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Mollisols of Sikkim: The Unique Soils of the Humid Temperate Zone of India

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Abstract: *Brown Forest Soils (Mollisols) from Sikkim state of northeastern India developed from the Daling group and granite gneiss parent rock. These soils are common under humid temperate climates with varying altitudes and vegetation in the Eastern Himalayas. These soils are mostly coarse-loamy to fine-loamy at the surface, and the clay content increases with soil depth. Soils are extremely to very strongly acidic at the surface with high content of organic matter, low in CEC with high base saturation. Clay CEC of these soils indicates mixed mineralogy with kaolin and smectite clay minerals. An advanced stage of weathering of the parent rocks and the presence of Ca-bearing weatherable minerals in the parent rocks, along with the temperate climate, might have helped in the formation and persistence of Mollisols in Sikkim. Besides the supply of bases through the decomposition of organic matter from the upper reaches, the basic volcanic lava in the form of basic rocks in the upper Paleozoic (Lower Gondwana) sequences in the Sikkim Himalayas continuously supplies the bases. This maintains the required base saturation (>50%) of soil to qualify for Mollisols, even in the humid temperate climate of Sikkim. These soils are precious and taxonomically represent Molliosl. This soil order is based on the characteristics of the surface diagnostic horizon and is the primary source of soil organic carbon, which helps to increase the SOC stock and, in turn, improves soil health. The occurrence of these soils also helps in carbon cycling in the terrestrial ecosystem mitigating the greenhouse gases from the environment and providing better ecosystem services. The high SOC content of Mollisols is a boon for agriculture in Sikkim, indicating better stabilization of organic matter in this temperate climate. Increased organic matter is beneficial in growing crops in these soils and perhaps justifies declaring Sikkim as an organic state. In Sikkim, brown forest soils (Mollisols) cover about 9.56 percent area out of which 2.51 percent area falls in the humid temperate climate under highly eroded/degraded conditions.*

***Keywords*:** Acid rock weathering; eco-system services; forest soils; granite gneiss parent rock; north-east India; SOC stock; vegetation effect on soil formation.

Brown Forest Soils (Mollisols), are generally characterized by thick, dark, humus-rich surface horizon (mollic epipedon) developed by the process of darkening of the soil by organic matter additions (melanization) - probably the most important process in the formation of Mollisol. The addition, decomposition, and accumulation of a relatively large amount of organic matter in soil profile, with the presence of calcium, forms the central concept of Mollisols. The high base saturation (>50%) is another important criterion for Mollisols. Due to their typical characteristics, Mollisols are considered abundant and precious soil resources.

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Mollisols are primarily distributed in semi-arid to subhumid areas of north and south America, Europe, and Asia under grass vegetation under a wide range of temperatures from the equator to the poles and in lowlands to high mountain meadows. They also form on a variety of parent materials, mainly the high base rich sediments and rocks such as limestone, marl, and basalt or alluvium in which there has been decomposition and accumulation of a large amount of organic matter at the surface.

Mollisols are common in temperate climates due to cold temperatures, which retards the decomposition of organic matter. However, due to the prevailing high temperature in humid tropics, agricultural lands cannot store sufficient organic matter to qualify for Mollisols. Mollisols in the USA were found to develop primarily on Quaternary materials on gentle to moderate slopes under a wide range of landscapes starting from flat alluvial plains to undulating plains and mountains (Fenton *et al*., 1983).

Brown forest soils or Prairie soils occupy about 916 million ha, representing 7% of the world's ice-free land surface (Liu *et al*., 2012). They are most prevalent in the mid-latitudes of North America, Eurasia, and South America. In North America, they cover 200 million ha of the USA, more than 40 million ha of Canada, and 50 million ha of Mexico. Across Eurasia, they cover around 450 million ha, extending from the western 148 million ha in southern Russia and 34 million ha in Ukraine to the eastern 35 million ha in northeast China. They are common in South America's Argentina and Uruguay, covering about 89 million and 13 million ha, respectively. Mollisols are inherently productive and fertile soils. They are extensively and intensively farmed and increasingly dedicated to cereals production, which needs significant inputs of fertilizers and tillage. Mollisols are also important in the pasture, range, and forage soils. Thus, these soils are prone to soil erosion and dehumidification (loss of stable aggregates and organic matter) and suffer from anthropogenic soil acidity. The distribution of Mollisols in the world is presented by Liu *et al.,* (2012).

Interestingly, Mollisols were identified in the tropical climate in India and reported in the northern part of India under subtropical climate developed from the micaceous alluvium of the Indo-Gangetic plains (Deshpande *et al*., 1971). Later it has also been identified in the subtropical parts of Indian forests (Bhattacharyya, 2014), similar to the climates in the United States and Europe. Acidic Mollisols developed from basalt in the Western Ghats, and Satpura ranges under humid tropical to sub-tropical climates were found to have better water storage mainly due to smectite clay minerals having high surface area and also more soil organic matter forming mollic epipedon (Bhattacharyya *et al*., 2006). Ca-zeolites in the basalt act as a mediator for a continuous supply of bases, especially Ca, to stabilize smectite in a humid environment (Bhattacharyya *et al*., 1993, 2006; Pal *et al*., 2006a). The presence of acidic Mollisols in the upper, middle, and foothill slopes of the Western Ghats was also reported by Shivaprasad *et al*., (1998).

About 14.64 percent area of the Sikkim State under the Himalayan Region were identified as Mollisols preferably in the moderately steep to very steeply sloping hill slopes (Das *et al*., 1996) under humid temperate climates. It seems probable that Mollisols, the most valuable soils on Earth, also occur more frequently in the eastern foothills of the Indian Himalayas.

Mollisols occupy about 7 percent of the world's soil resources and are mostly confined to the northern and southern hemispheres in mid-latitudes (Eswaran and Padmanabhan, 2012). In India, these soils occupy nearly 1.638 million ha representing 0.5% of the total geographical area. These are distributed chiefly in northern India (Jammu and Kashmir, Himachal Pradesh, and Uttar Pradesh), central India (Madhya Pradesh and Maharashtra), southern India (Andhra

Pradesh, Karnataka, Tamil Nadu, and Kerala), northeastern India (Sikkim) and Andaman & Nicobar Islands (Bhattacharyya *et al*., 2013).

