges. The forest vegetations found in the lower hill region (300 to 900m) of the study area includes *Tectona grandis, Shorea robusta, Pinus roxburghii* etc. In the middle hill (900 to 1800m), *Cryptomeria japonica* alone occupies maximum areas. Other species found are *Bucklandia populnea, Schima wallichii, Michelia champaca,* and *Jambosa formosa* with under growth of cardamom. In the upper hill area (1800 to 2700m), the forest species are *Castanopsis hystrix, Symplocos thiefolia, Quercus lamellose, Acer campbelli, and Michelia excelsa* . The hills of Sikkim mainly consist of gneissose and schistose rocks, producing generally poor and shallow brown clay soils. This type of soil tends to support evergreen and deciduous forests.

Material and Methods

The study was carried out along an altitudinal gradient between 300 and 2700m above mean sea level (msl) in southern and western Sikkim districts. In south Sikkim, out of 571 sq.km forest cover, 93 sq.km is very dense forest, 371 sq.km is moderately dense forests and 107 sq.km is open forest. Similarly, in west Sikkim district, out of 772 sq.km forest area, 110 sq.km, 489 sq.km and 173 sq.km areas are occupied by very dense, moderately forest and open forests respectively. After selecting randomly 50% of the total forest area in each district, representative sampling was done between 300-900 m, 900-1800 m and 1800-2700 m. At each of these elevation zones, 10 to 12 plots of 100 m x 100 m size were demarcated and six to eight sampling points in each plot were selected on the basis of canopy cover, aspect and slope. From each point, 3 soil samples were collected at 0-15 cm, 15-30 cm and 30-60 cm depth. The altitude of the sampling points was recorded by altimeter. Soil samples of each depth at the same altitude, aspect and slope were mixed separately and a composite sample of each depth was prepared. In this way, 47 composite samples of each depth were collected. In the present investigation, soil depth for sampling was restricted to 60 cm so as to maintain uniformity. The depth of the soil profile in many cases does not exceed 80 cm.

In the laboratory, the fresh soil samples were air dried, and sieved through 2 mm to remove gravels and roots and analyzed for different physical and chemical characteristics following standard procedures (Black, 1965; Jackson, 1973). Bulk density (BD) was determined by the field-moist method using core samples (dia. 50 mm) of known volume (100 cubic cm) (Blake and Hartge, 1986). The size of total SOC stock was calculated using the method described by Batjes (1996). In the first step soil organic C density (t/ha) was computed by multiplying organic C percent, soil bulk density (Mg/m^3) and thickness of horizon (cm) for individual soil profiles with different thickness varying from 0 to 15, 15 to 30 and 30 to 60 cm. The data is then grouped according to different altitudinal levels i.e., lower hill (300 to 900 m), middle hill (900 to 1800 m) and upper hill (1800 to 2700 m).

Results

In the present study, the characteristics of the soils averaged over different depth ranges i.e. 0-15, 15-30 and 30-60 cm showed that the pH of the upper hill soils varies from 3.6 to 4.6, followed by middle hill soils (3.9-4.8) and lower hill soils (4.8-5.7). However, the average surface soil (0-15 cm) acidity of the upper, middle and lower hills is 4.3, 4.4 and 5.4, respectively indicating the influence of climate, vegetation and altitude on soil acidity. The pH of the surface soil bears significant negative ($r = -0.7789$) correlation with altitude and organic carbon ($r = -0.4610$).

The KCl pH of these soils is always lower than water pH showing –pH (pH KCl–pH H_2O), negative indicating that the pH values of these soils are very near to their zero point of charge (Brady, 1984; Bleeker and Sageman, 1990). Organic carbon content of soils is high and it varies from 1.39 to 2.02% in the surface soils (0-15 cm) of lower hill with a mean value of 1.65%; 3.10 to 5.20% in the middle hill soils with a mean value of 3.98%; and 3.56 to 6.35% in the upper hill soils with a mean value of 4.78% reflecting the influence of elevation on the storage of soil organic carbon. Organic carbon content of the surface soils bears highly significant positive correlation with altitude ($r = 0.8930$).

