Chapter 7

Organic carbon stock in the forest soils of Himalayas and other areas in India

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1 Introduction

The Himalayas is a mountain range in Asia, developed mostly from sedimentary and metamorphic rocks and originated through collision between the Indo-Australian Plate and the Eurasian Plate with the development of Arakan Yoma highlands in Myanmar and the Andaman and Nicobar Islands in the Bay of Bengal. The Indian Himalayas occupies 16.2% of the total geographical area of the country. It consists of many Indian states and UTs, namely, Jammu, Kashmir, Ladakh, Uttarakhand, Himachal Pradesh, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura, two districts of Assam (Dima Hasao and Karbi Anglong), and West Bengal (Darjeeling and Kalimpong), covering an area of 625,000–750,000 km^2 (Fig. 7.1). Nearly 50 million people reside in the Indian Himalayan Region (IHR) alone. The Himalayas in India are categorized into northern Himalayas, western Himalayas, central Himalayas, and northeastern and eastern Himalayas (Nautiyal, Rajan, & Shibasaki, 2005).

The IHR is known for its tremendous ecological diversity. This diversity results from the variation of altitude, slope, and aspect of the mountains and complex glaciology and hydrology, including the climate and the microclimatic situation of the range. The IHR is characterized by diverse demographic, economic, environmental, social, and political systems. The Himalayan ecosystem is vital to the ecological security of the Indian landmass. It supports forest cover, feeds perennial rivers for the supply of drinking water, irrigation, and hydropower, conserves biodiversity, a rich source for high value agriculture and provides beautiful landscapes for tourism.

The most characteristic features of the earth are the existence of life that in turn provides the diversity. Topography, soil, climate, and geographical location of the region influence the vegetation diversity of the forest ecosystem of the Himalayas. The variation of forest vegetation in the Indian Himalayas varies with altitude showing tropical dry deciduous forests in the foothills to alpine meadows above timberline (Singh & Singh, 1992). India is one of the important mega-biodiversity centers of the world and the Himalayan ecosystem and contributes forest diversity that acts as the main source of livelihood for the people living in Himalaya. These forests are exploited variously for fodder, fuel wood, timber, leaf litter for manuring crop fields, construction, industrial raw materials, and several non-timber forests produce and consequently the vegetation cover is diminishing affecting the species richness and diversity, which influences the soil and environmental conditions. To protect the sustainability of land and to save human civilization, the conservation and management of these forests is of utmost importance. Otherwise, the socioeconomic and ecological condition of the region will be under threat due to this sort of disturbances and climatic change resulting in the species composition of these forests.

1.1 Ecology of the Himalayas

The Himalayas occupy a unique position in the mountain systems of the world. The ecology of the Himalayan ecosystem is mostly characterized by the altitude, climate, rainfall, and soils. With the variation in altitude, the climate shifts from tropical at the base of the mountains to permanent ice and snow at the highest elevations with the increase in rainfall from west to east along the southern front of the range and supports a variety of distinct plant and animal species under diverse pedogenic processes resulting in varied soil ecosystem (Bhattacharyya, 2014, Bhattacharyya, 2016).

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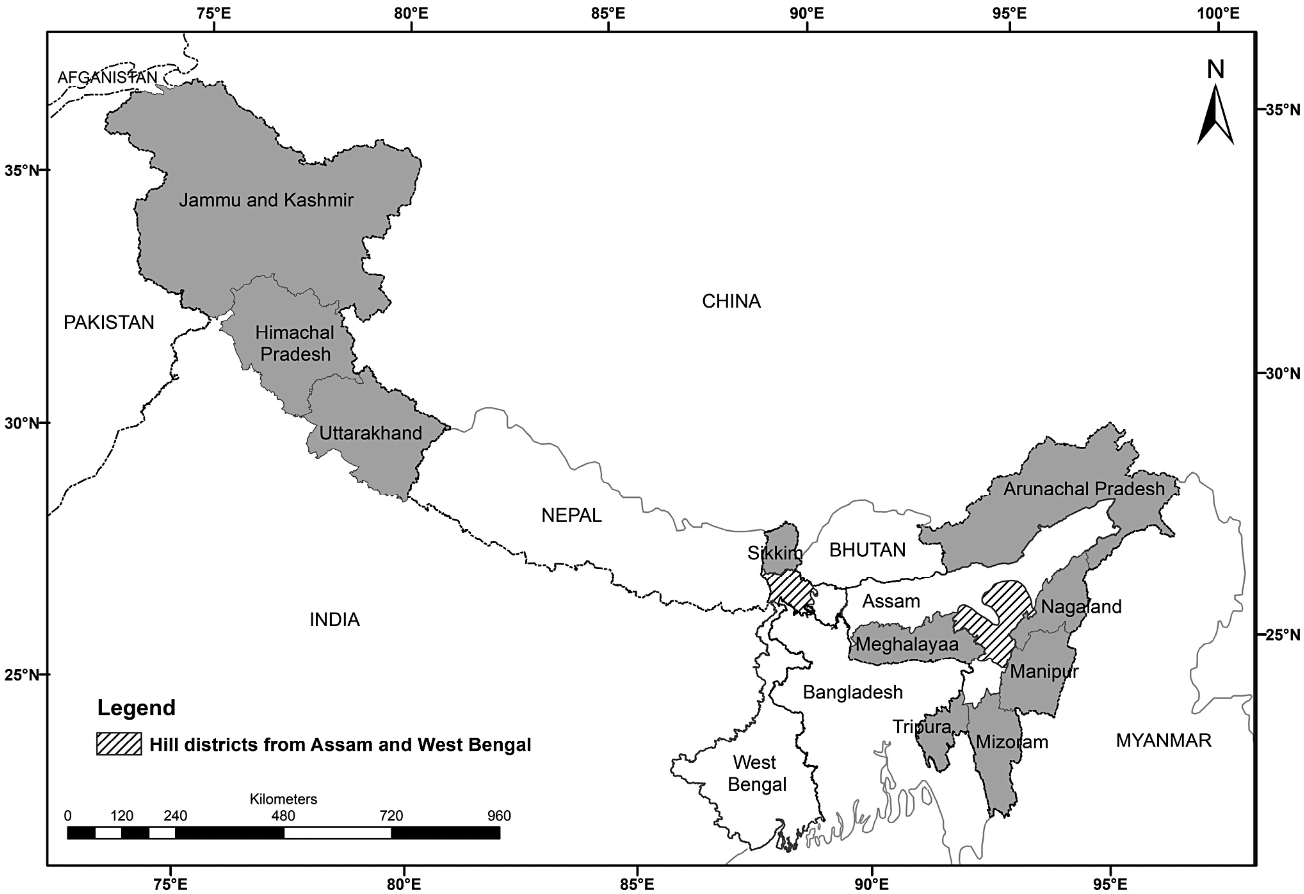

FIGURE 7.1 Indian Himalayan region (IHR) map. *NITI Aayog (2018).*

The presence of great variation in vegetation interferes greatly with the pedogenesis, as a result of which mighty variations in soil types are displayed frequently (Nath, Banerjee, & Chattoraj, 1988).

Altitude is an important ecological factor of soil formation that affects tropical, temperate, and alpine environs. With the variation in altitude, climatic condition changes and as a result quite contrasting flora grow at different altitudes which in turn influence the development of soil. High-altitude regions differ from low-altitude regions and plains in many respects. It has been reported that the temperature decreases at the rate of 1°C for every 166 m altitude (Lal & Shukla, 2004). This results in a change of the local climate and affects soil formation. High rainfall and low temperature result directly in low evapotranspiration ratio and more leaching of the soils. Indirectly, the climate influences the vegetation, which is an active factor of soil formation. Another important soil characteristic of high-altitude regions is the influence of the slope and aspect on soil formation. Thus altitude is an index for a variety of climatic functions governing the nature of the vegetation and the processes of soil formation, including soil organic matter (SOM) (Gangopadhyay, Bhattacharyya, & Banerjee, 2020).

Vegetation plays a pivotal role in developing the plant communities as well as structure of any ecosystem. It determines microclimate, energy budget, photosynthesis, water regimes, surface runoff, and soil temperature within the plant communities (Tappeiner & Cernusca, 1996), including their composition (Kharkwal, Mehrotra, Rawat, & Pangtey, 2005), and influences soil formation resulting in soil diversity. Vegetation interferes greatly with the pedogenesis, as a result of which various soil types are found frequently.

A unique characteristic of most forest ecosystem is the development of a distinct forest floor resulting from periodic return through litter fall of leaves, branches, bark, fruit, and sometimes entire trees. This litter fall contains a large portion of the nutrients extracted by the tree from the soil. The litter fall transfers much of the biomass beneath the canopy and its decomposition releases the nutrients to the soil. Thus the SOM and nutrient supplies are replenished and maintained in the forest ecosystem through this dynamic and rather complex system of geological, chemical, and biological cycling.

Decomposition of organic matter and the formation of humus provide much required energy for numerous microorganisms and animals inhabiting the soil. Maximum accumulation of biomass is observed in forest associations. The accumulation of biomass follows the order: humid tropical forests > subtropical forests > deciduous forests of the temperate zone.

The SOM is a complex mixture of carbon compounds associated with decomposing plant and animal tissues, microbes with soil materials. Forest ecosystem provides a significant carbon pool to global carbon budget and also contributes to mitigation of global climate change. The physical, chemical, and mineralogical characteristics of soil, solum depth, soil drainage, moisture, air availability, soil temperature, etc. are the key factors controlling the sequestration potential of a soil (Bhattacharyya, Pal, Mandal, & Velayutham 2000a, Bhattacharyya et al., 2008).

Soil stores more carbon than that in plants and the atmosphere combined. It is the largest pool of terrestrial organic carbon in the biosphere (Schlesinger, 1997; FAO, 2006; Lal, 2008) and contains globally approximately 2344 Gt (1 Gt = 1 billion tonnes) of organic carbon (Stockmann et al., 2013). Worldwide the first 30 cm of soil holds 1500 Pg C (Batjes, 1996) and for the soils of India, it is 11.397 Pg (Bhattacharyya, Tiwary, & Pal, 2017). About 40% of the total soil organic carbon (SOC) stock of the global soils resides in forest ecosystem (Eswaran, Reich, Kimble, & Beinforth, 1999). Forest serves as a source of carbon sequestration and carbon sink and plays an important role for the reduction of greenhouse gases and global warming. Thus forests are one of the most significant store houses of carbon and play a crucial role in reducing the atmospheric CO_2 levels through the process of photosynthesis and also by increasing the SOC content by maintaining carbon balance in the globe. The Himalayas with dense forest vegetation covers nearly 19% of India and contains 33% of SOC reserve of the country (Bhattacharyya et al., 2008).

Altitude, climate, vegetation, topography, and soil depth are the major factors that control SOC stock (Baldock & Nelson, 2000). The microclimate developed due to the variation in altitudinal gradient influences SOC content and the rate of mineralization due to the effect of temperature and moisture (Banerjee & Prakasham, 2012; Banerjee, 2014). Temperature is the key factor controlling the rate of decomposition of biomass that depends on temperature, and thus 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, Banerjee, & Gupta, 2001; IPCC, 2000) and is the main source of carbon from the decomposition of biomass. Thus the sequestration potential of a soil depends on the existing vegetation (IPCC, 2000; Houghton, 2003; Grace, 2004). Forest ecosystem contributes carbon pool to global carbon budget and serves in mitigation of global climate change for sustainable agriculture (Lal, 2004; Smith, 2004).

The SOC stock in the world's forest has been estimated 861 ± 66 Pg C, out of which 44% is in soil up to a depth of 1 m and 14% is contributed by Temperate forest (Pan et al., 2011). According to the average global or regional soil C densities, the SOC pool of Indian forest soil ranges from 5.4 to 6.7 Pg (Ravindranath, Somashekhar, & Gadgil, 1997; Dadhwal, Pandya, & Vora, 1998), while total SOC pools in the top 50 cm and top 1 m depths were estimated as 4.13 and 6.81 Pg, respectively (Chhabra, Palria, & Dadhwal, 2003). The global SOC stock was estimated (684–724 and 1462–1548 Pg) to a depth of 30 cm and 1 m, respectively (Batjes, 1996). The quantity of SOC in the depth of 30 cm layer is found to be double the amount of C in atmospheric carbon dioxide (CO_2) and triple of the global aboveground vegetation (Powlson, Whitemore, & Goulding, 2011).