Mollisols are inherently fertile soils because they are rich in humus that stores nutrients and water. They have a strong structured surface layer with high organic carbon content and a base saturation of more than 50% throughout. The dark colour of the A horizon and the upper B horizon of Mollisols results mainly from the accumulation of Ca-saturated humic acid in the humified organic matter (Fanning and Fanning, 1989). The presence of Ca^{2+} ions, either from the decomposition of plant residue or the company of Ca-bearing weatherable minerals in the parent materials, slow down the rate of decay of Ca-humate and thus render the high organic matter availability in the surface soils with high base saturation of Mollisols. These Mollisols are acidic and fairly weathered in the Satpura Range.

In Madhya Pradesh and the Western Ghats, under forest, zeolite present in the Deccan basalt plays a crucial role in replenishing the required Ca^{2+} and also restoring a sufficient amount of smectite towards the formation of Mollisols. This has led to the formation of bridge-linked compounds between inorganic clay colloids and humic acid in the presence of polyvalent cations like Ca and Mg (Varadachari *et al*., 1991; Bhattacharyya *et al*., 1994). The mollic epipedon is one of the essential requirements for Mollisols. Unlike the other soil orders, Mollisol is the only soil order in Soil Taxonomy which is based on the characteristics of the surface diagnostic horizon (Soil Survey Staff, 1999). However, soils with mollic epipedon are also found in the other soil orders, viz., Inceptisols, Vertisols, and Alfisols (Soil Survey Staff, 2014). These soils are common in the steep slopes of eastern and northeastern India, even under present cultivation. The residue from the aerial plant part is partially decomposed on the surface to enrich the upper part of the A horizon through incorporation by soil fauna. Other factors that enhance the organic matter content in soils under grass relate to processes favouring the production of humic acid. Additional factors are high exchange capacities, saturation with calcium, abundant mineral colloids, and a high content of smectitic minerals (Kononova, 1975; Bhattacharyya, 2021). Mollisols are formed where precipitation is sufficient to leach the soluble soil constituents and weathering products through the profile (Boul *et al*., 1973). Intensive cultivation, soil organic carbon (SOC) loss, soil erosion and associated yield suppression are still significant constraints that threaten the future sustainability of agriculture in different Mollisol regions (Liu *et al*., 2012). Many Mollisols, which were initially under forest and are now under cultivation, are subjected to erosion due to loosening soils on slopes. Since Mollisols are primarily based on the identification of the mollic epipedon, the eroded phase often may not permit such soils to be grouped under the Mollisol order. Instead, these soils are classified as mollic intergrades of Alfisols, Inceptisols, and Entisols (Bhattacharyya and Pal, 2015). As a result, Mollisols in the sub-Himalayan foothill areas of India at present qualify as Alfisols due to intense agricultural activities during the last few decades (Pal *et al*., 2012)

Sikkim, the smallest state in northeastern India, developed from the Daling group and granite-gneiss in Eastern Himalayas enjoys a wide range of climate, physiography, and vegetations influencing the formation of different kinds of soil under humid temperate climate (Gangopadhyay *et al.,* 1986,1992). In a temperate climate, Mollisols have been reported (Das *et al.,* 1996) in the moderately steep to very steeply sloping hill slopes of Sikkim state. About 9.56 percent of the state's total geographical area was reported to contain Mollisols, out of which 7.05 percent is under Mollisols only, and about 2.51 percent consists of Mollisols associated with acidic Entisols and Inceptisols (Das *et al*., 1996). Altitude is another important environmental factor that affects tropical, temperate, and alpine environments. Precipitation and temperature are the significant components of climate that changes with altitude. Soil organic matter increases with altitude affecting the formation of Mollisols that are dominant in Sikkim (Gangopadhyay *et al*., 2020). 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 (Gangopadhyay *et al*., 1990, 2021). Again, with the variation in altitude, vegetation also changes, which interferes significantly with pedogenesis, resulting in various types of soils displayed frequently (Gangopadhyay *et al*., 1987, 2020).

The Sikkim state extends to about 112 km from North to South and about 64 km from East to West, covering a total geographical area of 7096 km^2. Over 81% of the state's total geographical location is under forest with various natural flora and fauna. The forest vegetation in the study area consists mainly of evergreen and semi-evergreen with coniferous and deciduous forests in patches. Generally, deciduous species are primarily found in the lower hill areas, whereas coniferous species are mostly found in the middle and upper hill ranges. Cultivation is usually performed on the hill slope through terracing after clear-felling the forests. The addition of organic matter and its decomposition on the forest floor through litter fall plays a significant role, like the soil is formed. Mollisols of Sikkim are acidic, non-calcareous and highly weathered.

The dense forest vegetation of Sikkim, along with high rainfall and low temperature, helps to accumulate slowly decomposed forest biomass on the forest floor in the form of organic carbon imparting dark colour to the soil, which is a significant criterion for the development of mollic epipedon. The other essential criteria for qualifying Mollisols are the high (>50%) base saturation, a concern in Sikkim's acidic and highly weathered soils under a humid temperate climate.

In Sikkim, most soils occur on steep to very steeply sloping hill slopes resulting in the loss of surface soils through surface runoff. This is common in the soils occurring in the northeastern part of India. Although the maximum area of the state is under forest, the heavy precipitation along with steep slopes causes soil degradation through surface runoff resulting in landslides/mass movements. For the Sikkim Mollisols, continuous replenishment of soils from the upper niches enriched with the decomposed organic matter permits the persistence of these soils even in hostile natural conditions. With the increase of agriculture in these areas through deforestation, the hill slopes become more and more prone to soil degradation, raising the question of the persistence of Mollisols even in highly acidic and weathering conditions. Thus, natural resource managers must protect these valuable soils to maintain the ecosystem in this fragile Himalayan environment.

Information regarding the formation, characteristics, and persistence of Mollisols in a highly leaching and acidic environment in the humid Temperate climate under moderately steep to very steeply sloping hill slopes of Sikkim is meagre. The present attempt is to find out the causes behind the formation and persistence of Mollisols even in the humid temperate climate under severe land degradation in the state of Sikkim and to study the role of organic matter to increase the SOC stock in the forest and the hill and mountain agroecosystem and also the ecosystem services beneficial to the environment, human and animal population by restoring the soil and water for agriculture and thus should be protected against degradation.