The increasing trend of soil organic carbon with increase in altitude was also observed by several workers (Chambers, 1998, Garten *et al*., 1999; Bolstad and Vose, 2001). Banerjee (2014) while studying the forest soil carbon stock along an altitudinal gradient in Darjeeling Himalayan Region observed that the maximum SOC was in the alpine and high altitude forest sites, followed by middle altitude and low altitude forest sites. In each altitudinal zone, SOC gradually decreases from the surface with the increase in soil depth indicating higher biological activity associated with top layer (Bhattacharyya *et al*., 2000; Banerjee and Prakasham, 2012; Banerjee, 2014; Ahmad Dar and Somaiah, 2015; Sheikh *et al*., 2009; Gangopadhyay *et al*., 1990; Gupta and Sharma 2013; Charan *et al*., 2012). Bhattacharyya *et al*. (2008) reported that the lower atmospheric temperature at subzero levels causes hyper aridity which does not support vegetation growth and the reason of high SOC content at cold micro climate of high altitude soils is mainly due to higher organic carbon content in top soil (humus rich). Batjes (1996) stated that for the 0 to 100cm depth approximately 50% of soil organic carbon (SOC) appears in the first 30cm of the soil. Jobbagy and Jackson (2000) showed that 50% of the SOC is concentrated in the top 20cm in forest soils. Civeira *et al.* (2012) showed that SOC in the upper 30cm of soils in Argentina is much higher than in the 30-100cm interval. Data provided by these authors and the results obtained in this study may be comparable because in the present case we used a 60cm depth and the above mentioned authors used a 1m depth. A large proportion of input is from above ground litter in forest soils and hence soil organic matter tends to concentrate in the upper soil horizon. Soil organic matter is in a state of dynamic balance between inputs and outputs of organic carbon. Inputs are largely determined by the forest productivity, the decomposition of litter, root mortality, its incorporation into the mineral soil; rates of organic matter decay and the return of carbon to the atmosphere through respiration outputs (Pregitzer, 2003). These together contribute to soil carbon inputs along the elevation gradient. Although the rate of SOM decomposition varied throughout the year in response to fluctuations of soil temperature and moisture, the maximum apparent decay rate was higher at lower elevation sites than at the high elevation site because of the temperature difference (Wang *et al*., 2003). Lower temperature at higher elevation decreases soil organic matter decomposition and provides longer residence time and soil organisms play a major role in litter decomposition. Increasing trend of SOC content and stock with increasing altitude could also be due to constant carbon inputs and constant rate of carbon loss, but reduced decomposition of organic matter due to lower soil temperature at high altitude as compared to that of lower altitude. As storage of soil organic carbon is dynamic (i.e. C derived from the atmosphere is ultimately cycled back to the atmosphere, Bhattacharyya *et al*., 2004), the residence time of C in soil is a major determinant of the capacity of a soil to sequester C (Luo *et al*., 2003).

Sand is the major component of soil in the lower (62 to 83%) and middle (51 to 76%) hill sites and in the upper hill site it varies from 26 to 58%. The illuviation of clay from surface to the lower layers with the formation of well developed argillic sub-surface diagnostic horizon (Soil Survey Staff, 2014) has been observed in the upper hill soils. Similar observation has been made by Gangopadhyay *et al.* (1986) in the high altitude soils of Sikkim Forest Division. The clay percentage in the upper hill sites owes its existence to the parent materials which seem to contain biotite and muscovite as the major constituents. Biotite weathers through a series of interstratified minerals to vermiculite and/or smectite phases which may decompose rapidly to kaolinite (Fordham, 1990). Both vermiculite and smectite phases appear to be dioctahedral, on the basis of chemical compositions determined from microprobe data. Weathering products are first apparent on the edges of laminae, where interstratified minerals are formed at right angles to both the edge face and the cleavage. Weathering soon develops along cleavage planes, initially most strongly near the edges of flakes, but then permeating extensively into the body of flakes and subdivided segments. The orientation of interstratified minerals and kaolinite within cleavages is parallel to the cleavage (Fordham, 1990).

Cation exchange capacity (CEC) of soil varies from 6.8 to 20.9 cmol(p^+) kg^{-1} indicating mica may be the dominant clay mineral. CEC does not bear any correlation with the distribution pattern of clay and organic carbon. Base saturation is much higher in the surface soil (0-15cm) of the lower hill zone in comparison to middle and upper hill zones. It bears highly significant positive correlation with pH ($r = 0.8468$) and highly significant negative correlation with altitude ($r = –0.9057$). The concept of base saturation is important, because, the relative proportion of acids and bases on the exchange sites determine soil reaction (pH). As the number of base ions (Ca^{2+}, Mg^{2+}) decreases, the number of H^+ and Al^{3+} ions increases pH drops. The drop of pH is accompanied by a decrease in base saturation and a consequent increase in exchange acidity.

