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Forest soils of south and west Sikkim at various altitudes: their characteristics and soil organic carbon stocks

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Abstract : Forest soils in South and West Sikkim, developed from granite-gneiss at varying altitudes and under diverse vegetation types, were studied to assess their characteristics and soil organic carbon (SOC) stock up to a depth of 60 cm. Surface soils exhibit low pH values, which gradually increase with depth and show a significant negative correlation with altitude. SOC concentrations are highest at the surface and decrease with increasing depth, displaying a significant positive correlation with altitude. The SOC stock is influenced by both the aspect and vegetation type of the area. The increasing trend of carbon density with altitude suggests enhanced stabilization under cooler temperatures, higher precipitation, and reduced microbial activity. Conversely, the lower carbon density in the lower hill regions poses a potential threat to soil health. The total carbon stock up to 60 cm depth under forest cover in South and West Sikkim is estimated at 213.39 million tons.

Keywords: *Forest soils, South and West Sikkim, altitudinal variation, soil organic carbon stock.*

Introduction

The nature of soil-plant interaction and the role of vegetation in soil formation are well recognised. In forest soils, spatial variations in soil properties are primarily driven by the rooting and litter fall characteristics of the perennial vegetation (Banerjee *et al.*, 1986). As such, differences in vegetation cover may naturally lead to variations in the resultant soils (Gangopadhyay and Banerjee, 1987). Altitude, which affects tropical, temperate, and alpine environments, is an important ecological factor in soil formation. With variations in altitude, climatic conditions change, resulting in quite contrasting flora growing at different altitudes, which in turn influence the development of soils (Gangopadhyay *et al.,* 1990).

Soil is the largest pool of terrestrial organic carbon in the biosphere, storing more carbon than that in plants and the atmosphere combined (FAO, 2006; Lal, 2008). The most relevant factors that control SOC stock are altitude, climate, vegetation, topography and profile depth (Baldock & Nelson, 2000). Altitudinal gradients induce microclimates, which directly impact SOC content and the rate of mineralisation, primarily through the effects of temperature and moisture (Banerjee and Prakasham, 2012; Banerjee, 2014). The rate of SOC sequestration, as well as the magnitude and quality of soil C stock, depend on the complex interaction between climate, soils, tree species, management, and the chemical composition of the litter, as determined by the dominant tree species. Temperature is the key factor controlling the rate of decomposition of biomass; as a consequence, soils in cooler climates and in moist regimes usually contain more organic carbon due to a

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slower mineralisation rate (Banerjee, 2014). Vegetation also has a marked influence on SOC concentration (Berg 2000; Dutta *et al.* 2001; Berg and Meentemeyer 2002) and is the primary source of carbon, either from the decomposition of aerial plant parts or underground plant parts. Therefore, the sequential potential of a soil depends on the vegetation it supports (IPCC, 2000; Dutta *et al.,* 2001). The forest ecosystem represents a significant carbon pool in the global carbon budget and may significantly contribute to mitigating global climate change and promoting sustainable agriculture (Lal, 2004). In addition, the sequential potential of a soil also depends on its physical and chemical characteristics, mineralogical composition, depth of the solum, soil drainage, water and air availability, and the temperature of the soil environment (Bhattacharyya et al., 2000, 2008).

The primary way carbon is stored in the soil is as soil organic matter (SOM), a complex mixture of carbon compounds consisting of decomposing plant and animal tissues, microbes, and carbon associated with soil materials. The sequestration potential depends on the chemical characteristics of the SOM and its ability to resist microbial decomposition (Swift, 2001). To sustain the productivity of soils, knowledge of SOC in terms of its amount and quality is essential. An attempt has therefore been made to study the characteristics of the soils and estimate the SOC stock under varying altitudes, aspects, slopes, and vegetation cover in the physiographic region of the South and West Districts of Sikkim state.

Materials and Methods

Sikkim is a small, beautiful state of India in the Eastern Himalayas with Steep mountains and deep valleys. It lies between latitudes $27^0 5'$ N to $27^0 9'$ N and longitudes $87^0 59'$E to $88^0 56'$E. It is wedged between Nepal in the west, Bhutan in the east, and China in the north and north-east. In the south, it shares its border with India's West Bengal state. Sikkim is divided into four districts: East Sikkim, West Sikkim, North Sikkim, and South Sikkim. The study was conducted in South and West Sikkim, encompassing a total forest area of 1,343sq km (571 sq km in South Sikkim and 772 sq km in West Sikkim). Sikkim receives a significant amount of rainfall throughout the year. Average annual rainfall is 3208 mm. With an altitude ranging from 280 m to 8585 m, Sikkim has a diverse climate, ranging from tropical to high alpine. In the foothills and lower valleys, almost tropical conditions prevail. With an increase in altitude, temperature decreases and rainfall increases. The maximum average temperature is 39 °C during July and August, and the minimum is 70 °C in December.