The Indian Himalayas, characterized by the tremendous variation in altitude, slope, aspect, and vegetation, results in a change in microclimate influencing the SOC stock markedly. However, the information on SOC stock in the Himalayan forests is meager, and hence the present study is an attempt to assess the sequestered SOC stock of forest soils of IHR and other areas, namely, the brown forest soils of Western Ghats, Konkan (Maharashtra), Satpura, and also the reserved forests of Madhya Pradesh in India.

2 Materials and methods

2.1 Study area

The study was carried out in the forest soils of IHR consisting of northern Himalayas, western Himalayas, central Himalayas, and eastern and northeastern Himalayas, comprising 12 Indian States of the country (Table 7.1) and also the brown forest soils in the Western Ghats and the Satpuras and Konkan, Maharashtra and Reserved Forests of Maharashtra and Madhya Pradesh. In each and every zone, forest areas were selected at different elevations and at representative places, 10–12 plots of 100 m × 100 m in size, were demarcated, and six to eight sampling points in each plot were selected on the basis of canopy cover, aspect, and slope. The vegetation data were collected through sampling representative sites and of quadrate analysis following the method of Dombois and Ellenberg (1974) where in 100 m^2 (10 m × 10 m) was found as the minimal area and hence quadrates of this size were used to study tree quadrate, 25 m^2 (5 m × 5 m) for shrubs (shrub quadrate), 1 m^2 (1 m × 1 m) quadrate for regeneration study (regeneration quadrate).

TABLE 7.1 Extent of the Indian Himalayan Region and other parts showing excellent forest canopy.

State code	State/Region	Total geographical area, '000 ha (FSI, 2017)	Percent share of geographical area in the Indian Himalayan Region
Northern, Western, and Central Himalayas			
1	Jammu and Kashmir	222.236	41.65
2	Ladakh	59.146	0.06
3	Uttarakhand	53.483	10.02
4	Himachal Pradesh	55.673	10.43
Eastern Himalayas			
5	Sikkim	7.096	1.33
6	West Bengal hills	3.149	0.59
North Eastern Himalayas			
7	Meghalaya	3.149	4.20
8	Assam Hills	15.322	2.87
9	Tripura	10.486	1.97
10	Mizoram	21.081	3.95
11	Manipur	22.327	4.18
12	Nagaland	16.579	3.11
13	Arunachal Pradesh	83.743	15.69
Western Ghats			
14	Gujarat, Maharashtra, Goa, Karnataka, Tamil Nadu, and Kerala	14,000 (Bhattacharyya et al., 2008)	–
Coastal Maharashtra			
15	Maharashtra	3000 (Bhattacharyya et al., 2020)	–
The Satpuras			
16	Gujarat, Maharashtra, Madhya Pradesh, Chhattisgarh	52 (Bhattacharyya, Pal, Lal, Chandran, & Ray, 2006)	–
17	Reserved forests of Madhya Pradesh and Maharashtra	30	–

Source: FSI (2017).

The study was carried out along an altitudinal gradient between 300 and 2700 m above mean sea level (amsl). From each representative point, soil samples were collected. 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 the laboratory the soil samples were air dried and sieved to 2 mm to remove gravels and roots and analyzed for different physical and chemical characteristics following standard procedures (Black, 1965; Jackson, 1973). The bulk density (BD) was determined by the field-moist method using core samples (diameter 50 mm) of known volume (100 cm^3) (Blake & Hartge, 1986). The total SOC stock was calculated using the method described by Batjes (1996). In the first step, soil organic C density (t ha^{-1}) was computed by multiplying organic C percent, soil BD (Mg m^{-3}), and the thickness of horizon (cm) for individual soil profiles with different thicknesses.

3 Results and discussion

Forest soils of Indian forests encompassing the northern, western, central, eastern, northeastern Himalayas and Western Ghats, Satpuras, Konkan, Maharashtra, and the Reserved Forest areas of Maharashtra and Madhya Pradesh have been discussed with special reference to the SOC stock. Based on the minimum threshold value of SOC, proper management strategies were also discussed.

3.1 Northern, western, and central Himalayas

3.1.1 *Kashmir Himalayas*

Kashmir Himalayas in temperate zone (1550–3200 m amsl) of Jammu and Kashmir State of India represents 36.09% forest area. The forest types under different altitudes varied widely and the dominant species were considered for the estimation of SOC. The percent share of the forests in Kashmir Himalayas to the total geographical area in the IHR is 41.65 and the per hectare SOC stock was found to be 55.24 t.

3.1.1.1 Floristic composition

The forest species in the mountain of Kashmir Himalayas are temperate type with conifers as the main component. The forest species are distributed within a wide variation in altitude. The low altitude (1550–2000 m) is composed of broad-leaved species, namely, *Populus deltoides*, *Juglans regia*, *Salix species*, *Ulmus villosa*. whereas the middle altitude (2000–2800 m) is composed of conifers like *Pinus wallichiana*, *Cedrus deodara*, *Abies pindrow*, and *Picea smithiana*. In the high altitude (2800–3250 m) *Betula utilis* is dominant and constitutes as the timberline.

3.1.1.2 SOC stock

SOC stocks under different forest vegetations, namely, *P. deltoides*, *J. regia*, *C. deodara*, *P. wallichiana*, mixed type, *A. pindrow*, and *B. utilis* at varying altitudes and soil depths (0–10, 10–20, and 20–30 cm) (Table 7.2) in Kashmir Himalayas, indicated the decrease of SOC stocks with increasing soil depth (Dar & Somaiha, 2015).

The soils of temperate forest of Kashmir Himalayas have greater carbon sequestration potential at higher altitudes than that of lower altitude. Thus the forests should be preserved in such a way that no further rise in temperature may bring the deterioration of SOC stocks in these forests.

3.1.2 *Ladakh Himalayas*

3.1.2.1 Floristic composition

Ecologically, the Ladakh region is a rain shadow area of the Himalayas representing high altitude cold desert. The annual temperature of this region varies from −30°C to +40°C, annual maximum and minimum average relative humidity is 24.70% and 39.03%. Annual precipitation is less than 100 mm. The forests around agricultural fields and glacier valleys are mostly *Salix* spp. (Willow) and *Populus* spp. (Poplar). Grasslands are spread with *Carex melanantha* and *Agropyron repens* as major grass species.

3.1.2.2 SOC stock

The soil carbon storage and distribution patterns in the cold desert high altitude region of Ladakh revealed that with the increase in altitude SOC content increases but the soil inorganic carbon (SIC) content decreases (Charan et al., 2012) (Table 7.3).

The increase in SOC content and storage in the high altitude cold desert soils in Ladakh may be due to the decrease in mean annual temperature, lesser decomposition, longer residence time for SOM. An exactly opposite results were observed in the case of SIC content and storage in the studied area (Table 7.4).

TABLE 7.3 Soil organic and inorganic carbon contents at different altitudes.

Altitude range (ft. amsl)	SOC (%)	SIC (%)
10,000–11,000	$0.81^{a} \pm 0.04$	$0.96^{b} \pm 0.21$
11,001–12,000	$1.00^{b} \pm 0.05$	$0.31^{a} \pm 0.03$
>12,000	$1.32^{c} \pm 0.09$	$0.38^{a} \pm 0.04$

a,b, and c represents the significant variability at p = 0.001 in DMRT.
Source: (Charan et al., 2012)

TABLE 7.2 SOC stock along an altitudinal gradient in different forest type in Kashmir Himalayas.

Forest vegetation	Number of samples under each soil depth	C Mg ha^{-1} (0–10 cm)	C Mg ha^{-1} (10–20 cm)	C Mg ha^{-1} (20–30 cm)
Populus deltoides	n = 40	19.39 ± 2.1^{a}	12.78 ± 0.9^{a}	8.96 ± 1.0^{a}
Juglans regia	n = 35	18.85 ± 1.3^{a}	11.32 ± 0.9^{b}	8.91 ± 0.8^{a}
Cedrus deodara	n = 45	34.64 ± 1.6^{b}	15.20 ± 0.9^{c}	12.45 ± 0.6^{b}
Pinus wallichiana	n = 50	30.50 ± 2.1^{c}	20.22 ± 0.9^{d}	16.51 ± 1.3^{c}
Mixed type	n = 50	36.70 ± 2.1^{d}	14.35 ± 0.4^{e}	$11.60 \pm 1.5^{b,d}$
Abies pindrow	n = 50	32.15 ± 1.8^{e}	17.07 ± 0.6^{f}	$12.03 \pm 0.9^{b,d}$
Betula utilis	n = 25	54.10 ± 1.6^{f}	21.69 ± 0.5^{g}	15.60 ± 0.3^{c}
	F value	939.98	383.99	53.98

a,b,c,d,e,f, and g represents the significant variability at p = 0.001 in DMRT.
Source: Dar and Somaiha (2015).

TABLE 7.4 Soil organic and inorganic carbon stock (storage) at different altitudes.

Altitude range (ft. amsl)	SOC (t ha^{-1})	SIC (t ha^{-1})
10,000–11,000	16.74^{a} ± 0.80	19.51^{b} ± 3.99
11,001–12,000	21.69^{b} ± 1.08	6.82^{a} ± 0.74
>12,000	28.83^{c} ± 1.70	8.32^{a} ± 0.84

a,b, and c represents the significant variability at p = 0.001 in DMRT
Source: (Charan et al., 2012)

3.1.3 Uttarakhand Himalayas

3.1.3.1 Floristic composition

Out of the total geographical area (52,483 km^2) of the state, 61.15% area is under forest. Reserved forests constitute 71.10% followed by protected forests (28.52%) and unclassified forests (0.38%) of the total forest area. It mostly belongs to eight main types of forests as per the broad classification of forests (Champion & Seth, 1968). In the lower elevation the major species are *Acacia catechu* (khair), *Shorea robusta* (sal), *Dalbergia sissoo* (shechem), *Bombax ceiba* (bamboo), etc. In the middle hill area (900–1500 m), *Pinus roxburghii* is dominant along with *Cedrela toonaToon, Anogeissus latifolia*, and *Ehretia laevis*. In the high hill areas the main species include *Quercus semicarpifoliaBanj*, *Quercus incanaBanj*, *Rhododendron arboreunBurans*, *Rhus punjabensis, Cedrela toonaToon*, and *Vitis himalayansis*. Besides these, deodar is accompanied by blue pine (*Pinus excelsa*), silver fir and spruce.

3.1.3.2 SOC stock

SOC stock at different altitudes under various land uses in Uttarakhand state indicates that under natural forest covers SOC stock increased with increasing elevation. Considering all the vegetations, SOC stock was maximum above 2501 m elevation (138.37 Mg ha^{-1}), and the least SOC stock 41.73 Mg ha^{-1} was found at less than 500 m elevation (Gupta, Panwar, & Kumar, 2018). Negi, Gupta, & Sharma (2013) estimated SOC pool under different forest areas of Uttarakhand state and revealed that maximum SOC pool was in the soils under *A. pindrow* and *P. smithiana* (140.76 t ha^{-1}) while minimum SOC pool was under *S. robusta* forests (58.45 t ha^{-1}). In the plantation forest areas, maximum SOC pool was under *Cypress cashmeriana* plantations (66.32 t ha^{-1}) and minimum under barren lands (27.73 t ha^{-1}) and the total SOC pool in the forest areas of Uttarakhand was found to be 149.73 Mt.

3.1.4 Himachal Himalayas

3.1.4.1 Floristic composition

About 26.73% area of the state is under forest. Moderately dense forest occupies major area followed by open forest and very dense forest. Along the altitudes, the tree species and shrubs vary widely in Himachal Himalayas. In the lower elevation the dominant species are *Acer acuminatm, Aesculus indica, Alnus nepalensis, C. deodara, P. wallichiana, Ulmus wallichiana, Toona ciliate*, etc. along with shrubs like *Berberis aristata, Berberis lyceum, Desmodium triflorum,* and *Prinsepia utilis*. In the medium elevation the tree species are *A. pindrow, Acer acuminatum, P. smithiana*, *Quercus floribunda*, and *Betula alnoides* along with shrubs like *B. lyceum*, and *Debregeasia salicifolia, Indigofera heterantha*. In the upper elevation the tree species are *A. pindrow, Acer caesium, B. alnoides*, and *C. deodara* along with the shrubs mainly *Berberis jaeschkeana, Cotoneaster rosea, Elaeagnus parviflora*, and *Rosa sericea*.