Materials and Methods

The study was carried out in the Sikkim state under Eastern Himalayas (Fig.1). Eight soil series representing Mollisols were selected from different districts of Sikkim, India, with different elevations, slopes, and vegetation. The study was carried out along an altitudinal gradient between 750 to 2000m above mean sea level (msl) (Table 1). The soils were under natural forest cover earlier and are now partly under terraced cultivation. The parent material is gneiss mixed with mica schist. Mean annual rainfall varies from 2000 to 3000 mm; the mean annual maximum and minimum temperatures are 12°C and 6°C, respectively.

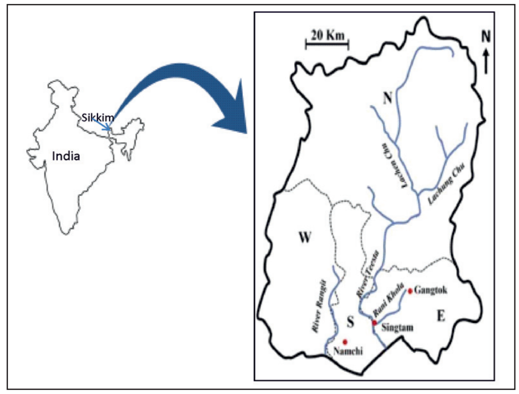

Fig. 1. Location map of Sikkim.

Table 1. Location, environmental conditions and classification of soils in the study area.

Soil Series	Location	Area (ha)	Elevation (m)	Landform	Erosion	Land use	Soil family Clasification
Maniram	South Sikkim	3449 (0.48%)	1770	Moderately steeply sloping (15-25% slope) medium hill slope	Moderate	Paddy/ maize - fallow	Loamy-skeletal, mixed, thermic family of Typic Hapludolls
Doling	South Sikkim	7765 (1.09%)	1780	steeply sloping(30-50%) hill slope	Severe	Paddy/ maize-fallow	Fine-loamy, mixed, thermic family of Typic Argiudolls
Singrep	West Sikkim	2216 (0.31%)	750	Very steeply sloping (>50%) escarpment	Severe	Maize-fallow	Loamy-skeletal, mixed, thermic family of Entic Hapludolls
Tinkitam	South Sikkim	12291 (1.73%)	1410	Very steeply sloping (>50%) hill slope	Severe	Paddy - fallow	Coarse-loamy, mixed, thermic family of Typic Haludolls
Martam	East Sikkim	3013 (0.42%)	2000	Steeply sloping (30-50%) side slopes	Moderate to severe	Paddy-fallow	Fine, mixed, thermic family of Typic Paleudolls
Nung	North Sikkim	4980 (0.70%)	1525	Steeply sloping (30-50%) side slopes	Severe	Paddy-fallow	Fine-loamy, mixed, thermicfamily of Typic Hapludolls
Tashiding	South Sikkim	4716 (0.66%)	2000	Steeply sloping (30-50%) side slopes	Severe	Paddy-fallow	Fine, mixed, thermic family of Typic Argiudolls
Yangang	South Sikkim	5997 (0.84%)	1600	Steeply sloping (30-50%) side slopes	Severe	Cardamom	Fine-loamy, mixed, thermic family of Typic Hapludolls

Morphological properties of the soil profiles in the field were accomplished (Soil Survey Staff, 1995). Representative soil samples from all the horizons were air dried and stored in the polythene container for laboratory analysis. The particle size distribution of soils was determined by following the International Pipette method. Sand (2000 - 50µm), silt (50-2 µm), and clay (<2 and 0.2µm) fractions in soil were separated following the standard procedure (Jackson, 1979). Soil organic carbon was estimated following the acid digestion procedure (Walkley and Black, 1934). The cation exchange capacity (CEC) of soils was determined by saturation of the soil with 1 (N) NaOAc (pH 8.2), and NH_4^+ replaced the absorbed Na by leaching with 1 (N) NH_4OAc (pH 7) and the extractable bases were estimated following the standard procedure (Jackson, 1973, Black, 1965). The soils developed mainly on granite gneiss under the 'udic' moisture regime and 'thermic' temperature regime as the mean annual soil temperature is more than 6°C at a depth of 50 cm or at a lithic contact, whichever is shallower.

Table 2. Climate of Sikkim (Average of data from 2009 to 2020)

Months	Mean Temperture (°C)	Rainfall (mm)
January	8.9	13.5
February	10.3	21.5
March	14.2	79.7
April	16.8	149.8
May	17.8	257.2
June	19.2	384.2
July	19.7	473.3
August	19.6	377.5
September	18.9	358.1
October	17	88.5
November	13.6	16.5
December	10.4	7.8
Average	15.5	-
Total	-	2227.6

Source: India Meteorological Department, Ministry of Earth Science, Govt. of India.

Results and Discussion

Climatic characteristics

Precipitation and temperature are the significant components of climate that changes with altitude. The climate of Sikkim ranges from tropical, temperate and alpine, with its great diversity in landform and close proximity to the Bay of Bengal makes Sikkim faces the best southern monsoon. Its geographical position makes Sikkim the most humid place in the entire Himalayas, sub-tropical in the south and tundra in the north. Most of the inhabited regions of Sikkim experience a temperate climate, with temperatures seldom exceeding 28°C (82 °F) in summer and sub-zero during winter. The average annual rainfall of Sikkim is 2227.6 mm (Table 2).

Temperature is an important parameter that regulates soil health, moisture, and microbial population, an essential element for crop production. With the variation in altitude, climatic condition changes, and as a result, quite contrasting flora grow at different altitudes, influencing soil development. It has been reported that the temperature decreases at 1°C for every 166 m altitude (Lal and Shukla, 2004). Thus, altitude is an index for various climatic functions governing the nature of the vegetation and the processes of soil formation, including soil organic matter (SOM) (Gangopadhyay *et al*., 1990).