Sikkim state is a real botanical paradise due to the existence of dense forests with new and phyto-geographically interesting taxa. The forest vegetation in the study area is predominantly evergreen, with semi-evergreen and coniferous forests interspersed 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 areas. The forest vegetation found in the lower hill region (300 - 900 m) of the study area includes Tectonagrandis, Shorearobusta, Pinus roxburghii, etc. In the middle hills (900 – 1800 m), Cryptomeria japonica alone occupies the maximum areas. Other species found are *Bucklandiapopulnea, Schimawallichii, Micheliachampaca, Jambosaformosa,* etc. with undergrowth cardamom. In the upper hill (1800 – 2700m) area, the forest species are *Castanopsishystrix, Symplocosthiefolia, Quercus lamellosa, Acer campbelli, Micheliaexcelsa,* etc. The hills of Sikkim mainly consist of gneissose and half-schistose rocks, producing generally poor and shallow brown clay soils. This type of soil tends to support evergreen and deciduous forests.

The study was carried out along an altitudinal gradient (300 - 2700 m above mean sea level) in the south and west 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 forest, and 107 sq km is open forest. Similarly, in west Sikkim, out of 772 sq km forest cover, 110 sq km, 489 sq km, and 173 sq km are very dense forest, moderately dense forest and open forest, respectively. After selecting randomly 50% of the total forest area in each district, the sampling was done from three strata (300 - 900 m, 900 - 1800 m and 1800 - 2700 m). At each of the selected strata, 10 to 12 plots of 100 m X 100 m in size were laid, 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 three depths (0 - 15 cm, 15 – 30c m and 30 – 60 cm). The altitude of the sampling points was recorded by an altimeter. Soil samples of each depth of the same altitude, aspect and slope were mixed separately, and a composite sample of each depth was prepared. In this way, a total of 47 composite samples of each depth were prepared. In the present investigation, soil depth was restricted to 60 cm to maintain uniformity, as thedepth of the soil profile in many cases does not exceed 75 to 80 cm.

Eleven representative profiles up to parent material were exposed along an altitudinal gradient (300 - 2700 m), the morphological features and soil characteristics of which were discussed elsewhere (Banerjee and Nath, 1991; Gangopadhyay*et al.,* 1986). Only the salient features of the pedons have been given here.

In the laboratory, fresh soil samples were air dried and sieved to 2 mm to remove gravels and roots and analysed for different physicochemical characteristics by standard procedures (Black, 1965; Jackson, 1973). The bulk density (BD) was determined by a field-moist method using core samples (dia. 50 mm) of known volume (100 cubic cm) (Blake & Hartge, 1986).

Results and Discussion

As a result of variation in altitude, aspect and climatic conditions, various types of forests are met with in this area. The vegetation patterns contain both natural and plantation stands. However, most of the plantations are old enough and have a pronounced influence on many soil properties. Moreover, at a particular site, after felling the old stands generally, new plantations of the same species are being tried. Therefore, the effect of that particular species on soil properties can easily be understood. Secondly, since a particular species can survive well in a particular altitudinal zone, the plantation of that species has been raised in that particular zone.

As previously mentioned, the hill forests of the two districts have been divided into three strata, viz., lower hill forests (300 - 900 m), middle hill forests (900 -1800 m) and upper hill forests (1800 - 2700 m). The lower hill forests occur in the Tista River Valley and the Rangeet River Valley. The forest species (*Shorearobusta, Tectonagrandis, Pinus roxburghii*, etc.) are 35 to 40 m in height and 120 to 140cm girth at breast height (gbh). Within the altitude of 900 to 1800 m, the forest is semi-evergreen to evergreen with trees of good height and diameter. *Phoebe attenuata, Bucklandiapopulnea, Schimawallichii, Castanopsistribuloides, Castanopsisindica, etc.,* are some of the important species of the first storey. The forest zone above 1800m is the most important in South and West Sikkim. The composition of the crop varies with the increase in altitude and variation in aspect and rainfall. The important species in the first storey are *Quercus lamellosa, Castanopsistribuloides, Andromeda elliptica, Q. pachyphylla, Machilus edulis, Nyssa sessiliflora, Acer campbellii, Prunus nepalensis, Symplocostheifolia, Alcimandracathcartii, Castanopsisindica,* etc. – all are natural species and attain maturity. In this altitudinal zone, the plantation of Cryptomeria japonica has been raised in some patches after clear-felling the old natural forests.