3.1.4.2 Soil organic carbon stock

SOC stocks under different forest types of Himalayan moist temperate forests in Shimla district, Himachal Pradesh, India (Reddy & Gupta, 2018) indicated that BD of soil decreases with the increase in elevation. The increase in SOC density with increasing altitude is largely due to increase in SOC concentration (Griffiths, Madritch, & Swanson, 2009). Temperature and precipitation were found to be the major climatic factors affecting the vertical distribution of SOC density in the profiles. A strong correlation was found between SOC density and mean annual temperature and precipitation (Jobbagy & Jackson, 2000).

The soils of Himachal Pradesh under *P. roxburghii* plantation developed on sandstone within the altitude range from 710 to 1235 m were acidic, clay loam to sandy loam in texture with low cation exchange capacity (Gangopadhyay, Nath, Bishayee, & Banerjee, 1987). The study further indicated that fulvic acid was dominant over humic acid in lower hill soils situated in northeasterly aspect. With the increase in altitude, the amount of carbon of humic acid increases and oxygen decreases. Carboxyl acidity, total acidity as well as E4/E6 values of humic acid gradually decreases with the increase in altitude while molecular size or molecular weight of humic acid increases as the altitude increases.

3.1.5 Garhwal Himalayas

3.1.5.1 Floristic composition

The forest vegetation at varying altitudes in the Garhwal Himalaya show that *C. deodara* is the dominant species followed by *Quercus leucotrichophora* and *Q. floribunda* in the upper altitude while *C. deodara* followed by *Q. leucotrichophora, Q. floribunda, Rhododendron arboreum, Lyonia ovalifolia, Benthamidia capitata*, and *Neolitsea pallens* in the middle altitude. In the lower altitude, *Q. leucotrichophora* is the dominant species, *Q. floribunda, R. arboreum, L. ovalifolia*, and *P. roxburghii* are the major tree species.

3.1.5.2 SOC stock

The SOC stock along the altitude in coniferous subtropical and broadleaf temperate forest in Garhwal Himalayas indicated the decrease in SOC stock with altitude (Sheikh, Kumar, & Bussmann, 2009). Soils of Tehri Garhwal district, Uttarakhand under coniferous species, namely, *P. roxburghii* forest at an altitude of 700, 900, and 1100 m amsl were considered to study the variation in SOC stock in the study area. The study revealed that both the forest species showed decrease in SOC stock with increasing altitudes. Similar findings were also noted by Krishnan et al. (2007) in the Western Ghats of southern India. Himalayan forests at lower elevations can be regarded as major sinks of mitigating atmospheric carbon dioxide while that at higher altitudes as potential carbon sinks.

Variation in carbon stocks on different slope aspects in the temperate region of Garhwal Himalaya, India indicated higher C stocks in the NE aspect which eventually sustains higher C stocks (Sharma, Gairola, Baduni, Ghildiyal, & Suyal, 2011). Temperate forests have significant potential for C storage with an estimated mean value of 64 C Mg ha^{-1} (Winjum & Schroeder, 1997). Therefore mature forest stands on northern aspects having higher amounts of C should be preferred for conservation purposes. Mahato, Dasgupta, & Todaria (2016) quantified the variation in carbon stock/storage by species and identified *Quercus leucotrichophora* to fulfill provisioning service needs such as supply of fuel wood, fodder, and grasses in the Rikhnikhal block of Pauri district of Garhwal Himalayas. These types of community conserved forests are important for long-term mitigation of green house gas (GHG) emissions.

3.2 Eastern Himalayas

3.2.1 *Sikkim Himalayas*

3.2.1.1 Floristic composition

Sikkim state is a botanical paradise due to the existence of dense forests with new and phyto-geographically interesting taxan. The forest vegetation varies mostly from evergreen to, semi-evergreen with coniferous and deciduous forest species. 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 vegetation found in the lower hill region (300–900 m) of the study area include *T. grandis, S. robusta*, and *P. roxburghii*. In the middle hill (900–1800 m), *Cryptomeria japonica* alone occupies most of the areas. Other species found are *Bucklandia populnea, Schima wallichii, Michelia champaca,* and *Jambosa formosa* with under growth of cardamom (*Cinnamon cardamom*). In the upper hill area (1800–2700 m), the forest species are *Castanopsis hystrix, Symplocos theifolia, Quercus lamellosa, Acer campbellii*, 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 forest species.

The study was carried out along an altitudinal gradient between 300 and 2700 m in the southern and western Sikkim districts. In south Sikkim, moderately dense forests cover a major area (371 km^2) followed by open forest (107 km^2) and very dense forest (93 km^2). Similarly, in west Sikkim district, very dense forest, moderately dense forest, and open forest occupy 110, 489, and 173 km^2 areas. After selecting randomly 50% of the total forest area in each district, representative sampling was done between 300 and 900, 900 and 1800, and 1800 and 2700 m amsl. From each point, soil samples were collected at 0–15, 15–30, and 30–60 cm depth. Total 47 composite samples were collected and soil depth for sampling was restricted to 60 cm to maintain uniformity.

3.2.1.2 Soils

The characteristics of the soils of Sikkim Himalayas averaged over different depth ranges (0–15, 15–30, and 30–60 cm) showed that the upper hill soils are highly acidic (pH 3.6–4.6) followed by middle hill soils (pH 3.9–4.8) and lower hill soils (pH 4.8–5.7). Organic carbon content varies from 13.9 to 20.2 g kg^{-1} in the lower hill soils with a mean value of 16.5 g kg^{-1}, in the middle hill soils it varies from 31.0 to 52.0 g kg^{-1} with a mean value of 39.8 g kg^{-1}, and in the upper hill soils from 35.6 to 63.5 g kg^{-1} with a mean value of 47.8 g kg^{-1}. The organic carbon content bears highly significant positive correlation with altitude ($r = 0.8930$, $P > .01$).

Cation exchange capacity (CEC) of soil varies from 6.8 to 20.9 cmol(p+)kg^{-1} indicating that mica may be the dominant clay mineral. CEC does not bear any correlation with the distributional pattern of clay and organic carbon. Base saturation is much higher in the lower hill zone in comparison to middle and upper hill zones. It bears highly significant positive correlation with pH ($r = 0.8468$, $P > .01$) and highly significant negative correlation with altitude ($r = -0.9057$, $P > .01$).

BD of soil varies from 1.26 to 1.61 Mg m^{-3} in the lower hills with a mean value of 1.39 Mg m^{-3}, 0.95 to 1.22 Mg m^{-3} in the middle hills with a mean value of 1.09, and 0.90 to 1.22 Mg m^{-3} in the upper hills with a mean value of 1.09 Mg m^{-3} (Gangopadhyay, 1989). In the subsurface (15–30 cm) and subsoil (30–60 cm), BD varies from 1.54 to 1.77 Mg m^{-3} in the lower hills (300–900 m) with a mean value of 1.66 Mg m^{-3}, from 0.95 to 1.11 Mg m^{-3} in the middle hills (900–1800 m) with a mean value of 1.25 Mg m^{-3}, and from 1.11 to 1.19 Mg m^{-3} in the upper hills with a mean value of 1.16 Mg m^{-3}, respectively. The results indicate that organic matter content reduces BD values (Bhattacharyya et al., 2007a). BD of the surface soils bears highly significant negative correlation with SOC ($r = -0.9294$).

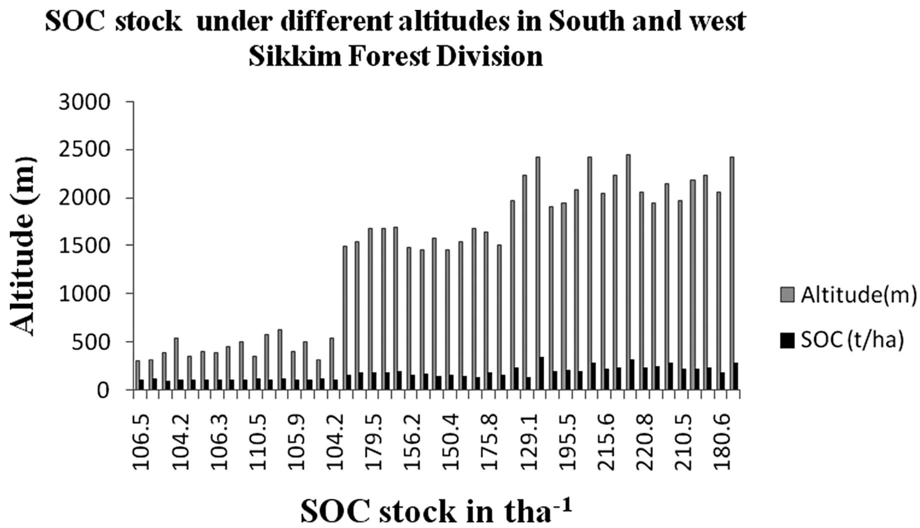

FIGURE 7.2 SOC stock under different altitudes in south and west Sikkim Forest Division. *Gangopadhyay et al. (2020).*

3.2.1.3 SOC stock

Maximum SOC stock within 60 cm soil depth varies from 181.2 to 237.0 t ha^{-1} with a mean value of 205.80 t ha^{-1} in the altitudinal range 1800–2700 m. Minimum carbon stock ranges from 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. 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 SOC pool (Fig. 7.2). 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 that decomposes most of the organic carbon. Again, the vegetations present in the lower hill soils are mainly deciduous forest species along with some coniferous species that influences 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 combined effect of altitude and nature and characteristics of forest vegetation.

The middle hill areas in comparison to the lower hill areas are cooler with less microbial activity and mostly consist of coniferous species with needle-shaped leaves that are resistant to decomposition. Lot of organic matter accumulation on the forest floor increases the organic carbon content in the soil through slow decomposition processes resulting high SOC stock of the soils. Again, within the conifer species, the nature and content of organic debris returned to the forest floor also vary (Nath, Singh, Das, Ganguly, & Banerjee, 1986). The upper hill soils mainly consist of evergreen broad-leaved forest species (*C. hystrix, S. theifolia*, and *M. excelsa*) in combination with conifers (*Q. lamellosa*, *A. campbellii*, and *Abies densa*). Relatively cool environment in the upper hill areas retards the decomposition of organic matter due to lower microbial activity under very strongly acidic environment (Bhattacharyya et al., 2000b; Bhattacharyya et al., 2006; Velmourougane et al., 2013a, 2013b, 2014; Kumar et al., 2014). However, the variation in SOC stock even in these soils is mainly influenced by the variation of forest species with higher accumulation of leaves, litter, and their decomposition to humus. The average carbon stock altogether starting from 300 to 2700 m altitudes is 158.89 t ha^{-1} (Table 7.5), which is slightly lower than the national average because of much lower organic carbon content in the lower hill zone.

The study showed that SOC stock of the forest soils of Sikkim Himalayas are high at high altitude and the SOC pool increases with altitude that virtually reduces the BD. Thus the increasing tendency of SOC with altitude indicates its better stabilization at cooler temperature, higher precipitation, and lesser microbial activity.

3.2.2 *Darjeeling Himalayas (West Bengal)*

In Darjeeling Himalayas, the variation in altitude, aspect, and climate have influenced the forest types resulting in the

TABLE 7.5 **Soil organic carbon stock (t ha^{-1}) up to 60 cm soil depth at different altitude.**

Altitude (m)	Number of sites	Range of carbon stock	Mean (t ha^{-1})
300–900	16	63.0–94.4	74.45
900–1800	13	166.8–264.0	196.44
1800–2700	18	181.2–237.0	205.80
Over all mean	158.89		

occurrence of various types of forests in lower, middle, and upper hills, including the subalpine regions.

3.2.2.1 Floristic composition

The lower hill forests mostly dominated by the *Shorea–Terminalia–Schima* community. In some places, chirpine (*P. roxburghii*) is also found along with *S. robusta*. The floristics are generally deciduous in nature, but evergreen species are also dotted here and there. The community is a multistoried structure comprising shrubs and sapling of tree species, herbs, and climbers. The most frequent species are *S. robusta*, *Terminalia bellirica*, *S. wallichii*, *Terminalia ctenulata*, and *Nyssa sessiliflora*.