Morphological characteristics of soil

Morphologically, Mollisols represent soft, darker-coloured soils with relatively higher moisture storage capacity. The morphological properties of the soils (Table 3) indicate that soils are generally deep to very deep, well to excessively drained with rapid permeability, and are severely eroded. The soils have been developed on steep to very steeply sloping hills within the altitude range of 750 m to 2000 m above msl. Soils are dark grey (10YR 3/2) in colour on the surface, which varies from brownish yellow (10YR 6/6) to yellowish red (5YR 6/3) in the subsurface. The reddish colour in the subsurface horizon of the soil indicates better drainage conditions. The change in soil colour on the surface and subsurface suggests soil development through eluviation. Soil texture varies from sandy loam (sl) to clay loam (cl) at the surface and from gravelly sandy loam (gsl) to clay (c) in the subsurface to the subsoil. The gravel content in the subsurface to subsoil is primarily common in these soils, and it varies from Pedon to pedon, reflecting the severity of soil erosion. The soil structure in most of the soils is weak fine granular (f1gr) to weak fine subangular blocky (f1sbk) at the surface and weak fine subangular blocky (f1sbk) to medium moderatesubangular blocky (m2sbk) at the subsurface to the subsoil. The granular structure at the soil's surface is mainly due to the high organic matter content. Soils are friable to the firm as moist consistency and non-sticky and non-plastic to very sticky and very plastic as wet consistency. Clear smooth to gradual smooth horizon boundaries were identified in the soil profiles. The soils are primarily under terraced cultivation of paddy-maize, maize, paddy-fallow, and cardamom.

Physical and chemical characteristics of soil

Soil separates vary widely among the Pedons (Table 4). Sand and silt content of soils do not follow any definite trend among the soils under study. The illuviation of clay is common in these soils showing an increasing trend with the increase in soil depth resulting in the development of cambic subsurface diagnostic horizons except in the soils of Pedons 2,6 and 7 where argillic subsurface diagnostic horizons were identified (Fig. 2).

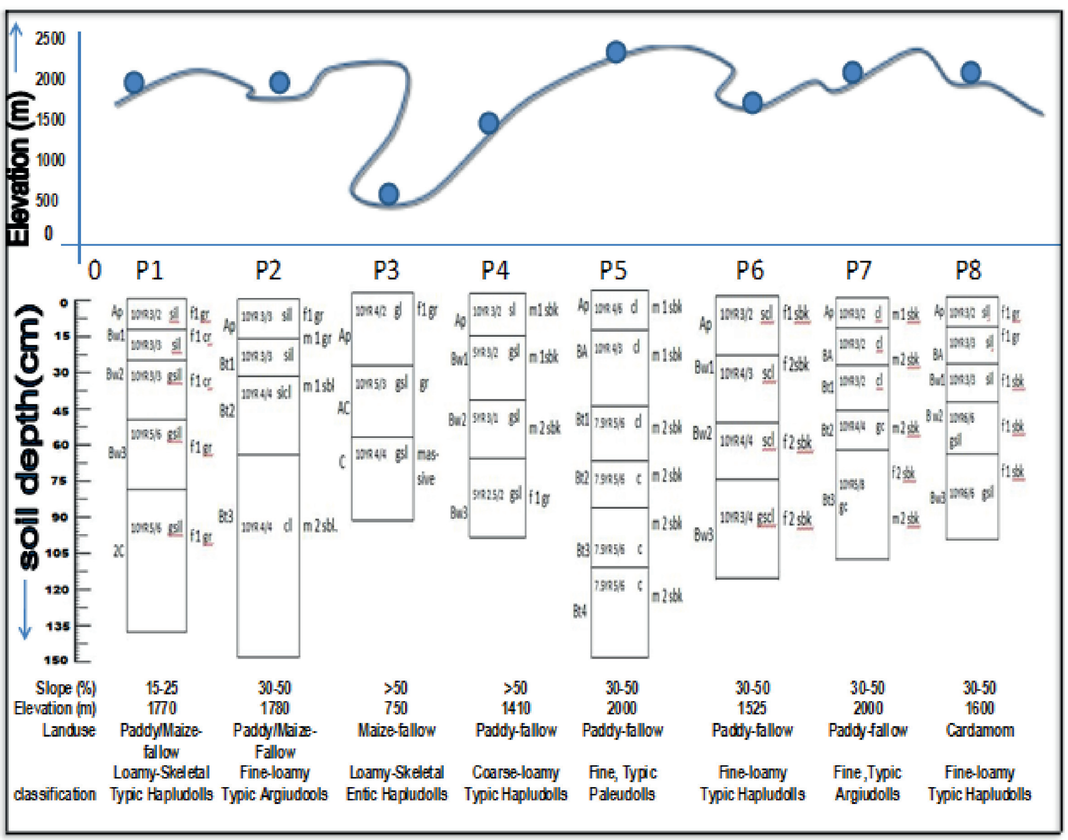

Fig. 2. Mollisols of Sikkim distributed under different elevations, slope and land use.