The salient features of the morphological characteristics of some typical pedons under different forest covers at different altitudes are described below.

1- **Typic Udipsamments** (altitude 300 m): The soils are well drained, shallow and bouldery, developed on alluvial/colluvial materials derived predominantly from sandstone. A litter layer of 3-4 cm exists above the mineral soil. Due to the westerly aspect and dense undergrowth, the profiles are usually moist in most parts of the year. The soils are acidic and pH of the surface soils varies from 5.2 to 5.6. Organic carbon in the surface soils varies from 3.0 to 3.5% and decreases sharply down the profile. Base status is very high in the surface as also in the subsurface horizons. The Ca:Mg ratio in the surface soil is higher under *Tectonagrandis,* indicating the recycling of Ca and Mg from lower to the surface horizon.

2. **Typic Udorthents (altitude 325 m):** The soils are well drained, moderately deep and derived predominantly from sandstone. The coarse texture of the parent material derived from sandstone, with predominance of quartz and its high permeability, does not allow pedo-genesis to proceed normally under the prevalent environment, and as such, horizons are indistinct and profile development is minimal. pH of the surface soil is more or less at par with pedon 1 and decreases sharply down the profile. However, the fertility status of the soil is satisfactory. Ca and Mg are recycled from the subsurface to the surface horizon under *Shorearobusta.*

3. **Humic Hapludults (altitude 450 m):** The soils are developed under mixed broad-leaved species. The slope is gentle, and the parent material is gneiss and micaceous schists. The soil is highly acidic, and the pH of the surface soil varies from 3.8 to 4.1, and organic carbon varies from 3.4 to 3.8%. The subsurface is a moderately thick argillaceous horizon (75-90cm).

4. **Typic Hapludalfs (altitude 500 m):** The soils have presented a unique feature. Within an altitude limit of 325 to 700 m, there has been an association of natural *Shorearobusta* and *Pinus roxburghii.* Solum depth varies from 60 to 150 cm and has a litter layer followed by an A1 horizon. The general red colour of the soils is due to their iron content derived from ferromagnesium silicate. Translocation of clay is distinct, as evidenced by the presence of clay skins on the ped surface. The soils are slightly acidic, and the pH of the surface soils varies from 6.0 to 6.2. Organic carbon content is low in comparison to other pedons. The base status is above 50% throughout the profile.

5. **Lithic Udorthents (altitude 1050 m):** The soils are situated on extremely steep slopes (60%) and developed on sandstone. The soil depth is very shallow and has a lithic contact within 50cm of the surface. The soils are acidic. pH of the surface soil varies from 4.6 to 4.8. Organic carbon is high, and in the surface soil, it varies from 4.5 to 4.9 per cent. As the fertility status of the soil is quite satisfactory, the plant stand comprising evergreen Broad-leaved species are very good. However, these soils are susceptible to severe erosion and landslides, causing great loss of valuable forest trees.

6. **Typic Dystrudepts (altitude 1490 m):** The soils are developed from gneiss and micaceous schists. The soils are very deep, well-drained and porous. The physiographic positions of the soils are such that they remain under the influence of a cloudy and moist microclimate for the most part of the year. Soils do not have distinct horizonation. Soil pH is acidic (pH of surface soils varying from 4.5 to 4.8) and is uniform down the profile. Organic carbon in the surface soils is very high, varying from 6.5 to 6.8 per cent, and gradually decreases with depth. The granular structure throughout the profile is due to the intimate mixing of the organic matter with soil separates. Ca and Mg have been recycled from lower to surface horizons, as evidenced by higher values of Ca: Mg ratios in the surface soils. The fertility status of the soils is satisfactory, and the forest is semi-evergreen to evergreen types of good height and diameter.