The middle hill forest is mostly dominated by the species, Dhupi (*C. japonica*). Most of the trees are evergreen/semi-evergreen attaining good height and girth. The main type of forests within this altitude range is the *Castanopsis–Quercus–Alcimandra* community. The floristics composition is generally evergreen though some deciduous trees occur. The community is a multistoried structure comprising shrubs, herbs, climbers, saplings of tree species. The most frequent species are *C. hystrix*, *Quercus spicata*, *Q. lamellosa*, *Alcimandra cathcartii*, and *B. populnea*.

The upper hill forest, by and large, is of mixed type and the main type represents the *Quercus–Acer–Castanopsis* community. The floristics are evergreen in nature. Deciduous species occur at higher elevation. The community is a multistoried structure comprising shrub, herb, climbers, etc. The most frequent occurring species are *Quercus theifolia*, *Quercus lineata*, *A. campbellii*, and *M. excels*.

The decomposition of four conifers and one broad leaved species in Himalayan soils indicated that the rate of decomposition of broad-leaved species was higher than the coniferous species (Das, Mukhopadhyay, & Banerjee, 1993). They observed that both bacteria and actinomycetes multiplied rigorously up to 60 days and declined later irrespective of the type of litter, and the reverse was the case with fungi. Decomposition of litter increased the acidity of soil with the depletion of bases, organic carbon, available N and P but did not affect K markedly.

3.2.2.2 Soils

The soils of Darjeeling Forest Division are acidic (pH 4.0–5.3). Soil pH varies from 5.0 to 5.3 with a mean value of 5.1 in the lower hill soils, pH from 4.0 to 5.0 with a mean value of 4.4 in the middle hill soils, and pH from 4.2 to 4.9 with a mean value of 4.5 in the upper hill soils. Organic carbon content of the lower hill soils ranges from 13.2 to 28.0 g kg^{-1} with a mean value of 20.4 g kg^{-1}; in the middle hill soils, it varies from 2.2 to 34.8 g kg^{-1} with a mean value of 16.9 g kg^{-1}; and in the upper hill soils, it ranges from 5.6 to 61.6 g kg^{-1} with a mean value of 38.0 g kg^{-1}. Soils are low to medium in CEC with a mean value of 15.1 cmol(p+) kg^{-1} in the lower hill soils, 17.8 cmol(p+)kg^{-1} in the middle hill soils, and 25.4 cmol(p+)kg^{-1} in the upper hill soils. Soils are low to high in base saturation (3.7%–70.1%) with a higher mean value of 64.8% in the low hill soils, 7.7% in the middle hill soils, and 20.8% in the upper hill soils indicating that the soils of low hill areas are highly base saturated.

BD of soil varies from 0.64 to 1.33 Mg m^{-3} with a mean value of 0.97 Mg m^{-3} in the upper hill soils; 0.93 to 1.57 Mg m^{-3} with a mean value of 1.21 Mg m^{-3} in the middle hill soils; 1.21 to 1.26 Mg m^{-3} with a mean value of 1.23 Mg m^{-3} in the lower hill soils indicating the decreasing trend of BD with the increase in elevation.

3.2.2.3 SOC stock

Temperature and precipitation are the key factors toward the decomposition of organic carbon. SOC stock results from the balance between inputs and outputs of carbon within the below ground environment. In the Darjeeling Himalayan Region, maximum SOC stock was found in the top soil layer from the subalpine/alpine and high altitude forest sites (59.8 and 58.2 g kg^{-1}) followed by mid-altitude (46.1 g kg^{-1}), and low altitude (35.8 g kg^{-1}) (Banerjee, 2014). However, the value was still less (26.9 g kg^{-1}) in the Tarai region and generally decreases with soil depth.

Carbon sequestration potential of two conifers, namely, *C. japonica* (75, 30, 23, and 15 years of age) and *Pinus patula* (30, 23, 21, and 15 years of age) in the Darjeeling Himalayan Region were studied by Banerjee and Prakasham (2012), and they observed that the total biomass carbon varies from 65.85 to 78.19 tC ha^{-1} and 75.95 to 82.73 tC ha^{-1} for *C. japonica* and *P. patula*, respectively (Fig. 7.3).

The study reveals that the SOC stock up to 60 cm is more under *C. japonica* than *P. patula* and decreases with the decrease of age of the plants. Under *C. japonica*, the SOC stock varies from 133.6 to 183.2 tC ha^{-1} and under *P. patula*, from 143.4 to 161.6 tC ha^{-1} (Fig. 7.4).

In Darjeeling Himalayas, SOC stock increased along the altitudinal gradient (Devi & Sherpa, 2019). SOC stock shows a positive correlation with elevation, but there also exists a negative correlation of SOC stock with precipitation and temperature. Different forest types of the Darjeeling Himalayas contribute different levels of soil carbon stocks under wide elevation gradient demanding proper management to maximize their soil carbon sequestration potential.

3.2.3 *Kalimpong Himalayas (West Bengal)*

3.2.3.1 Floristic composition

The variations in altitude, aspect, and climate have influenced the forest type in Kalimpong Himalayas. Such factors result in various types and subtypes of forests in this part of the Himalayas. These forests are subdivided according to the elevation as lower hill forest and middle hill forest.

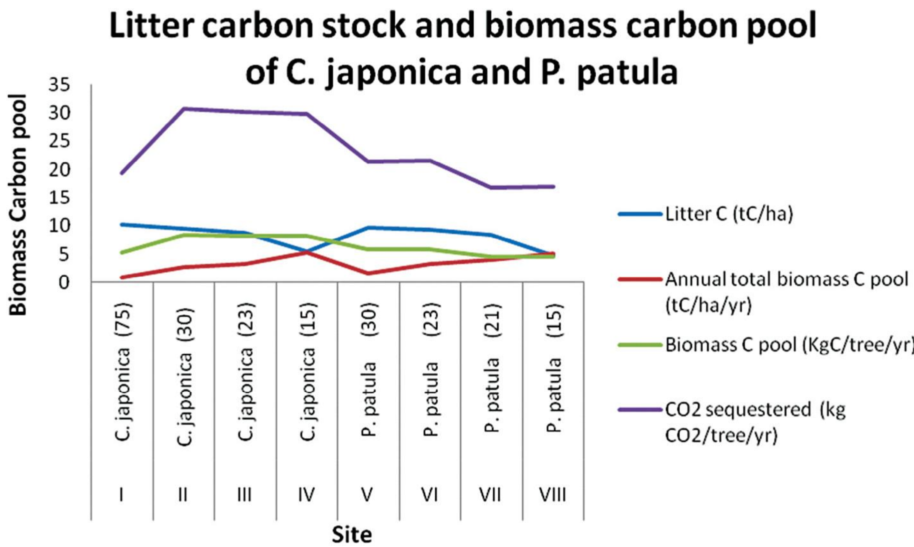

FIGURE 7.3 **Litter carbon stock and biomass carbon pool of the two species.** *Banerjee and Prakasham (2012).*

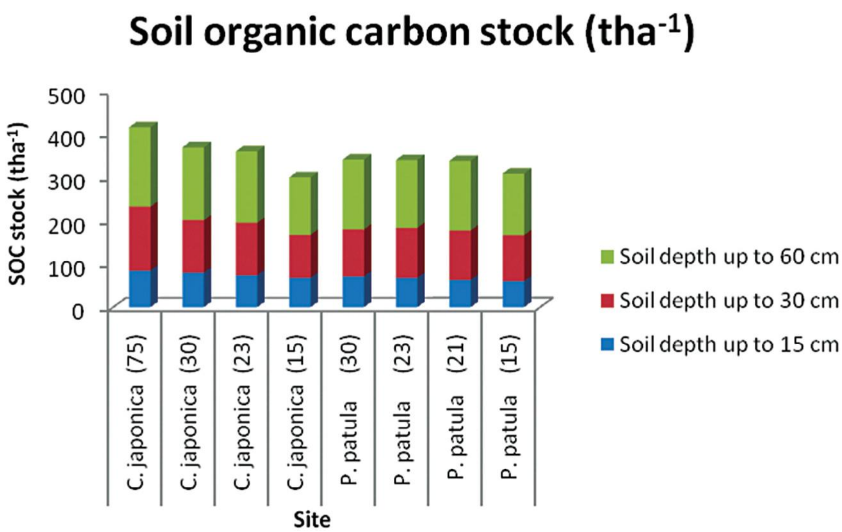

FIGURE 7.4 **Soil organic carbon stock (t ha^{-1}) up to 60 cm soil depth.** *Banerjee and Prakasham (2012).*

The main types of forests in the lower hill area are *Duabanga sonneratioides*, *Acrocarpus fraxinifolius*, *Terminalia myriocarpa*, *S. robusta*, *T. grandis*, and *M. champaca* under Eastern Himalayan Moist Deciduous forest of Northern Moist Deciduous group 3b/E6 (Champion & Seth, 1968). The floristics are generally deciduous in nature, but evergreen species are also dotted here and there.

The middle hill forests are represented as the Northern Subtropical wet hill group 7b/C1 with *A. cathcartii*, *S. wallichii*, *Viburnum coli*, *Engelhardtia* species, *Elaeocarpus lanceifolius*, *Machilus gammieana*, and *B. alnoides* (Champion & Seth, 1968). The floristics are evergreen in nature. The community is of multistoried structure and consists of different coniferous species, namely, *C. japonica*, *Cupressus cashmeriana*, and *P. patula*.

3.2.3.2 Soils

The soils are acidic with pH ranging from 3.8 to 5.0. The pH of the soil varies from 3.8 to 4.3 in the lower hill soils with a mean value of 3.9 and in the medium hill soils; it varies from 3.7 to 5.0 with a mean value of 4.5. Soils are medium to high in organic carbon, and it varies from 0.62% to 3.32% in the lower hill soils with a mean value of 1.72%, and in the middle hill areas, it varies from 0.51% to 4.84% with a mean value of 2.22%. CEC of soil ranges from 4.0 to 20.5 cmol(p+)kg^{-1} with their mean value of 12.7 cmol(p+) kg^{-1} in the lower hill soils and in the middle hill soils, it

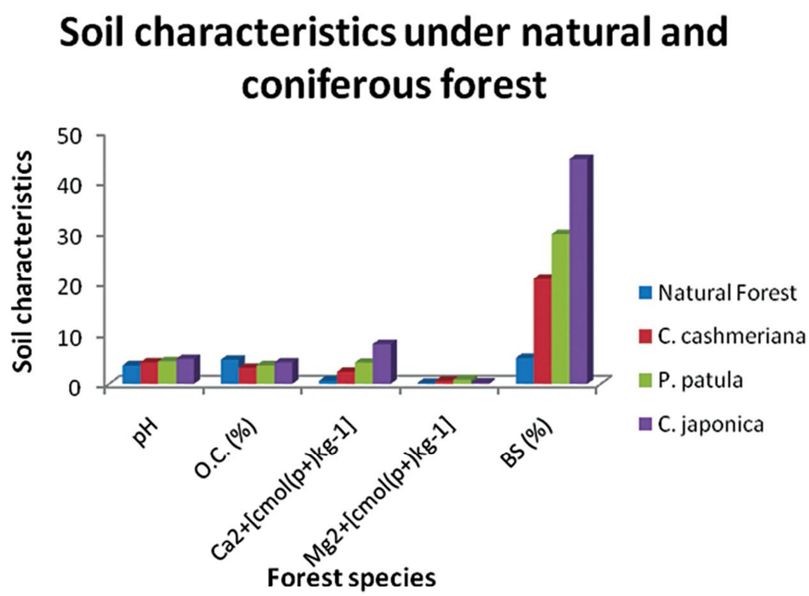

FIGURE 7.5 Soil characteristics in a contiguous area under natural and coniferous forest. *Nath et al. (1988).*

ranges from 9.0 to 29.4 cmol(p+)kg^{-1} with mean value of 18.3 cmol(p+)kg^{-1}. Soils are low in base status, and it varies from 3.6% to 13.7 % in the lower hill soils with a mean value of 7.2%, and in the middle hill soils, it varies from 3.9% to 44.5% with a mean value of 14.4%.

BDs of the lower hill soils are higher with a mean value of 1.37 Mg m^{-3} than the middle hill soils with a mean value of 1.0 Mg m^{-3}.

The influence of the age of vegetation on soil characteristics in the Kalimpong Forest Division revealed that there is significant increase in pH and base saturation in the surface soils under teak (*T. grandis*) as the age of the plantation increases from 12 to 28 years (Nath et al., 1988) reflecting the transformation of the soil from Inceptisol to Mollisol at order level.