Table 3. Morphological properties of soils

Horizon	Depth (m)	Matrix colour (M)	Texture [a]	Structure [b]	Consistency[c] (m) (w)	Boun dary	Existing Land use
Pedon 1. Maniram Series, South Sikkim. Moderately steeply sloping (15-25% slope) medium hill slope							
Ap	0-0.12	10YR 3/2	sil	f 1 gr	sh fr ss ps	c s	Paddy-
Bw1	0.12-0.27	10YR 3/3	sil	f 1 cr	- vfr ss ps	g s	maize
Bw2	0.27-0.54	10YR 3/3	gsil	f 1 cr	- vfr ss ps	g s	
Bw3	0.54-0.83	10YR 5/6	gsil	f1 gr	- vfr ss ps	g s	
2C	0.83-1.50	10YR 5/6	gsil	f1 gr	- vfr ss ps		
Pedon 2. Doling Series, South Sikkim. steeply sloping(30-50%) hill slope							
Ap	0-0.18	10YR 3/3	sil	f 1 gr	sh vfr ss ps	g s	Paddy-
Bt1	0.18-0.32	10YR 3/3	sil	m 1 gr	- fr ss ps	g s	maize
Bt2	0.32-0.65	10YR 4/4	sicl	m 1 sbk	- fr ss ps	g s	
Bt3	0.65-1.50	10YR 4/4	cl	m2 sbk	- fr ss ps		
Pedon 3. Singrep Series, West Sikkim, Very steeply sloping (>50%) escarpment							
Ap	0-0.29	10YR 4/2	gl	f1gr	s fr ss ps	c w	Maize
AC	0.29-0.57	10Y5/3	gsl	gr	- fr ss ps	g s	
C	0.57-0.90	10YR 5/3	gsl	massive	- fr ss ps		
Pedon 4. Tinkitam Series, South Sikkim, Very steeply sloping (>50%) hill slope							
Ap	0-0.15	10YR 3/2	sl	m1sbk	sh fr ss ps	c s	Paddy-
Bw1	0.15-0.42	5YR 3/2	gsl	m1 sbk	- fr ss ps	c s	fallow
Bw2	0.42-0.69	5YR 3/1	gsl	m2 sbk	- fr s_0 p_0	c s	
Bw3	0.69-1.00	5YR 2.5/2	gsl	f1gr	- fr s_0 p_0		
Pedon 5. Martam series, East Sikkim, Steeply sloping (30-50%) hill slope							
Ap	0-0.16	10 YR 4/6	cl	m 1 sbk	sh fr ss ps	c s	Paddy-
BA	0.16-0.42	10 YR 4/3	cl	m 1 sbk	- fr ss ps	a s	fallow
Bt1	0.42-0.67	7.5 YR 5/6	cl	m 2 sbk	- f r ss ps	g s	
Bt2	0.67-0.83	7.5 YR 5/6	c	m 2 sbk	- fi s p	d s	
Bt3	0.83-1.10	7.5 YR 5/6	c	m 2 sbk	- fi s p	d s	
Bt4	1.10-1.50	7.5 YR 5/6	c	m 2 sbk	- Vfi v s vp		
Pedon 6. Nung series, North Sikkim, Steeply sloping (30-50%) hill slope							
Ap	0-0.20	10 YR 3/2	scl	f 1 sbk	sh fr ss ps	c s	Paddy-
Bw1	0.20-0.46	10 YR 4/3	scl	f 2 sbk	- fr ss ps	g s	fallow
Bw2	0.46-0.70	10 YR 4/4	scl	f 2 sbk	- fr ss ps	g s	
Bw3	0.70-1.15	10 YR 3/4	scl	f 2 sbk			
Pedon 7. Tashiding series, South Sikkim, Steeply sloping (30-50%) hill slope							
Ap	0-0.11	10 YR 3/2	cl	m 1 sbk	h fr ss ps	c s	Paddy/ maize
BA	0.11-0.30	10 YR 3/2	cl	m 2 sbk	- fr ss ps	c s	
Bt1	0.30-0.50	10 YR 3/2	cl	m 2 gr	- fr ss ps	c s	
Bt2	0.50-0.71	10 YR 4/4	gc	f 2 sbk	- fi s p	c w	
Bt3	0.71-1.10	10 YR 5/8	gc	m 2 sbk	- fi vs vp		
Pedon 8. Yangang series, South Sikkim, Steeply sloping (30-50%) hill slope							
Ap	0-0.13	10 YR 3/2	sil	f 1 gr	sh fr ss ps	g s	Carda-
BA	0.13-0.29	10 YR 3/3	sil	f 1 gr	- fr ss ps	g s	mom
Bw1	0.29-0.50	10 YR 3/3	sil	f 1 sbk	- fr ss ps	g s	plantation
Bw2	0.50-0.76	10 YR 6/6	gsil	f 1 sbk	- fr ss ps	g s	
Bw3	0.76-1.00	10 YR 6/6	gsil	f 1 sbk	- fr ss ps		

Note: [a] : l- loam, sl-sandy loam, ls-loamy sand, sicl- silty clay loam, sic- silty clay, cl- clay loam, c- clay; [b] : m1 sbk- weak medium subangular blocky, m2 sbk- moderate medium subangular blocky, f1 gr- weak fine granular : f 1 sbk - weak fine subangular blocky; f 2 sbk - medium fine subangular blocky; m 2 gr - medium moderate granular - single grain, f1cr – weak fine crumb structure ; [c] : fr- friable, fi- firm , vfi-very firm, S_0P_0- non sticky and non plastic , ss ps-slightly sticky and slightly plastic , s p- sticky and plastic ; vs vp- very sticky very plastic; [d] : cs- clear smooth, gs- gradual smooth, cw- clear weavy

All the soils are acidic, and the pH of the soil varies from 4.4 to 5.1 at the surface and 4.4 to 6.1 at the subsurface to subsoil (Table 4). The pH of the soil is low at the surface, and it increases with the increase in soil depth. The increasing soil acidity is mainly due to acidic parent materials, the preponderance of exchangeable aluminium, and high rainfall, which removes most of the bases from the surface through leaching. The surface soil acidity is lowest in Pedon 5 followed by Pedon 2 and Pedon 3.

The soil's organic carbon content is high and varies from 23.0 to 58.0 g kg^{-1} at the surface and 4.0 to 57.0 g kg^{-1} at the subsurface to the subsoil. The organic carbon content of the soil is high at the surface, and it gradually decreases with the increase in soil depth. The decrease in organic carbon content with soil depth is mainly due to the leaching of organic matter along with clay with the formation of the clay humus complex. The higher organic carbon in the surface soil is mainly attributed to constant carbon inputs and limited rate of carbon loss, but reduced decomposition of organic matter due to lower soil temperature at high altitudes. However, continuous replenishment of soils from the upper niches enriched with the decomposed organic matter also supports the presence of high organic matter in soils, even in hostile natural conditions.