7. **Humic Dystrudepts (altitude 1540 m):** The soils are well drained and developed from alluvium/colluvium deposits of gneiss and micaceous schists under *Cryptomeria japonica*. The soils are situated on a 10% slope in the N-W aspect. The soils are moderately eroded and loam to gravelly loam in texture. Over the mineral soil, there is a thick litter layer followed by a thin humus layer. The surface soil is highly acidic, and the pH varies from 3.9 to 4.1. Organic carbon

content in the surface soil is also high and varies from 4.1 to 4.3 per cent. The soil is very low in base status. Illuviation of clay is common but not sufficient to qualify for an argillaceous subsurface diagnostic horizon. The Ca:Mg ratio decreases down the profile, indicating recycling of bases in the soil.

8. **Humic Dystrudepts (altitude 1800 m):**The soils are well drained and developed from gneiss. In spite of having been developed on very steep slopes (>25%), the soils possess a fairly deep solum. The soils have a thick litter layer followed by a comparatively thin humus layer. The colour of the surface mineral soil varies from dark reddish brown to dark brown. The soil structure is granular up to a considerable depth (78 to 85cm)of the solum. Although a major portion of the soils has very steep slopes, the plant cover, particularly the broad-leaved species, is fairly satisfactory. The soils are acidic, and the pH of the surface soils varies from 4.6 to 4.9; organic carbon content is very high in the surface soils and varies from 5.0 to 5.5 per cent and decreases regularly with depth. The fertility status is quite satisfactory, and therefore, the plant stand comprising evergreen broad leaf species is very good.

9. **Typic Hapludults** (1970 m): The soils are situated on a steep slope (20 – 25%) in the westerly aspect under a mixed natural forest of broad leaf species. The parent materials are alluvium/colluvium deposits of gneiss and micaceous schists. Over the mineral soil, there is a thick litter layer followed by a moderately thick humus layer. The soil is poorly drained and slightly eroded. The texture in the surface mineral soil is sandy loam, and the amount of clay increases down the profile, forming an argillaceous subsurface diagnostic horizon. The soil is highly acidic, with a pH of the surface soil varying from 4.3 to 4.6. Organic carbon is very high in the surface (6.34%) and decreases gradually down the profile. The decrease in exchangeable Ca:Mg ratio down the profile indicates considerable recycling of bases in the soil.

10. **Mollic Hapludalfs** (altitude 2240 m): The soils have a thick litter layer followed by a comparatively thin humus layer. The soil is very deep and distinct clay skins are present in the lower illuvial horizons which are very deep. The structure is granular, and iron concretion is present throughout the profile. The soils are highly acidic, and the pH of the surface soils varies from 4.4 to 4.6. Translocation of clay in the profile is very distinct. Organic carbon in the surface soils varies from 4.0 to 5.0 per cent and decreases gradually down the profile. Base status is high in the surface soils, varying from 52 to 58 per cent, but is surprisingly low (<25 per cent) under the *Cryptomeria japonica* plantation area. Broad-leaf species show very good performance in these soils.

11. **Humic Hapludults** (altitude 2375 m): The soils possess fairly deep solum in spite of having been developed on very steep slopes (>30%), and the plant cover is fairly to extremely satisfactory, and this feature mitigates the threat of alarming erosion, which otherwise would be an uncontrolled factor. The soils are highly acidic pH ranging from 3.5 to 4.0. Organic carbon content is also very high, varying from 6.4 to 6.6 per cent in the surface soils, and up to a certain depth, the high content is maintained, and then it falls sharply. Captivity of the base ions on the soil exchange complex is less than 50 per cent. Translocation of clay in the profile is very distinct. The clay percentage owes its existence to the parent material, which seems to contain biotite and muscovite as the major constituents. Broad-leaf species thriving on these soils are original species. Undergrowth Comprising mosses, lichens, grasses, and shrubs, they are abundant and tightly bind the soil.

The characteristics of the soils averaged over different depth ranges, i.e. 0-15, 15-30, and 30 – 60cm, reveal 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 surface soils (0 – 15 cm) of the upper, middle and lower hills vary from 4.2 to 4.4 with a mean value of 4.3, 4.0 to 4.8 with a mean value of 4.4 and 4.8 to 5.7 with a mean value of 5.4, respectively (Table 1). Altitude is one of the factors that influence the level of acidification. The effect of altitude determines several factors. These are:(1) Forest composition changes along the transect resulting the accumulation of different types of organic matter (broad leaved, conifers etc. having different decomposition rate) in soil, (2) Generally decreasing temperatures towards the higher elevations slows down organic matter mineralization and (3) Increasing precipitation at higher altitudes enhances soil leaching, causing loss of base cations and decrease of pH. Surface soil pH bears a significant negative correlation ($r = -0.7789$, $p > 0.01$) with altitude. The pH KCl of these soils is always lower than the pH of water, showing ΔpH (pH KCl – pH water) is negative.