To understand the variation in soil characteristics, a study was conducted by Nath et al. (1986) at an altitude of 1700 m of the Kalimpong Forest Division under old natural and coniferous forests and also within the different coniferous species, *C. cashmeriana*, *P. patula*, *C. japonica*, and natural forest (Fig. 7.5).

Soils under conifers differed much from that of natural forest in terms of litterfall. The soils under natural forest were highly acidic in comparison to that under conifers. Within the conifers, soils under *C. cashmeriana* and *P. patula* were more acidic than that under *C. japonica*. Exchangeable Ca^{2+} was maximum in the surface soils under *C. japonica* and least under natural forest. Soils under *C. japonica* showed a highest amount of carbon in the mineral soil and least under *C. cashmeriana* and had a close relationship with the litterfall.

3.2.3.3 SOC stock

The variation of the SOC stock in the forest soils of Kalimpong Himalayas at varying depths indicated that the organic carbon stock increases with the increase in elevation (Fig. 7.6).

3.3 Northeastern Himalayas

3.3.1 Floristic composition

Depending on the variation in altitude and climate, different types of forests are found in the northeastern India, namely, tropical forests, subtropical forests, temperate forests, subalpine forests, and alpine forests.

Tropical forests confine up to an elevation of 1000 m altitude with heavy rainfall and humidity and are highly rich in floral diversity. Depending upon the location and degree of precipitation they are classified as (1) tropical evergreen and semi evergreen forests, (2) tropical dry and moist deciduous forest, and (3) tropical grassland. Under tropical evergreen and semi-ever green forests, the dominant tree species are *Ailanthus integrifolia*, *Castanopsis echinocarpa*, *Dipterocarpus retusus*, *Mesua ferrea*, and *Shorea assamica*, the dominant species under tropical moist and dry deciduous forests are *S. robusta*, *A. catechu*, *Albizia* species, *B. ceiba*, *Duabanga grandiflora*, *Lagerstroemia* species, *Sterculia villosa*, and *T. grandis*.

Under subtropical forests (1000–2000 m), the different forest types are subtropical mixed forests, subtropical pine forests, and subtropical to temperate grasslands. The dominant tree species under subtropical mixed forests are *A. nepalensis*, *Albizia chinensis*, *A. cathcartii*, *Artocarpus dadah*,

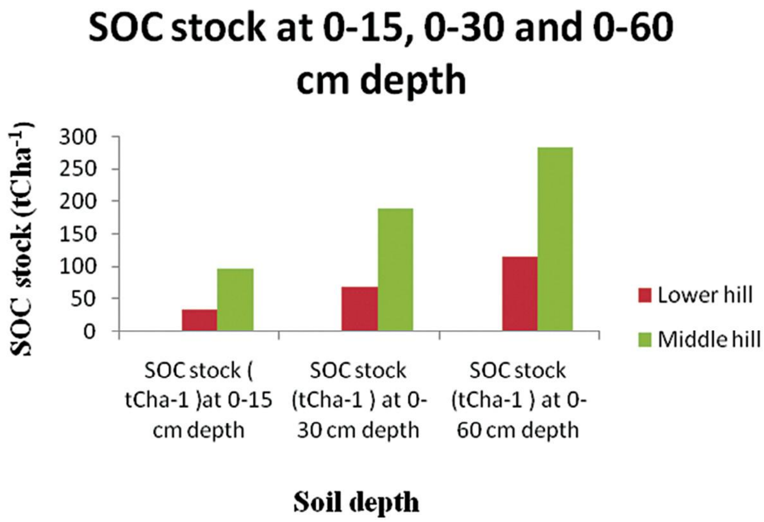

FIGURE 7.6 SOC stock in the forest (soils of Kalimpong Forest Division at different depths. *Nath et al. (1986).*

Betida alnoides, *Castanopsis indica*, *Elaeocarpus* species, *Engelhardtia spicata*, and *Terminalia* species.

Under subtropical pine forests, *Pittus khasiya* is the most dominant species in the Khasi and Jaintia Hills, whereas *P. wallichiana* is found in the Rupa valley area along with *Berberis*, *R. arboreum*, *Quercus griffithii*, and members of *Rosaceae*. The associates of *Pinus insularis* are *Cinnamomum* species, *Engelhardtia spicata*, *S. wallichii*, *Temstroemia gymnanthera*, and *Quercus species*.

Under temperate forests (2000–3500 m), the dominant species are *Acer laevigatum*, *A. nepalensis*, *Beilschmiedia gemmiflora*, *B. alnoides*, *Castanopsis armata*, *Cinnamomum bejolghota*, *Ehretia acuminata*, *Elaeocarpus braceanus*, *Engelhardtia spicata*, *Erythroxylum species*, *Euonymus grandiflorus*, *Lithocarpus dealbata*, *Magnolia insignis*, *Myrica esculenta*, *Persea* species, *Pinus kesiya*, *Prunus cerasoides*, *Q. griffithii*, *R. arboreum, Rhododendron formosum*, *Schima khasiana*, and *S. wallichii*.

The vegetation under subalpine forests (3500–4500 m) are associated with shrubby and bushy species of *A. densa*, *Spectabilis berberis*, *Betida utilis*, *Cotoneaster*, *Cupressus torulosa*, *Juniperus, Lonicera*, *Picea spimdosa Rhododendron*, *Salix*, and a few others.

Vegetation from the subalpine region gradually merges with complete disappearance of tree growth into the alpine type as the altitude increases from 4500 up to 5000 m, which is more or less the limit of plant life. Moreover, the zone is mostly covered with snow for the major part of the year and multicolored flora that is extremely short lived. *Juniperus pseudosabina*, and *Juniperus recurva* grow in the higher ranges of north and east Sikkim especially on the exposed sunny hill slopes around Thangu and Changu. In Arunachal Pradesh, it occupies the Pangchen and Delei, Dichu Valleys of Lohit.

3.3.2 Soils

Soils are mostly acidic in reaction. Acid soils below pH 5.5 occupy more than 60% of the north eastern region. The Al toxicity, deficiency of bases (Ca, Mg, and K) due to extensive leaching and their poor retention power in clay complex, and high P-fixation capacity are some of the major constraints in achieving optimum crop productivity.

3.3.3 SOC stock

The northeastern region (NER) is highly variable in climatic conditions, topography, rainfall pattern, vegetation, land use, and cultural diversity and ethnicity. As a result, the SOC content is expected to be highly variable across the entire region. The variation in SOC content and stock depends generally on the type of land use, degree of land use change, and postconversion land management (Post & Kwon, 2000). Thus NER covering 15.61 mha area varies in organic carbon content, and their spatial variability was measured by Chaudhury et al. (2013) (Fig. 7.7).

The plain land covers about 84.4% area in Assam, and in the NER Region, it occupies 35% area. About 15.3% area is under cultivation, 35.28%–90.68% area under forest cover, and 3.36% under shifting cultivation.

The SOC content at the surface layer varies considerably across the region (Fig. 7.8). SOC content of more than 1% occupies 98.54% area, whereas SOC content of more than 1.5% occupies 57.68% area. About 43.25% of the area had SOC content 1.5%–2.5%, and very high organic carbon content (3.5%–5.5%) was recorded in 9.98% area. More than 93% area in Sikkim had very high SOC content (2.5%–3.5%). Relatively low SOC content (1.0–1.5%) covered maximum area of Tripura (>93%) followed by Assam (62.83%) and Meghalaya (19.9%). SOC content of

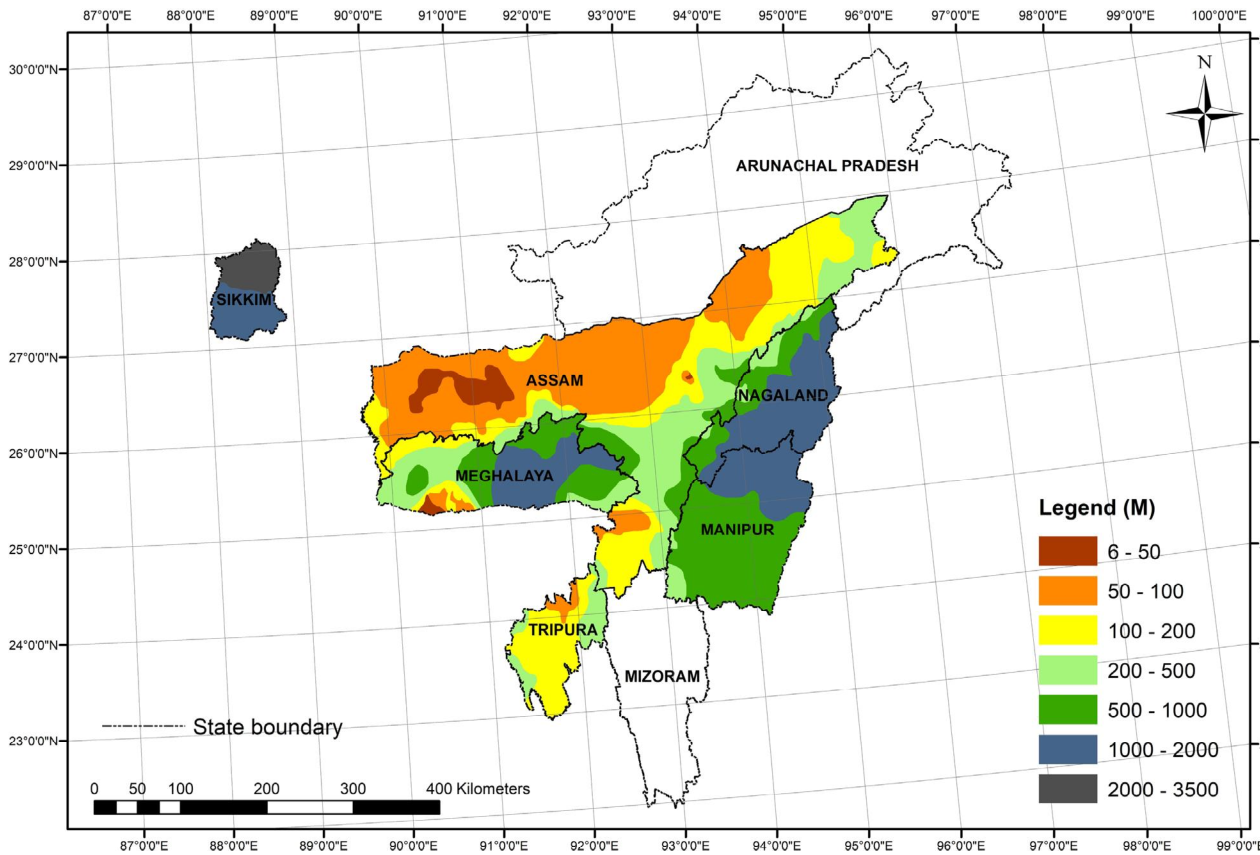

FIGURE 7.7 Study area representing geographical location including relative elevation (m). Chaudhury et al. (2013).

<1% was obtained in small area of Tripura (7.55%), Assam (1.74%) and Nagaland.

A wide variation of SOC density among and within each state was observed in the NER (Table 7.6).

SOC stocks of the NER states (15.61 mha) were estimated for 64.71% of the area (10.10 mha) representing only major land use systems. Total SOC stock of 339.82 Tg was estimated from an area of 10.1 mha surface soils of the study area in NER (Table 7.7).

SOC density in this area varies widely among different land use systems, and average SOC density was higher in Sikkim and Tripura (Fig. 7.9).

3.3.4 Tripura

3.3.4.1 Floristic composition

The forests in Tripura are mostly tropical moist deciduous forest. The dominant species are sal (*S. robusta*), Chamal (*Artocarpus chapalasha*), and Simul (*Bombax malabaricum*). The principal deciduous trees are Teak (*T. grandis*), Gamar (*Gmelina arborea*), Koroi (*Albizia procera*) are common. Bamboo (muli) is also one of the major plants along with grasses, Bontulsi (*Ocimum basiliem*), etc.

3.3.4.2 Soils

Forest soils of south Tripura mostly developed on flat topped denudation hills and low relief structural hills with slope varying from 3 to 15%, derived from sandstone and shale, were studied by Gangopadhyay, Bhattacharyya, & Sarkar (1999). All the soils were acidic, low in CEC, high in organic carbon in the surface, and the extractable acidity increases with soil depth. The study indicated that redder soils with a relatively higher organic carbon are associated with the prevalent forest with higher average height and girth at breast height.