The exchangeable characteristics (Table 5) indicate that soils are generally low in cation exchange capacity (CEC). It varies from 6.8 to 18.6 c mol (p^+) kg^{-1} at the surface and 4.1 to 24.0 c mol (p^+) kg^{-1} at the subsurface to the subsoil, indicating the dominance of low-activity clay minerals with low nutrient and water-holding capacity. However, the clay CEC value of the soils reflects the mixed mineralogy with kaolin and smectitic clay minerals. The amount of smectite in the soil holds enough moisture to maintain a pedo-environment for the accumulation of organic matter, resulting in mollic epipedon forming even in the humid temperate climate. The study area was previously under dense forest for quite a long time, and presently the forest has been removed for agriculture; as a result, the formation of mollic epipedon in the study area can also be explained due to earlier deposition of the huge amount of leaf/ litter on the surface which after slow decomposition gives rise to the formation of humic acid. Ca^{2+} ions released through slow decomposition of organic matter results in the formation of Ca-humate. Ca^{2+}ions usually slow down the rate of decomposition of Ca-humate, resulting in high organic matter content in the soils (Fanning and Fanning, 1989).

The soils are highly base saturated, and it is more than 50 percent in all the layers, which is the characteristic feature of Mollisols. Among the exchangeable bases, Ca^{2+} is the dominant cation, followed by Mg^{2+}, K^+, and Na^+. The Ca^{2+}/ Mg^{2+} ratio indicates considerable recycling of nutrients in the soil. Under high rainfall situations and at higher altitudes, the accumulation and decomposition of high amount of organic matter will make the soil highly acidic with low base status.

Vegetation plays a crucial role in maintaining the base saturation (Ca, Mg, K and Na) of Mollisols (Laudelot. and Robert, 1994). Probably, the dominance of Ca^{2+} released from the decomposition of a considerable number of leaves, litters remain mostly absorbed on the higher surface area of a large amount of organic matter, and they don't leach out quickly. Besides this, the continuous replenishment of soils from the upper niches enriched with the decomposed organic matter also helps to increase the Ca^{2+}. The accumulation of Ca^{2+} on the surface increases the soil's base saturation and fulfils the surface soil's criteria as mollic epipedon (Nath *et al*., 1988). Again, the high base saturation throughout the profile is also supported by the presence of Ca-bearing weatherable minerals in the soil, which plays a crucial role in the continuous supply of Ca^{2+} and thus increases the base

Table 4. Physical and chemical characteristics of soils

Hori-zon	Depth (m)	Sand (%)	Silt (%)	Clay (%)	pH H_2O	Org. C g kg^{-1}	Sand/ silt	Silt/ silt + clay
Pedon 1. Maniram Series, South Sikkim. Moderately steeply sloping (15-25% slope) medium hill slope.								
Ap1	0-0.12	24.0	61.8	14.2	5.1	31.0	0.38	0.81
Bw1	0.12-0.27	22.0	62.9	15.1	5.6	26.0	0.35	0.80
Bw2	0.27-0.54	23.6	64.4	12.0	5.9	23.0	0.36	0.84
Bw3	0.54-0.83	26.5	61.3	12.2	6.1	11.0	0.43	0.83
2C	0.73-1.50	40.4	46.6	13.0	6.0	10.0	0.86	0.78
Pedon 2. Doling Series, South Sikkim. steeply sloping (30-50%) hill slope								
Ap	0-0.18	12.0	66.4	21.6	4.4	35.0	0.18	0.75
Bt1	0.18-0.32	21.4	50.4	28.2	5.2	29.0	0.42	0.64
Bt2	0.32-0.65	17.3	49.2	33.5	5.5	25.0	0.43	0.59
Bt3	0.65-1.50	21.1	43.4	35.5	5.6	20.0	0.48	0.55
Pedon 3. Singrep Series, West Sikkim, Very steeply sloping (>50%) escarpment								
Ap	0-0.29	50.0	36.5	13.5	4.8	29.0	1.36	0.73
AC	0.29-0.57	69.2	20.3	10.5	5.2	21.0	3.40	0.62
C	0.57-0.90	71.0	17.5	11.5	5.4	4.0	4.06	0.60
Pedon 4. Tinkitam Series, South Sikkim								
Ap	0-0.15	57.4	30.1	12.5	5.1	37.0	1.90	0.70
Bw1	0.15-0.42	59.4	26.1	14.5	5.2	50.0	2.11	0.65
Bw2	0.42-0.69	56.0	31.5	12.5	5.4	24.0	1.80	0.71
Bw3	0.69-1.00	65.5	20.8	13.7	5.4	13.0	3.15	0.60
Pedon 5. Martam Series, East Sikkim								
Ap	0-0.16	38.7	24.0	37.3	5.0	23.0	1.61	0.60
BA	0.16-0.42	39.7	22.0	38.3	4.4	22.0	1.80	0.89
Bt1	0.42-0.67	27.7	25.0	47.3	4.6	18.0	1.10	0.91
Bt2	0.67-0.83	26.7	27.0	46.3	4.8	15.0	0.98	0.90
Bt3	0.83-1.10	24.7	28.0	47.3	4.8	13.0	0.88	0.90
Bt4	1.10-1.50	20.7	29.0	50.3	5.0	12.0	0.71	0.90
Pedon 6. Nung Series, North Sikkim								
Ap	0-0.20	61.9	11.6	26.5	5.0	35.0	5.33	0.84
Bw1	0.20-0.46	59.5	11.6	28.9	5.1	21.0	5.12	0.85
Bw2	0.46-0.70	57.8	11.2	31.0	5.2	14.0	5.16	0.87
Bw3	0.70-1.15	53.8	12.4	33.8	5.4	12..0	4.33	0.86
Pedon 7. Tashiding Series, South Sikkim								
Ap	0-0.11	25.0	47.0	28.0	5.0	58.0	0.51	0.62
BA	0.11-0.30	21.3	46.7	32.0	5.2	57.0	0.44	0.59
Bt1	0.30-0.50	21.0	43.5	35.5	5.3	51.0	0.48	0.55
Bt2	0.50-0.71	18.0	39.4	42.6	5.3	34.0	0.47	0.48
Bt3	0.71-1.10	18.0	38.8	43.2	5.4	20.0	0.46	0.47
Pedon 8. Yangang Series, South Sikkim								
Ap	0-0.13	23.6	57.9	18.5	4.5	29.0	0.49	0.75
BA	0.13-0.29	22.4	59.1	18.5	4.6	25.0	0.38	0.76
Bw1	0.29-0.50	26.4	52.1	21.5	5.1	15.0	0.50	0.70
Bw2	0.50-0.76	29.6	49.9	20.5	5.3	13.0	0.59	0.70
Bw3	0.76-1.00	26.4	50.1	23.5	5.4	11.0	0.52	0.68

saturation and converts the soils into Mollisol order.