Organic carbon content of soils are high and in the surface (0 – 15cm), it varies from 2.69 to 3.22 per cent with a mean value of 2.95 per cent in the lower hill soils, 3.10 to 5.20 per cent with a mean value of 3.98 per cent in the middle soils and 3.56 to 6.35 per cent with a mean value of 4.78 per cent in the upper hill soils (Fig. 1). Organic carbon in the surface soils bears highly significant positive correlation with altitude ($r = 0.8930$, $p > 0.01$). The increasing trend of soil organic carbon with the increase of altitude was also obtained by Chambers (1998), Garten *et al.* (1999), and Bolstad & Vose (2001). Banerjee (2014), while studying the forest soil carbon stock along an altitudinal gradient in the Darjeeling Himalayan Region, observed that the maximum SOC was in the alpine and high altitude forest soils, followed by mid altitude and low altitude forest sites. In each altitudinal zone, SOC gradually decreases from the surface to lower soil depth, indicating higher biological activity associated with the top layer (Banerjee & Prakasham, 2012). Batjes (1996) states that for the 0 to 100 cm depth, approximately 50% of soil organic carbon appears in the first 30 cm of the soil. Jobbagy & Jackson (2000) showed that 50% of the SOC is concentrated in the first 20 cm in forest soils to 1m depth. The high SOC

Table 1: pH of soils in water and KCl at different altitudes

Altitude (m)	No. of sites	Soil depth (cm)	Range of pH in water	Mean	Range of pH in KCl	Mean
300 – 900	16	0 – 15	5.2 – 5.7	5.4	4.6 – 5.0	4.7
		15 – 30	4.8 –5.6	5.4	4.9 – 5.3	5.0
		30 - 60	5.3 – 5.7	5.5	4.6 – 5.4	5.0
900 – 1800	13	0 – 15	4.0 – 4.8	4.4	3.6 – 4.1	3.8
		15 – 30	3.9 – 4.6	4.3	3.6 – 4.0	3.7
		30 - 60	4.0 - 4.5	4.2	3.6 – 4.0	3.8
1800 - 2700	18	0 – 15	4.2 – 4.4	4.3	3.5 – 3.8	3.6
		15 – 30	3.6 – 4.4	4.0	3.3 – 3.6	3.4
		30 - 60	3.7 – 4.6	4.2	3.2 – 3.8	3.6

content of brown forest soils of Sikkim under a humid temperate climate is also a source of organic carbon, which helps to increase the SOC stock and, in turn, improves soil health (Gangopadhyay&Bhattacharyya, 2022). Civeira*et al.* (2012) showed that SOC in the upper 30 cm of soils in Argentina is much higher than in the 30 – 100 cm interval. A large proportion of input is from above-ground litter in forest soils, as a result, soil organic matter tends to concentrate in the upper soil horizon, and it is in a state of dynamic balance between inputs and outputs. Inputs are largely determined by the forest productivity, the decomposition of litter and its incorporation into the mineral soils; rates of organic matter decay and the return of carbon to the atmosphere through respiration control outputs (Pregitzer, 2003). Carbon cycles globally among three distinct pools: the atmosphere, the oceans and terrestrial ecosystems. The atmosphere currently contains 770 Pg (Pg = 1Gton) of carbon with nearly all of it as CO_2. The oceans store about 40,000 Pg, and terrestrial systems contain 2000 Pg, most of which resides in soil. Carbon sequestration in terrestrial ecosystems is referred to as the absorption of CO_2 from the atmosphere by photosynthesis. After absorption, carbon is stored in forests for a period of time in a variety of forms before it is ultimately returned to the atmosphere through the respiration and decomposition of plants and animals, or harvested from forests for use in paper and wood products. A substantial pool of carbon is stored in woody biomass. Another portion eventually ends up as organic matter in forest floor litter and the soil horizons.Although the rate of SOM decomposition varies throughout the year in response to fluctuations of soil temperature and moisture, the maximum apparent decay rate is higher at lower elevation site than at the high elevation site because of the temperature difference (Wang *et al.,* 2000). Lower temperature at higher elevation decreases the rate of SOM decomposition and provides longer residence time, and soil organisms play a major role in litter decomposition. As storage of soil organic carbon is dynamic, the residence time of C in soil is a major determinant of the capacity of a soil to sequester C (Banerjee, 2014). Soil carbon sequestration is the process of transforming carbon dioxide from the atmosphere into the soil through crop residues and other organic solids and in a form that is not immediately re-emitted (Lal, 2008).