3.3.4.3 SOC stock

SOC stock of the soils of Tripura state in the Northeastern Region was found to be 0.05 Pg in comparison to the SOC stock of India as 11.397 Pg (Bhattacharyya, Sarkar, & Pal, 2010). SOC stock in Tripura is maintained at 0.046 Pg ha^{-1} with respect to the all India average of 0.0346 Pg ha^{-1} (Table 7.8). As per the agro-climatic zones (ACZs), the entire NER was found to store organic carbon at 0.064 Pg mha^{-1} (Table 7.8).

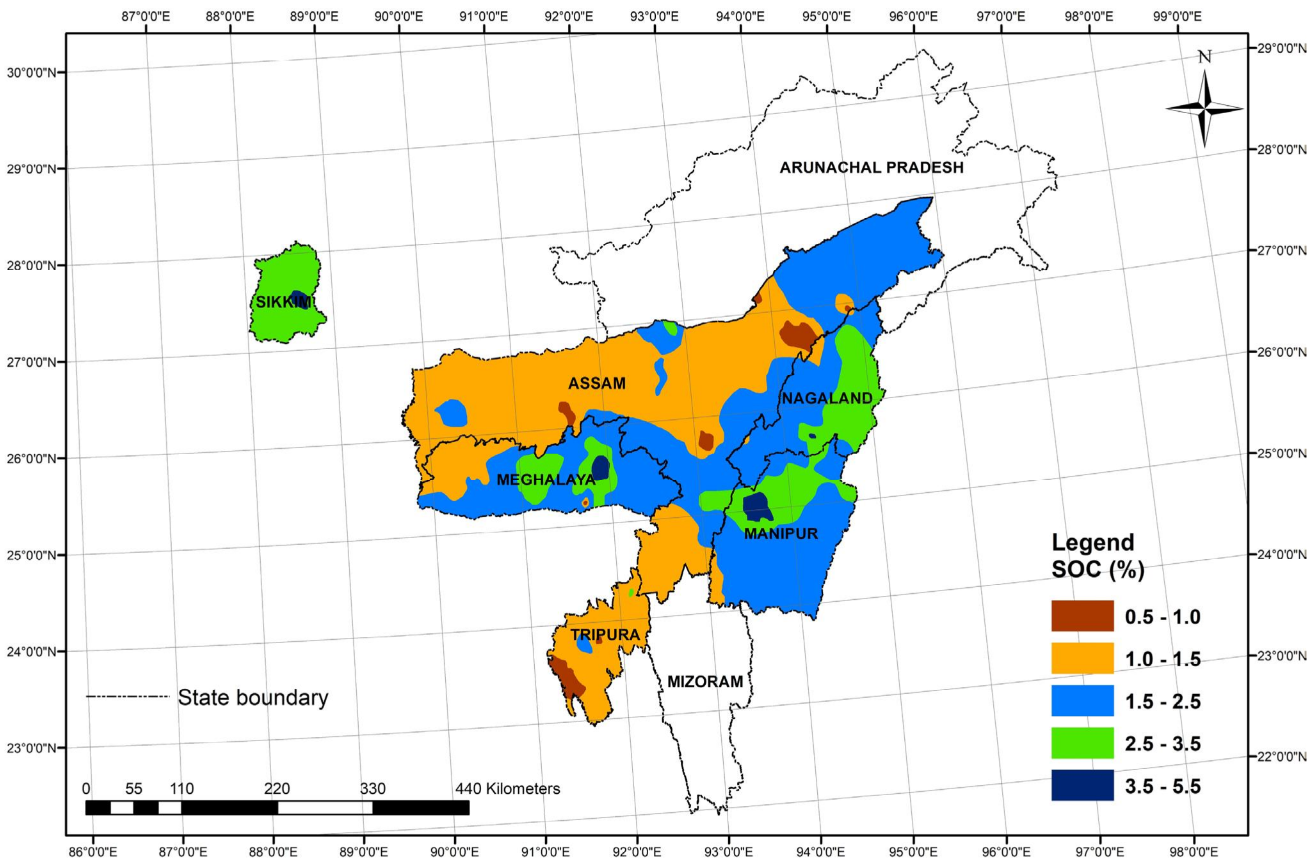

FIGURE 7.8 **Spatial distribution map of SOC content across NER.** *Chaudhury et al. (2013).*

TABLE 7.6 Different classes of SOC density across NER.

State	Geographical area (million ha)	SOC density (Mg ha^{-1}) in percentage of total geographical area					
		10–20	20–30	30–40	40–50	50–60	60–80
Manipur	2.218	Nil	49.39	36.51	13.03	1.07	Nil
Meghalaya	2.238	1.42	49.51	42.56	4.06	1.72	0.73
Nagaland	1.649	1.71	40.43	57.51	0.35	Nil	Nil
Sikkim	0.699	Nil	Nil	7.17	81.98	10.86	Nil
Tripura	1.017	81.80	18.20	Nil	Nil	Nil	Nil

Source: (Chaudhury et al., 2013)

3.3.4.4 Arunachal Pradesh and Mizoram Himalayas

Studies conducted under different land uses of Arunachal Pradesh in NER indicated that the total carbon stock in the mixed forests of Arunachal Pradesh was estimated 195.81, 162.26 t ha^{-1} in the pine forests and 31.10 t ha^{-1} in agricultural lands (Bordoloi, Das, Yam, Deka, & Tripathi, 2019). SOC content and SOC stock in the soils of Mizoram under different land uses and at varying depths indicated that SOC stock decreased with increasing soil depth (Kenye, Sahoo, Singh, & Gogoi, 2010). They also observed that the conversion of forest to other land uses also influence the SOC stock loss significantly.

TABLE 7.7 Distribution of SOC stock (Tg) under major land use systems in NER.

State	%of Geographical area	Total SOC stock (Tg)							
		Crop land	Dense forest	Open forest	Plantation crop	Shifting cultivation	Waste land	Grass land	Total stock
Assam	66.2	77.0	48.5	13.0	12.6	0.8	8.2	12.5	172.6
Manipur	65.5	5.1	24.9	9.0	0.1	2.0	7.5	–	48.6
Meghalaya	52.8	4.4	21.9	1.2	1.8	2.4	7.2	–	38.8
Nagaland	59.3	5.7	17.5	0.2	0.1	4.8	4.2	0.0	32.5
Sikkim	61.3	2.1	7.2	2.5	0.0	–	1.3	2.2	15.3
Tripura	87.9	4.0	20.5	4.0	1.6	0.8	1.1	–	32.0
Total	64.7	98.3	140.4	30.0	16.2	10.7	29.5	14.7	339.8
SOC density (Mg ha^{-1})	–	30.7	38.8	35.3	32.1	31.8	23.0	47.0	–

Source: (Chaudhury et al., 2013).

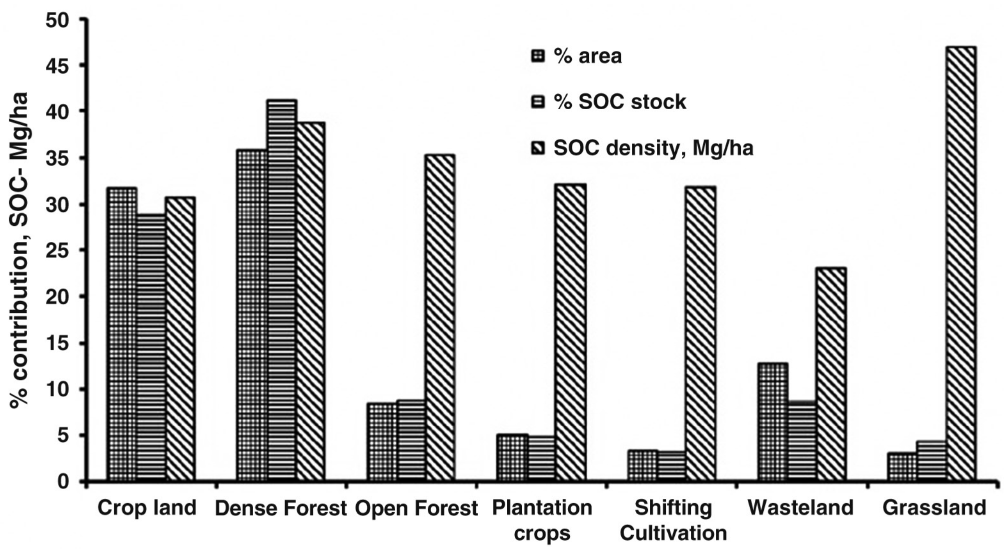

FIGURE 7.9 **Distribution of SOC stock and SOC density under major land-use systems of the NE region of India.** *Chaudhury et al. (2013).*

TABLE 7.8 SOC stock in Tripura and India—a comparison.

SOC stock	Soil depth (0–30 cm) SOC stock (Pg)	SOC stock (Pg million ha^{-1})
India	9.550	0.029
ACZ-2	1.792	0.064
Tripura	0.05	0.046

Source: (Bhattacharyya, Sarkar, & Pal, 2010)

3.4 Organic carbon in brown forest soils in the Western Ghats and the Satpuras

The brown forest soils (Mollisols) have been reported in subtropical parts of Indian forests (Bhattacharyya, 2014) similar to the temperate climates in the United States and Europe. However, Mollisols of the Western Ghats and Satpura Range developed on Deccan basalt are acidic and fairly weathered (Bhattacharyya et al., 2006) (Table 7.9). The Indian Mollisols of humid tropical climate contain Ca-zeolites, which act as a source of base-rich heulandites that helps them persist even in adverse humid tropical climate with mean annual rainfall ranging from 1400 to 3300 mm (Bhattacharyya et al., 2006). The loss of bases during the leaching of soils has thus been continuously replenished by the steady supply of bases from heulandites (Ca-zeolites). Conservation of forests can thus maintain these valuable brown forest soils.

3.4.1 Konkan

Konkan, Maharashtra represents a part of the Western Ghats (Challa, Gajbhiye, & Velayutham, 1999). The topographical

TABLE 7.9 **Organic matter content in brown forest soils in the Western Ghats and the Satpuras.**

Soil depth (cm)	Clay (%)	pH	Organic matter (%)
Brown forest soil (Vertic Haplustoll): Madhya Pradesh: Forest (*Tectona grandis, Madhuca indica*) (the Satpuras)			
0–6	30	5.9	6.1
6–20	39	5.8	5.2
20–37	29	5.8	3.5
37–74	31	5.9	2.1
74–106	31	5.6	1.4
106–150	28	5.5	0.9
Brown forest soil (Vertic Argiudoll): Maharashtra: Forest (*Syzygium cumini, Terminalia chebula, Carissa caranadas, Ficus glomerata*) (Western Ghats)			
0–15	51	5.7	3.5
15–40	53	5.7	2.1
40–74	61	5.7	1.2
74–108	61	6.1	0.7
108–146	59	6.1	0.5
146–175	53	6.1	0.2
175–190	51	6.1	0.2

variation of Konkan landscape develops a relation with soil carbon stock and altitude resulting in the change in altitude, climatic and so do the flora. Precipitation and temperature are the major components of climate that changes with altitude. SOM increases with altitude effecting the formation of Mollisols that are dominant in Sikkim (Gangopadhyay et al., 2020). There is a strong SOC stock–altitude relationship for soils that are formed between 550 and 125 m amsl (Fig. 7.10) and are mostly under forest and plantation crops with orchards of a host of horticultural crops (Bhattacharyya, Chandran, & Ray, 2015a, Bhattacharyya, Mandal, & Mandal, 2015b). These soils are known as brown forest soils and are classified as Mollisols in US soil Taxonomy (Soil Survey Staff, 2014). Such soils were reported to contain nearly 3%–4% SOC and are spatially associated with red (Alfisols) and black (Vertisols and their intergrades) soils in the Western Ghats (Bhattacharyya, Pal, & Srivastava, 1999, Bhattacharyya, Pal, Velayutham, Chandran, & Mandal, 2001, Bhattacharyya et al., 2006).