The Mollisols of Sikkim are acidic and developed primarily on steep to very steeply

Table 5. Exchange characteristics of soils

Horizon	Depth (m)	CEC soil	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Clay CEC	Ca^{+2} / Mg^{+2}	B. S. (%)
		.... c mol (p+) kg -1							
Pedon 1. Maniram 2.1 Series, South Sikkim, Loamy-skeletal, mixed, thermic, Pachic Hapludolls.									
Ap1	0-0.12	13.0	5.1	2.0	0.0	0.4	91	2.5	58
Bw1	0.12-0.27	10.9	3.8	3.1	0.0	0.3	72	1.2	66
Bw2	0.27-0.54	9.5	3.1	2.9	0.0	0.3	79	1.0	66
Bw3	0.54-0.83	6.0	2.6	1.2	0.1	0.2	49	2.1	68
2C	0.73-1.50	6.4	2.6	1.2	0.1	0.3	49	2.1	66
Pedon 2. Doling Series, South Sikkim, Fine-loamy, mixed, thermic. Typic Argiudolls.									
Ap	0-0.18	14.0	7.2	3.7	0.2	0.1	64	1.9	80
Bt1	0.18-0.32	15.0	7.6	2.8	0.3	0.1	53	2.7	72
Bt2	0.32-0.65	18.5	8.0	3.1	0.2	0.1	55	2.6	62
Bt3	0.65-1.50	19.2	8.8	2.8	0.2	0.1	54	3.1	62
Pedon 3. Singrep Series, West Sikkim, Loamy-skeletal, mixed, thermic family of Entic Hapludolls									
Ap	0-0.29	7.0	3.3	1.6	0.2	0.1	51	2.0	52
AC	0.29-0.57	5.9	3.3	1.3	0.2	0.2	49	2.5	55
C	0.57-0.90	5.2	1.7	1.4	0.2	0.2	45	1.2	56
Pedon 4. Tinkitam Series, South Sikkim, Coarse-loamy, mixed, thermic, Typic Haludolls									
Ap	0-0.15	11.5	2.7	1.8	0.1	0.2	92	1.5	55
Bw1	0.15-0.42	11.0	3.8	2.2	0.1	0.2	75	1.7	57
Bw2	0.42-0.69	8.4	2.6	1.8	0.1	0.1	67	1.4	55
Bw3	0.69-1.00	7.2	2.3	1.5	0.1	0.1	52	1.5	56
Pedon 5. Martam Series, East Sikkim, Fine, mixed, thermic Typic Paleudolls									
Ap	0-0.16	14.8	5.3	2.8	0.2	0.2	39	1.8	57
BA	0.16-0.42	13.9	5.7	2.1	0.1	0.2	36	2.7	58
Bt1	0.42-0.67	17.2	7.1	2.8	0.1	0.2	36	2.5	59
Bt2	0.67-0.83	17.5	8.0	2.1	0.1	0.1	37	3.8	59
Bt3	0.83-1.10	16.8	7.9	2.0	0.1	0.1	35	3.9	60
Bt4	1.10-1.50	15.1	6.9	2.0	0.1	0.1	30	3.4	60
Pedon 6. Nung Series, North Sikkim, Fine-loamy, mixed, thermic, Typic Hapludolls									
Ap	0-0.20	17.5	5.5	3.7	0.2	0.2	66	1.5	55
Bw1	0.20-0.46	13.5	5.3	1.9	0.2	0.2	46	2.7	56
Bw2	0.46-0.70	14.2	5.2	2.7	0.1	0.2	45	1.9	58
Bw3	0.70-1.15	11.2	4.0	2.4	0.1	0.2	33	1.6	60
Pedon 7. Tashiding Series, South Sikkim, Fine, mixed, thermic family of Typic Argiudolls									
Ap	0-0.11	18.6	7.5	2.0	0.2	0.3	66	3.7	54
BA	0.11-0.30	20.8	8.2	3.3	0.2	0.3	65	2.4	57
Bt1	0.30-0.50	22.4	8.0	3.7	0.1	0.2	63	2.1	53
Bt2	0.50-0.71	24.0	8.1	3.7	0.1	0.1	56	2.2	50
Bt3	0.71-1.10	24.0	9.1	4.7	0.1	0.1	55	1.9	58
Pedon 8. Yangang Series, South Sikkim, Fine-loamy, mixed, thermic, Typic Hapludolls									
Ap	0-0.13	6.8	1.5	1.5	0.2	0.2	36	1.0	50
BA	0.13-0.29	6.5	1.5	1.5	0.2	0.2	35	1.0	51
Bw1	0.29-0.50	4.5	1.2	1.0	0.2	0.2	21	1.2	56
Bw2	0.50-0.76	4.1	1.0	1.0	0.2	0.2	20	1.0	56
Bw3	0.76-1.00	4.7	1.5	1.0	0.2	0.1	20	1.5	59

sloping hills. The high rainfall, coupled with the severe erosion hazard, is the critical factor that restricts the formation of Mollisols in this area. Under the prevailing high weathering and leaching environment, the increasing base saturation in the soil is possible either from the decomposition of leaf/litter from broad-leaved forest species or from the parent materials which provides a high amount of Ca^{2+}, and thus restrict the complete transformation of smectite to kaolin to maintain very high base saturation level of the Mollisols (Shivaprasad *et al*., 1998).

The soils developed from gneiss sedimentary deposits show an abundance of kaolin and other hydroxy-interlayered clay minerals. This indicates the presence of Ca-bearing weatherable minerals in the soil parent materials under forest vegetation which might have influenced the weathering rate, influencing the nature of the soil silicate clay minerals and thus enhancing the base saturation through a constant supply of Ca^{2+} towards the formation of Mollisols (Pal *et al*., 1989). The Clay mineralogical studies of some soils of Sikkim indicate that the soils contain kaolinite, illite (mica), and chlorite as the clay minerals (Lahiri and Chakraborty, 1992). Hence it is understood that the soils are in a very advanced stage of weathering and the presence of Ca-bearing weatherable minerals in the parent materials helps increase base saturation even in the humid temperate climate of Sikkim. The increasing base saturation of soil may also be due to the presence of *ba*sic volcanic lava in the form of basic rocks in the upper Paleozoic (Lower Gondwana) sequences in the Sikkim Himalayas (Sinha Roy. and Furnes, 1978). The alkaline basalt thus developed embedded with gravels/pebbles, sandstone, shale, etc., plays the vital role in supplying the required base saturation (>50%) of soil (Sinha Roy and Furnes, 1978) and restricts the conversion of smectite to kaolin for development of Mollisols even in the humid temperate climate of Sikkim.