Soil formation in a leaching environment is accompanied by a gradual loss of base cations, especially Ca^{2+} from the cation exchange complex. The soils thus become progressively unsaturated and increasingly acidic. The hydrogen ions in solution which cause this, originate from the soluble acids that form during the decomposition of organic matter in the surface horizon of the soils (Encyclopedia of Soil Science, 2008).

Bulk density (BD) of the surface (0-15cm) soil varies from 1.26 to 1.61 Mgm^{-3} in the lower hill sites with a mean value of 1.39 Mgm^{-3}; 0.95 to 1.22 Mgm^{-3} in the middle hill sites with a mean value of 1.09 Mgm^{-3}; and 0.90 to 1.22 Mgm^{-3} in the upper hill sites with a mean value of 1.09 Mgm^{-3}. In the sub-surface (15-30 cm) and subsoil (30-60 cm), BD varies from 1.54 to 1.77 Mgm^{-3} in the lower hill sites (300-900 m) with a mean value of 1.66 Mgm^{-3}; from 0.95 to 1.11 Mgm^{-3} in the middle hill sites (900-1800 m) with a mean value of 1.25 Mgm^{-3}; and from 1.11 to 1.19 Mgm^{-3} in the upper hill sites with a mean value of 1.16 Mgm^{-3} respectively. The results indicate that lower content of organic carbon is associated with higher values of soil BD. BD of the surface soils bears highly significant negative correlation with SOC ($r = –0.9294$).

Inverse correlation between SOC and BD is normal (Jeffrey, 1970). The results also indicate that with the increase in the altitude, there is a decrease in BD at three depths. Altitude bears significant negative correlation with BD of the surface soils ($r = - 0.7917$); the correlation between altitude and SOC is positive.

The maximum carbon stock up to 60 cm soil depth varies from 181.2 to 237.0 tha^{-1} with a mean value of 205.80 tha^{-1} and is present in the altitudinal range between 1800-2700 m. Minimum carbon stock ranges from 63.0 to 94.4 tha^{-1} with a mean value of 74.45 tha^{-1} in the altitudinal range of 300-900 m. The carbon stock present in the upper hill sites (1800- 2700 m) and middle hill sites (900-1800 m) is more than double in comparison to that in lower hill zone (300-900 m). The results thus indicate that with the increase in altitude, there is an increase in soil organic carbon pool (Fig. 1). The SOC stock is comparatively low in the lower hill soils mainly due to increasing temperature in the lower hill areas with more microbial activity which decomposes most of the organic carbon present in the soil. Again, the vegetation present in the lower hill soils mainly represents deciduous forest species along with some coniferous species which influence the soil properties including the SOC stock through the differential nature and content of organic debris returned to the forest floor through litter fall. However, the higher rate of deforestation in the lower hill areas also may be an important cause for low SOC stock of the soils. As a result, the variation in SOC stock in the lower hill soils is due to the combine effect of altitude, and nature and characteristics of forest vegetation.

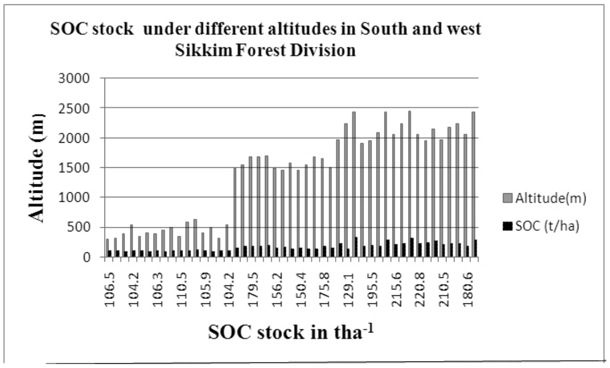

Fig. 1: SOC stock under different altitudes in south and west Sikkim Forest Division

The middle hill areas in comparison to the lower hill areas are cooler with less microbial activity and mostly consists of coniferous species with needle shaped leaves which are resistant to decomposition. The huge amount of organic matter accumulates on the forest floor in the form of leaves and litter increases the organic carbon content in the soil through slow decomposition process resulting in high SOC stock of the soils. Again, within the conifer species, the nature and content of organic debris returned to the forest floor also varies (Nath *et al*., 1986). The upper hill soils mainly consist of ever green broad-leaved forest species in combination with conifers. The lower temperature in the upper hill areas retards the decomposition of organic matter due to lower microbial activity under highly acidic conditions. However, the variation in SOC stock, even in these soils, is mainly influenced by the variation in the forest species that in turn determine the extent of accumulation of leaves, litter and their decomposition to humus.