The soil carbon data of Konkan, Maharashtra helps to find out the soil health in terms of organic matter content in soils vis-à-vis soil physical and microbial growth. The ACZ number 2 representing the entire north eastern region was found to store organic carbon at the rate of 0.064 Pg mha^{-1} (Bhattacharyya et al., 2009) (Fig. 7.11). The present datasets indicate that Konkan soil is maintaining the SOC stock of 0.062 Pg mha^{-1} and, therefore, is falling within the norms of green belt to suggest that existing Konkan ecosystem is currently maintaining the soil quality and health in terms of SOC.

3.4.2 *Reserved forests in Maharashtra and Madhya Pradesh*

Organic carbon in soils maintains soil quality and inorganic form of carbon in soils formed by pedogenic processes

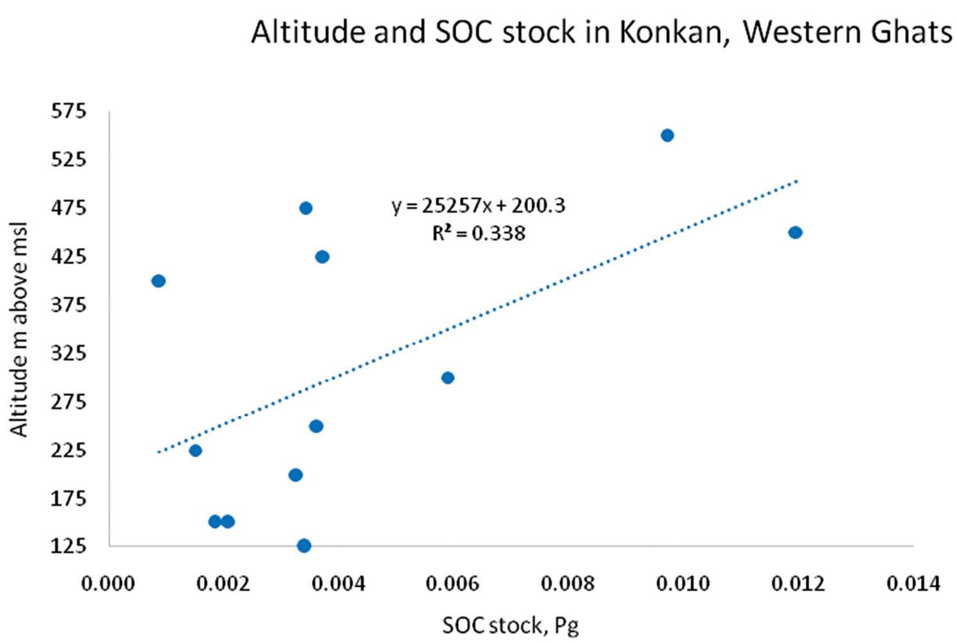

FIGURE 7.10 **Relationship of altitude and soil organic carbon in the Konkan, Maharashtra.** *Bhattacharyya et al. (2015a,b).*

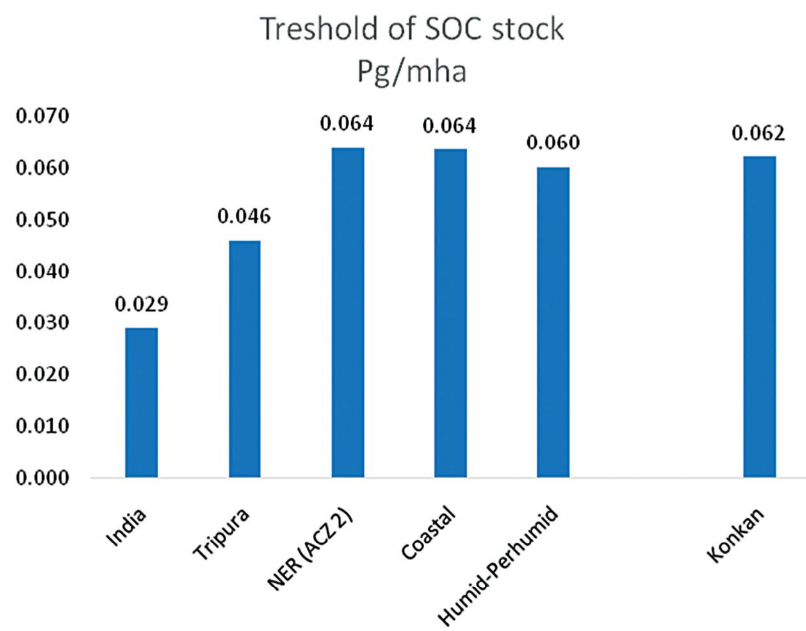

FIGURE 7.11 Threshold limit of soil organic carbon stock in different parts of country as compared to Konkan, Maharashtra. *Bhattacharyya et al. (2020). The all India values for SOC per million ha has since been revised from 0.029 Pg to 0.0346 Pg.*

TABLE 7.10 Total carbon stock in black soils under forests in Maharashtra and Madhya Pradesh.

Soil carbon stock (Pg)	Bioclimate: mean annual rainfall (mm)	Soil depth (cm)			
		0–30	0–50	0–100	0–150
Karkeli, Madhya Pradesh, Reserve Forest, Sal					
SOC	Sub-humid: moist: 1352	0.035	0.045	0.059	0.073
SIC		0	0	0	0
TC		0.035	0.045	0.059	0.073
Dadarghugri, Madhya Pradesh, Forest, Teak					
SOC	Sub-humid: moist: 1420	2.42	2.052	1.626	1.484
SIC		0	0	0	0
TC		1.08	1.11	1.125	1.13
Boripani, Maharashtra, Forest, Teak					
SOC	Sub-humid: moist: 1279	0.005	0.007	0.009	0.010
SIC		0.003	0.005	0.017	0.029
TC		0.007	0.012	0.025	0.038

during soil formation deteriorates soil health. Therefore it is important to know how and to what extent SIC stock is degrading soils. Fortunately, forest soils do not contain inorganic carbon as $CaCO_3$. In a few cases (like Boripani in soils formed in the basalts, Table 7.10) SIC has started to form in the degraded forests that demand proper care for appropriate and recommended canopy cover. Ideally pedogenically formed $CaCO_3$ is formed in soils as and when land surfaces are kept fallow and/or under sparse vegetation (Bhattacharyya et al., 2004, Bhattacharyya, 2016). SOC and SIC stocks in three forests from Maharashtra and Madhya Pradesh are shown in Table 7.10. Most of these soils are maintaining the minimum threshold level of organic carbon and need to be protected (Bhattacharyya et al., 2006).

3.5 Indian forests

SOC pool in Indian forests at top 50 and 100 cm depth under various types of forests was estimated by (Chhabra, Palria, & Dadhwal, 2003). High SOC pools (1.73 and 2.64 Pg C in top 50 cm and 1 m soil depth) were found under moist deciduous forests. The total SOC pool has been estimated as 4.13 (top 50 cm) and 6.81 Pg C (top 1 m soil depths). The estimated SOC densities by forest types can form input in models for net C release from forest by deforestation.

As per the India State of Forest Report 2017, India's carbon stock has been estimated as 7083 Mt. The per hectare carbon stock among the states revealed that Arunachal Pradesh contributed highest per hectare carbon stock (148.52 t) followed by Sikkim (145.14 t) and Karnataka (126.52 t). It has been found that Tropical Wet Evergreen Forest possesses highest organic carbon stock (157.18 t). The total carbon stock in country's forest is estimated as 7124.6 Mt with an increase of 42.6 Mt of the carbon stock of the country as compared to the last assessment of 2017.

Based on the estimation of the SOC stock in the different states under IHR and the Western Ghats, Satpuras, Konkan, and Reserved forest areas, it is evident that most of the states contain SOC stock more than 0.04 Pg mha^{-1}. Table 7.11 indicating that the states/region maintained a minimum threshold value of organic carbon stock and, therefore, declared as the green belt and need to be protected. However, the Assam Hills, Mizoram, and India possesses below the minimum threshold value in respect of SOC stock, and appropriate conservation measures are needed to improve the quality of soil as well as forest.

4 Conclusion

The Himalayan ecosystem with tremendous ecological diversity is characterized by the various altitudes, slope, aspects, and the climate and microclimate of the mountains. The effect of altitude and vegetation influences the soil characteristics mainly through the addition of organic matter resulting from periodic return through litter fall of leaves, branches, bark, fruit, and sometimes entire trees. The higher organic carbon content at the surface horizon plays a vital role for SOC stock in the soil. The comparison of the forest soil carbon of Sikkim Himalayas with other Himalayan region revealed that SOC of the forest soils of Sikkim Himalayas is high at high altitude and within the profile, which is more on the surface and decreases with the increase in soil depth. It reveals that SOC pool increases with altitude that virtually reduces the BD and also indicates its better stabilization at cooler temperature, higher precipitation, and lesser microbial activity. Similar findings were also found in Kashmir Himalayas (Dar & Somaiha, 2015). However, a similar study in Garhwal Himalayas (Sheikh, Kumar, & Bussmann, 2009) and in the Shimla district of Himachal Pradesh (Reddy & Gupta, 2018) indicated decrease in soil carbon density with the increase in soil depth indicating the inability of soil to stabilize organic matter with elevation probably due to the removal of forest cover through severe deforestation.

SOC stock in the Darjeeling Himalaya, India, increased along the altitudinal gradient (Devi & Sherpa, 2019). Although SOC stock bears a positive correlation with elevation, but there exists a negative correlation of SOC stock with precipitation and temperature. Different forest types have varying level of SOC stocks under wide elevation gradient. It demands proper management to maximize their soil carbon sequestration potential.

The type of land use, degree of land use change, and post-conversion land management are the key factors for the variation in SOC content and stock in NER. Total SOC stock of 339.82 Tg was estimated from an area of 10.1 mha surface soils of the NER.

SOC stock of the soils of Tripura state in North Eastern Region indicated that total estimated SOC in Tripura was found to be 0.05 Pg in comparison to the SOC stock of India as 11.397 Pg (Bhattacharyya, Sarkar, & Mandal, 2010). The study shows that SOC stock in Tripura is maintained at 0.0346 Pg mha^{-1} compared to the all India average of 0.029 Pg mha^{-1}. As per the ACZs of the Planning Commission, the entire NER was found to store organic carbon at 0.064 Pg mha^{-1}. Such threshold values of SOC stock (0.05–0.06 Pg mha^{-1}) should, therefore, be maintained in the areas declared as the green belt to protect natural ecosystems.

Kashmir Himalayan soils have a greater potential of carbon sequestration and the SOC stock at higher altitudes is more than lower altitude. Thus the SOC stocks in these forests will decrease by further rise in atmospheric temperature. In Garhwal Himalayas the forest types have shown higher C stocks on the NE aspects resulting in the development of more stable communities along with more fertile soils that eventually sustain higher C stocks. Therefore, mature forest stands should be preferred on northern aspects having higher amounts of C for conservation purposes.

Besides the soils of IHR, the brown forest soils of Western Ghats and Satpuras basically Mollisols developed on Deccan basalt are acidic and fairly weathered. The presence of Ca-zeolites in soil helps one to replenish the bases even in the adverse humid tropical climate. The conservation of forests can thus maintain these valuable brown forest soils. The Mollisols of Konkan contain 3%–4% SOC and are spatially associated with Alfisols, Vertisols, and their intergrades in the Western Ghats. The Konkan soil is maintaining the SOC stock of 0.062 Pg mha^{-1} and, therefore, is falling within the norms of green belt to suggest that existing Konkan ecosystem is currently maintaining the soil quality and health in terms of SOC. As per the current assessment the total carbon stock in country's forest is estimated 7124.6 Mt. The total SOC stock in the IHR was thus found to be 0.872 Pg mha^{-1}, while the total SOC stock in the soils of Western Ghats, Satpura, Konkan (Maharashtra), and Reserved Forest was found to be 0.669 Pg mha^{-1} with a grand total of 1.541 Pg mha^{-1} in the studied area.

TABLE 7.11 SOC stock in the representative forest soils of the Indian Himalayan Region and other forest areas.