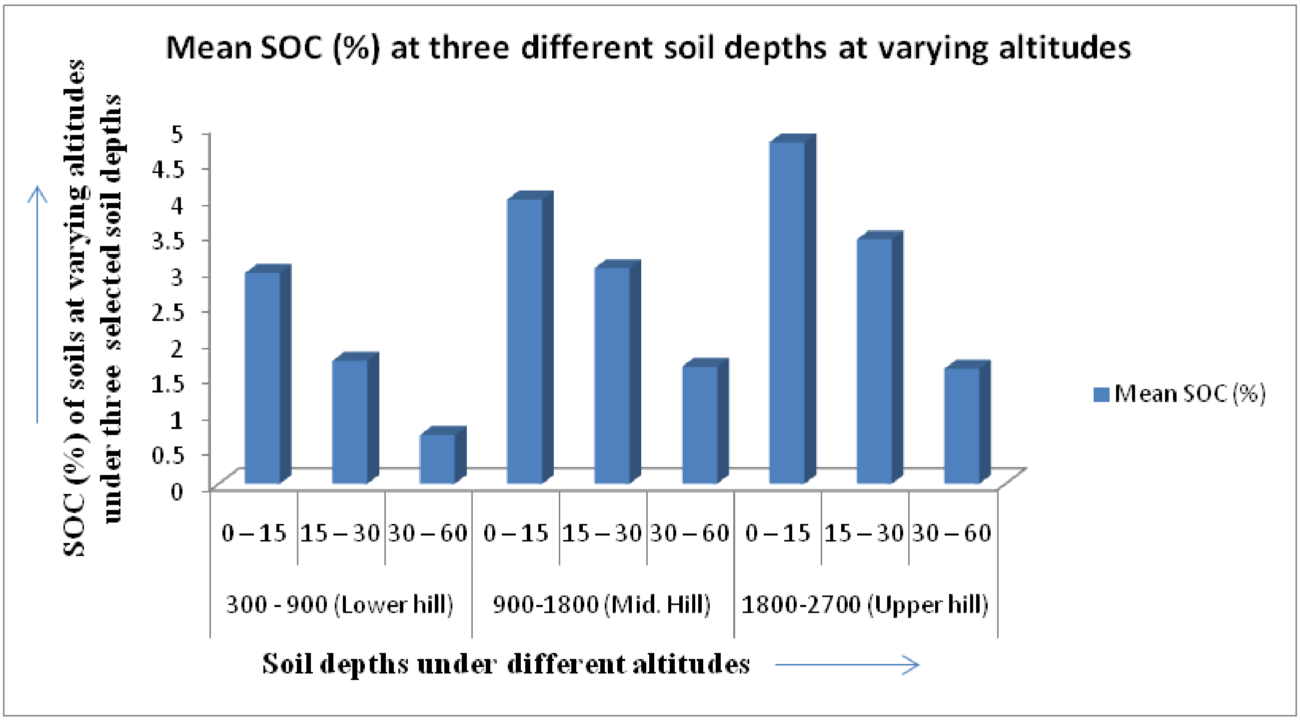

Fig. 1: Mean SOC (%) in the soils of South and West Sikkim under varying altitudes

The translocation of clay in some upper hill soils with the formation of a well-developed argillaceous subsurface diagnostic horizon has been observed in the present investigation. The clay percentage in the upper hill sites (Table 2) owes its existence to the parent materials, which seem to contain biotite and muscovite as the major constituents (Chandran *et al.*, 1998). Cation exchange capacity (CEC) of soils varies from 6.8 to 20.9 me/100g indicating illite may be the dominant clay mineral. CEC does not bear any correlation with the distribution pattern of clay and organic carbon.