Except in the lower hill site (up to 900 m), the soil organic carbon stock up to 60cm soil depth is much higher as compared to national average of SOC stock of India which is 183.2 tha^{-1} (Jha *et al*., 2003). But, when we consider the carbon stock altogether starting from 300 to 2700 m, the average comes to 158.89 tha^{-1} which is slightly lower than the national average because of much lower organic carbon content in the lower hill zone.

The forest cover of south and west Sikkim combined, based on interpretation of satellite data (FSI, 2011) is 1343 km^2 (very dense forest 203 km^2, medium dense forest 860 km^2 and open forest 280 km^2) which is 70.1% of the total geographical area of south and west Sikkim. Therefore, the carbon density up to 60 cm soil depth under forest cover of south and west Sikkim combined turns out to be 213.39 million ton.

Discussion

The soil organic carbon content in the surface is much higher in comparison to sub-surface and subsoil due to accumulation of a large proportion of inputs in the form of litter on the surface. SOC increased with increasing precipitation, clay content and altitude and decreased with increasing temperature (Jobbagy and Jackson, 2000) and the correlation is positive due to decrease in temperature at higher altitudes with increase in precipitation; but, forest type and large SOC accumulation depend not only on climate, but also on vegetation type. Coniferous forest soils contain lower SOC compared to those of broad-leaved forests. Former generally has smaller needle shaped leaves with high net litter fall but the rate of decomposition is slow in comparison to that of the broad-leaved forests. Lower values of SOC are observed in the middle altitude coniferous forests when compared with high altitude broad-leaved forest. However, the soils of broad-leaved forests at lower elevation accumulate low C, which may be due to climate. The increase of SOC with the increase in altitude is influenced by decreasing temperature, increasing precipitation causing soil acidity. Cooler temperature and higher precipitation retard the decomposition of litter. The amount of organic matter in soils and its rate of decomposition vary in different climatic conditions. Since the rate of carbon dioxide efflux increases as a function of soil temperature (Davidson and Janssens, 2006), soils in cold climate keep more soil organic matter (SOM) than those of warm climate. The production of carbon dioxide in soils is almost entirely from root respiration, microbial decomposition of organic matter and microbial respiration. Chambers (1998) reported that the soil respiration declines with increasing altitude leading to reduced loss of carbon. The significant negative correlation of BD (bulk density) with altitude confirms the observation of increasing SOC with the increase in altitude. The soils with high organic matter accumulation have higher per cent pore space in the soil and these results in lower bulk density. By contrast, the soils with lower amount of organic matter are lower in per cent pore space that results in higher BD (Ali *et al*., 2014). In our study, pH had negative correlation with SOC and altitude. The decrease in pH with increasing altitude could be due to the increase of base cation leaching at higher altitude because of greater rainfall. From the study, it is evident that the forest soils of Sikkim originating from granite-gneiss and supporting different types of vegetation at different altitudes differ in SOC stock at all the depths (0-15, 15-30 and 30-60 cm). This could be explained because of the changes in forest type; quality and quantity of litter; above and below ground biomass; and local area under the vegetation. In addition, changes in the mean annual temperature and precipitation along an altitudinal gradient also play an important role.

The comparison of the forest soil carbon of Sikkim Himalayas with other Himalayan regions revealed that SOC of the forest soils of Sikkim Himalayas are higher at high altitude; and within the profile, it is more on the surface and decreases with the increase in soil depth. It indicates that soil organic carbon pool increases with altitude which virtually reduces the bulk density. Thus, the increasing tendency of SOC with altitude indicates its better stabilization at cooler temperature, higher precipitation and lesser microbial activity. Similar findings were also recorded for Kashmir Himalayas (Dar and Somaiah, 2015), and Western and Central Bhutan under Eastern Himalayas (Simon *et al*., 2018). However, a similar study in Garhwal Himalayas (Sheikh *et al*., 2009) and in Shimla district of Himachal Pradesh (Reddy and Gupta, 2018) indicated decrease in soil carbon density with the increase in soil depth showing the non-ability of soil to stabilize organic matter with elevation probably due to the removal of forest cover through severe deforestation.

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