State code	Country/ State/Region	Total geographical area ('000 ha)	Percent share of geographical area in the Indian Himalayan Region (IHR)	SOC stock (Pg mha^{-1})	Remark	References
India						
	India	328.7 million ha	–	0.029	Below the minimum threshold	Bhattacharyya et al. (2000a)
		Himalaya zones				
	Himalaya zones (ACZ-1 and -2)	62.453 million ha		0.048	Maintaining minimum threshold of organic carbon stock	Bhattacharyya et al. (2008)
Northern, Western, and Central Himalayas						
1	Jammu and Kashmir	222.236	41.65	0.055	Maintaining minimum threshold of organic carbon stock	Dar and Somaiha (2015)
2	Ladakh	59.146	0.06	0.067	Maintaining minimum threshold of organic carbon stock	Charan et al. (2012)
3	Uttarakhand	53.483	10.02	0.060	Maintaining minimum threshold of organic carbon stock	Gupta et al. (2018)
4	Himachal Pradesh	55.673	10.43	0.055	Maintaining minimum threshold of organic carbon stock	Reddy and Gupta (2018)
Eastern Himalayas						
5	Sikkim	7.096	1.33	0.091	Maintaining minimum threshold of organic carbon stock	Gangopadhyay et al. (2020)
6	West Bengal hills	3.149	0.59	0.059	Maintaining minimum threshold of organic carbon stock	Banerjee (2014), Devi and Sherpa (2019)
North Eastern Himalayas						
7	Meghalaya	22.429	4.20	0.068	Maintaining minimum threshold of organic carbon stock	Chaudhury et al. (2013)
8	Assam Hills	15.322	2.87	0.040	Below the minimum threshold	Chaudhury et al. (2013)
9	Tripura	10.486	1.97	0.055	Maintaining minimum threshold of organic carbon stock	Chaudhury et al. (2013)
				0.046	Maintaining minimum threshold of organic carbon stock	Bhattacharyya et al. (2010)
10	Mizoram	21.081	3.95	0.040	Below the minimum threshold	Kenye et al. (2010)

(Continued)

TABLE 7.11 SOC stock in the representative forest soils of the Indian Himalayan Region and other forest areas. (*Cont.*)

State code	Country/ State/Region	Total geographical area ('000 ha)	Percent share of geographical area in the Indian Himalayan Region (IHR)	SOC stock (Pg mha^{-1})	Remark	References
11	Manipur	22.327	4.18	0.059	Maintaining minimum threshold of organic carbon stock	Chaudhury et al. (2013)
12	Nagaland	16.579	3.11	0.081	Maintaining minimum threshold of organic carbon stock	Chaudhury et al. (2013)
North Eastern Region						
13	Arunachal Pradesh	83.743	15.69	0.101	Maintaining minimum threshold of organic carbon stock	Bordoloi et al. (2019)
Western Ghats						
14	Gujarat, Maharashtra, Goa, Karnataka, Tamil Nadu, and Kerala	14,000	–	0.062	Maintaining minimum threshold of organic carbon stock	Bhattacharyya et al. (2001)
Coastal Maharashtra						
15	Maharashtra (Konkan)	3000	–	0.062	Maintaining minimum threshold of organic carbon stock	Bhattacharyya et al. (2020)
The Satpuras						
16	Gujarat, Maharashtra, Madhya Pradesh, Chhattisgarh	52		0.062	Maintaining minimum threshold of organic carbon stock	Bhattacharyya et al. (2006)
Reserved forests						
17	Reserved forests of India	30	–	0.0562	Maintaining minimum threshold of organic carbon stock	FSI (2017)

The Himalaya zones (ACZ 1 and ACZ 2; Anonymous 1989) cover nearly 19% area and contribute 33% of SOC reserves of the country, largely due to the thick forest vegetation (Figs. 7.12 and 7.13). The northern mountains of the country have maximum concentration of forest ecosystem, except parts of central and western India. Within the Himalayas Western part sequester more SOC per unit area as compared to the eastern part (Fig. 7.13). This is in spite of the fact that The Eastern Himalaya covers more area as wellas more SOC stock in first 30 cm depth of soils (Figs. 7.12 and 7.13). Nearly 40% of the total SOC stock of the global soils resides in forest ecosystems (Eswaran et al., 1999). The carbon stored in the upper soil horizons represents the pool most sensitive to changes if the forest is used for agriculture or converted to pasture for ranching. It has been reported that the conversion of the Amazonian forest to well-managed pastures will cause an initial fall in the SOC reserves followed by a slow rise (Cerri, Easter, & Paustian, 2007). The estimates of SOC in any ecosystem represent a valuable baseline for evaluating the original status of SOC (Bhattacharyya et al., 2007a, 2008). The SOC stock of the Himalayas as well as plateu and hills housing forest species in the central and western part of India (ACZs 1, 2, 7,8, 9, 10; Bhattacharyya et al., 2008) may thus act as a baseline dataset to assess the effects of land-use changes in the Himalayan range of India (Bhattacharyya et al., 2000a).

Thus the forest soils of Himalayas and other forests of India are the major source of SOC which helps one to increase the SOC stock in soil that in turn not only improves the soil health but also helps in carbon cycling in the terrestrial ecosystem and mitigating the greenhouse gases from the environment. Hence, for the cause of science and society, this important resource should be preserved through afforestation and other soil and water conservation measures. This study is the base for SOC stock of the forest ecosystem in the present climatic scenario and will be an important issue for future under the changing climatic condition.

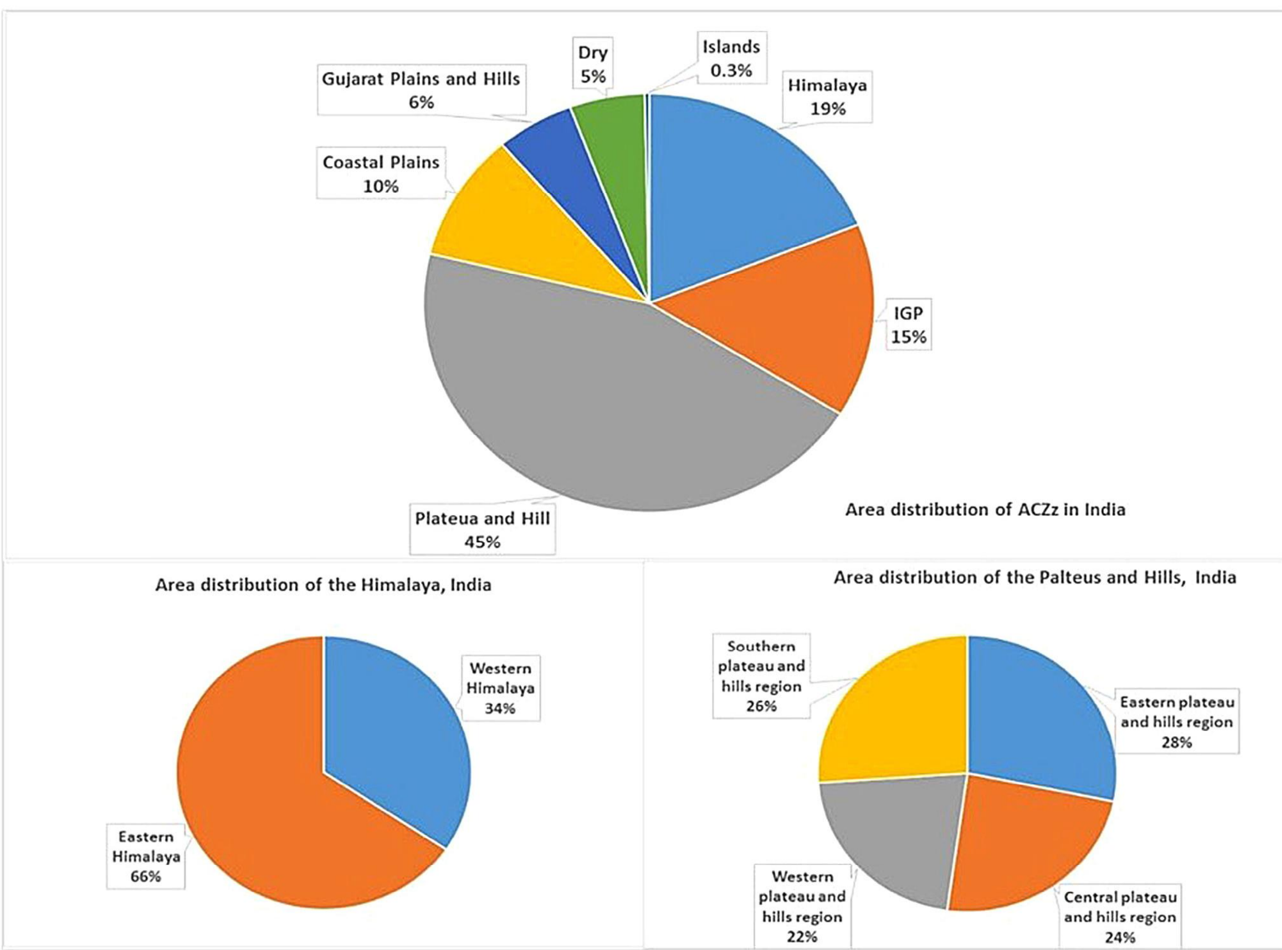

FIGURE 7.12 Area distribution of different zones in India and the Himalayan and Plateau and Hill zones in India. *Bhattacharyya et al. (2008).*

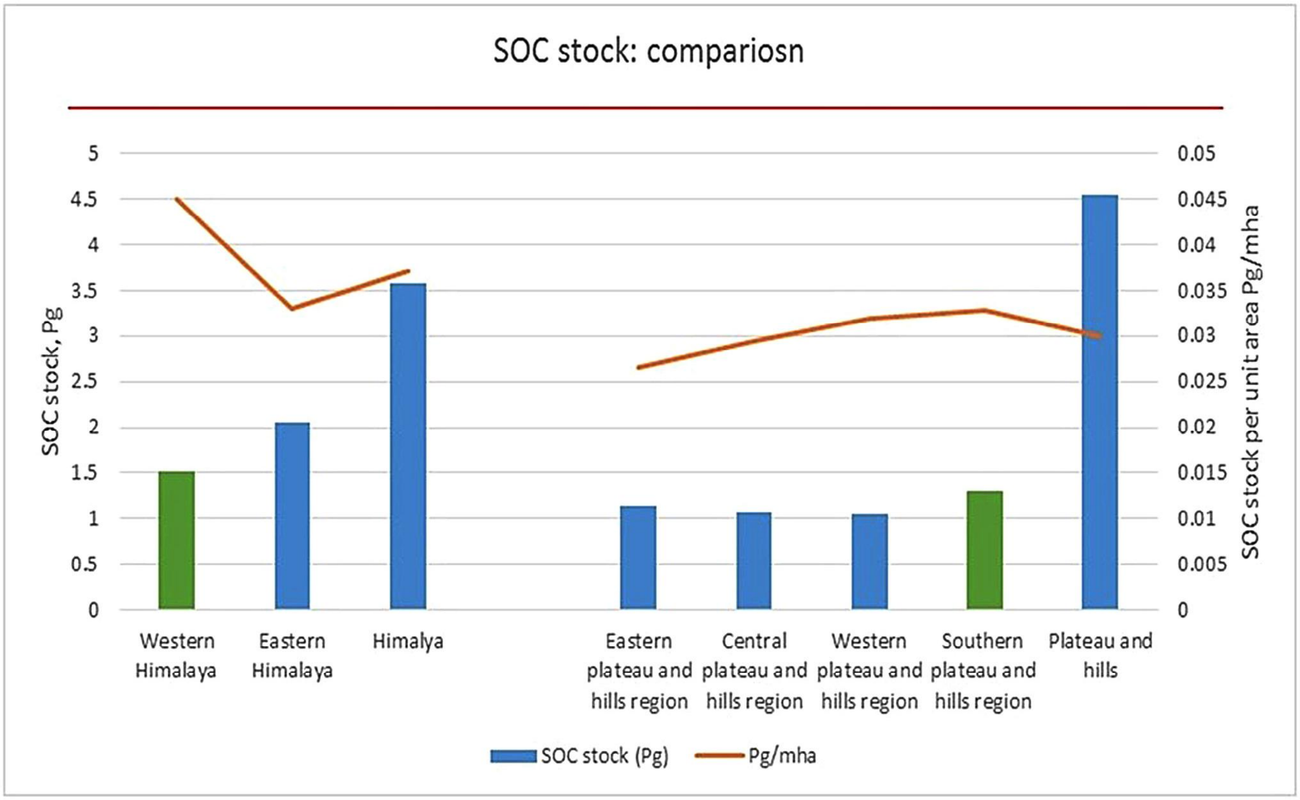

FIGURE 7.13 Soil organic stock compared in the Himalayas and the hills in other part of India. *Bhattacharyya et al. (2008).*

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