Table 2: Clay content (%) and C.E.C. (me/100g) of soils at different altitudes

Altitude (m)	No. of sites	Soil depth (cm)	Clay range	Mean	CEC range	Mean
300-900	16	0 – 15	10.7 - 17.6	13.5	11.8-15.3	13.4
		15 – 30	11.0 – 19.0	15.1	7.9 – 9.7	9.1
		30 - 60	10.1 – 20.0	15.2	6.8 – 9.5	7.9
900 - 1800	13	0 – 15	14.4 – 28.7	20.1	14.5 – 20.9	18.9
		15 – 30	15.0 – 23.8	16.1	13.3 – 18.7	16.6
		30 - 60	17.0 – 24.0	20.2	13.2 – 15.7	14.3
1800-2700	18	0 – 15	13.0 – 37.6	24.0	14.5 – 17.7	16.4
		15 – 30	20.2 – 45,0	31.7	14.6 – 16.8	15.3
		30 - 60	31.6 – 47.0	37.4	14.0 – 14.7	14.3

Base saturation per cent is much higher in the surface soil (0 – 15cm) of the lower hill zone in comparison to middle and upper hill sites (Table 3). It bears a highly significant positive correlation with pH ($r = 0.8468$, $p>0.01$) and a highly significant negative correlation with altitude ($r = -0.9057$, $p>0.01$).

Table 3: Base saturation percentage of soils at different altitudes

Altitude (m)	No. of sites	Soil depth (cm)	Range of base saturation (%)	Mean
300 – 900	16	0 – 15	40 – 59	47.1
		15 – 30	25 – 48	38.5
		30 – 60	22 – 35	33.7
900 – 1800	13	0 – 15	6 – 35	20.5
		15 – 30	4 – 24	11.6
		30 – 60	5 – 24	11.8
1800 – 2700	18	0 – 15	7 – 20	13.6
		15 – 30	8 – 17	12.0
		30 – 60	6 – 24	13.0

Bulk density (BD) of the surface soil (0 - 15 cm) varies from 1.26 to 1.61g cm^{-3} with a mean value of 1.39 g cm^{-3} in the lower hill site, 0.95 to 1.22 g cm^{-3} with a mean value of 1.09 g/cc in the middle hill site and 0.90 to 1.22 g cm^{-3} with a mean value of 1.09 g cm^{-3} in the upper hill site. In the sub-surface (15 – 30 cm) and subsoil (30 – 60 cm), BD varies from 1.54 to 1.77 g cm^{-3} with a mean value of 1.66 g cm^{-3} in the lower hill site (300 – 900 m), from 0.95 to 1.11g cm^{-3} with a mean value of 1.25g cm^{-3} in the middle hill site (900 – 1800 m) and from 1.11 to 1.19 g cm^{-3} with a mean value of 1.16 g cm^{-3} in the upper hill site (1800 – 2700 m). BD of the surface soils bears a highly significant negative correlation with SOC (r = - 0.9294, p>0.01). An inverse relation between SOC and BD is normal (Jeffrey, 1970). The results also indicate that with the increase of the altitude, there was a decrease in the BD of the three depths, and altitude bears a significant negative relation with BD (r = - 0.7917, p>0.01) of the surface soils.

The maximum carbon stock up to 60 cm soil depth (181.2 to 237.0 t ha^{-1} with a mean value of 205.80 t ha^{-1}) is present in the altitudinal range 1800 – 2700 m and minimum (63.0 to 94.4 t ha^{-1} with a mean value of 74.45 t ha^{-1}) in the altitudinal range 300 – 900 m (Fig. 2). The carbon stock present in 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) indicating that with the increase in the altitude there is an increase in soil organic carbon pool. Except in the lower hill site (up to 900 m), the soil organic carbon stock up to 60 cm soil depth is much higher than the national average of SOC stock of India, which is 183.2 t ha^{-1} (Jha *et al.*, 2003). But when we consider the carbon stock altogether, starting from 300 to 2700 m, the average comes to 58.89 t ha^{-1} (Table 5), which is slightly lower than the national average because of lower organic carbon content in the lower hill zone.

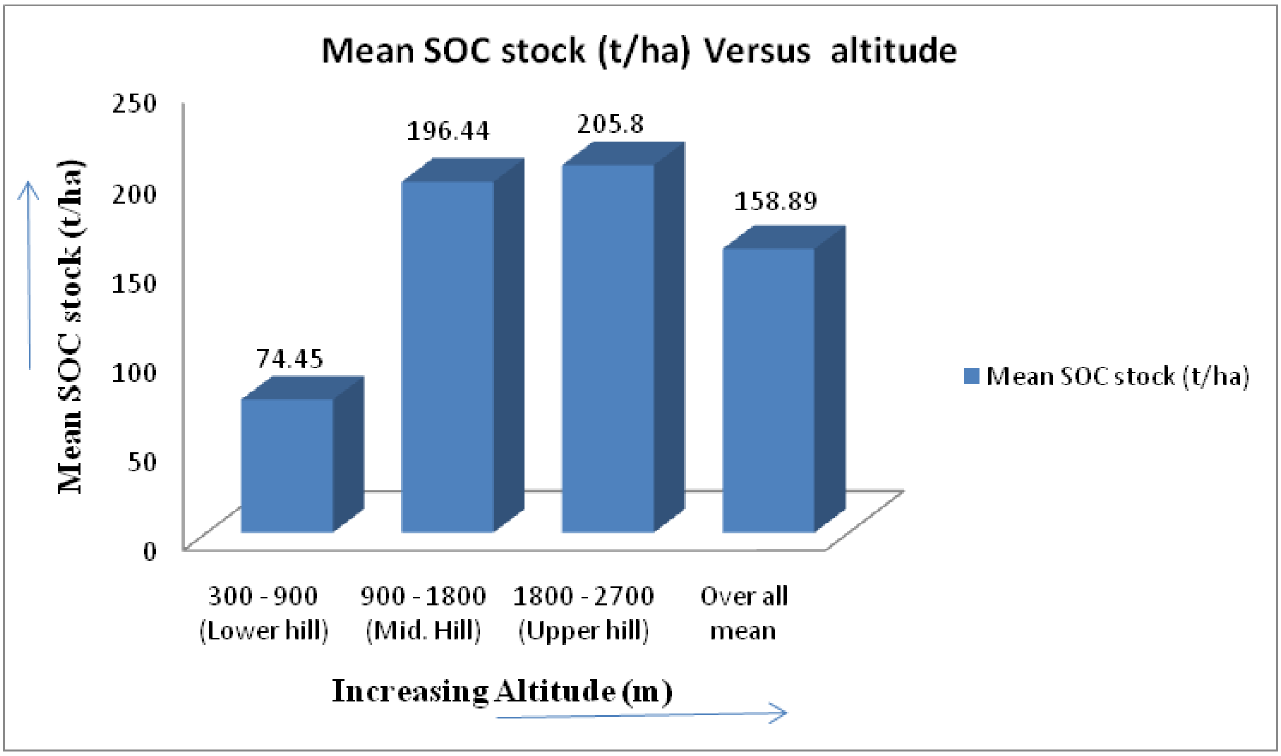

Fig. 2: Soil organic carbon stock (t ha^{-1}) up to 60 cm soil depth at different altitudes.

The forest cover of south and west Sikkim, based on interpretation data (FSI 2011), is 1,343 km² (very dense forest: 203 km², medium-dense forest: 860 km², and open forest: 280 km²), which accounts for 70.1% of the total geographical area of south and west Sikkim combined. Thus, with the increase in altitude, there is an increase in the soil organic carbon pool, which virtually reduces the bulk density of the soil. Therefore, the carbon density up to 60 cm soil depth under forest cover of south and west Sikkim combined was 213.39 million tons (Gangopadhyay *et al*., 2020).

Conclusion

The amount of higher organic matter in surface soils and its rate of decomposition play a vital role in soil organic carbon stock. The increasing tendency of carbon density with the increase in altitude indicates its better stabilisation at a cooler temperature and higher precipitation with lesser microbial activity. Since rates of carbon dioxide efflux increase as a function of soil temperature (Davidson & Janssens, 2006), soils in cold climate keep more soil organic matter than that of warmer 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 forest soil carbon of the Sikkim Himalayas is higher at high altitude as compared to the other Himalayan regions, and it is high at the surface and decreases with the increase in soil depth (Gangopadhyay *et al*., 2021).The brown forest soils (Mollisols) in the humid temperate climate of Sikkim also act as a source of organic carbon, which increases the SOC stock and, in turn, improves soil health. From the present study, it is evident that the forest soils of south and west Sikkim covered with different vegetations at different altitudes are in a form that is not immediately re-emitted. The results also suggest that the soil organic carbon pool depends on the quality of the litter, climatic conditions and microbial activities. The SOC pool also varies widely among eco-regions, being higher in cool and moist than warm and dry regions. These soils should be protected against erosion/landslide, since they store a high quantity of organic matter, not only for increasing crop production but also to provide better ecosystem services.

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