Comparison of Mollisols of Sikkim with that of other parts of the country

In the Indo-Gangetic plain of north India under a subtropical climate, the formation of Mollisols on micaceous alluvium under an environment similar to the temperate climate of the USA and Europe was first reported by Deshpande *et al*., 1971, Murthy *et al*., 1982. Subsequently, Mollisols have been reported from the hilly mountains of the southern Peninsula (Shivaprasad *et al*., 1998) and northeastern India by Krishnan *et al*., 1996, Das *et al*., 1996. Mollisols reported in the subtropical parts of Indian forests (Bhattacharyya, 2014) were similar to the temperate climate in the United States and Europe. However, the Mollisols of the Western Ghats and Satpura Range developed on Deccan basalt were acidic and somewhat weathered (Bhattacharyya *et al*., 2006).

Mollisols of Sikkim developed from the Daling group and granite gneiss and mica schists within the altitude range from 750 to 2000m on moderately steeply to very steeply sloping hills under humid temperate climate with high rainfall (2000 to 5000 mm) are generally deep to very deep, acidic (pH 4.4 to 5.1) at the surface with high content of organic carbon and are highly weathered. The Mollisols typically possess some development in terms of colour and texture, forming a cambic subsurface diagnostic horizon / argillic subsurface diagnostic horizon and are non-calcareous. Being acidic in nature, the soils are low in cation exchange capacity (CEC) but interestingly high (at least >50%) in base saturation. This fact indicates the presence of some other sources to supply the excess bases under such acidic and leaching environments and to qualify for Mollisols. These soils contain illite (mica), chlorite, and kaolinite as clay minerals (Lahiri and Chakravarty, 1992). The continuous supply of bases especially Ca, is possible due to the presence of Ca-bearing weatherable minerals in the parent materials under forest vegetation which might have inuenced the nature of the soil silicate clay minerals and enhanced the base saturation through a constant supply of Ca^{2+} towards the formation of Mollisols and also from the slow decomposition of the leaf litter derived from the coniferous/broad-leaved forest species above the mineral surface. However, the increasing base saturation of the Mollisols under the highly weathering and highly acidic environment of Sikkim under a humid temperate climate may also be supplemented not only due to continuous replenishment of soils from the upper niches enriched with the decomposed organic matter even in hostile natural conditions but also due to the presence of basic basaltic rocks in the form of embedded with gravels/ pebbles, sandstone, shale, etc., which on weathering releases and supplies continuously the bases even in an adverse humid temperate climate to overcome the loss of bases during leaching and restricts the transformation of smectitic clay to kaolin and thus resulting the development of Mollisols (Sinha Roy and Furnes, 1978).

The brown forest soils (Mollisols) in subtropical parts of Indian forests (Bhattacharyya, 2014) resemble more or less the soils of temperate climates in the United States and Europe. Soils of Satpura ranges, central India and the Western Ghats of India are deep to very deep, slightly acidic, non-calcareous, mainly developed on the side slopes of hills and plateaus under dense forest from Deccan basalt parent materials in the humid tropical climate. This information is more or less similar in the soils of Sikkim under temperate climates except for the soil acidity and parent materials. The soils of Sikkim are highly acidic and developed from acidic parent materials i.e., granite-gneiss and mica-schist. The variations in the characteristics of Mollisols from central India and Sikkim are presented in Table 7.

The primary concern for developing Mollisols in humid tropical and temperate climates is the higher base saturation (>50%). In the soils of the Satpura ranges and the Western Ghats, the zeolites of amygdaloidal basalt play a pivotal role in supplying bases and moisture for the stabilization of smectites under humid tropical climates (Bhattacharyya *et al*., 2006). But in the case of Sikkim Mollisols, the highly weathering and highly acidic environment under a humid temperate climate may also be supplemented due to the presence of basic volcanic lava in the form of basaltic rocks embedded with gravels/ pebbles, sandstone, shale, etc., which on weathering releases and supplies continuously the bases even in an adverse humid temperate climate to overcome the loss of bases during leaching and severe erosion by restricting the transformation of smectitic clay to kaolin (Sinha Roy and Furnes, 1978). Thus, the Mollisols from different parts of India varies mostly depending on the geological set up even in the humid tropical and humid temperate climate. Thus, it may be assumed that the formation of Mollisols in Indian soils mostly depends on the geological setup of the respective study areas irrespective of their climatic conditions, in other words, the geological history of the place can explain the reasons for increasing base saturation determines, a critical factor for the formation of Mollisols.

Soil organic carbon stock

The soil organic matter (SOM) is a complex mixture of carbon compounds associated with decomposing plant and animal tissues and microbes with soil materials. Forests serve as a

Table 6. The variations in the characteristics of Mollisols from central India and Sikkim

Soil Characteristics	Mollisls of M.P. & Maharashtra	Mollisols of Sikkim
pH	5.7-5.9	4.4-5.1
O.C. (g kg^{-1})	20-35	23-58
Clay (%)	30-51	12.5-37.3
CEC [c mol (p^+) kg^{-1}]	18.6-52.2	6.8-18.6
Clay CEC	36-174	36-91

source of carbon sequestration and carbon sink and play an essential role in reducing greenhouse gases and global warming. The forest ecosystem provides a significant carbon pool to the global carbon budget and also contributes to the mitigation of global climate change. Worldwide the first 30 cm of soil holds 1500 Pg carbon (Batjes, 1996) while that in Indian soils is about 11.4 Pg (Bhattacharyya *et al*., 2017). About 40% of the global soil's total organic carbon (SOC) stock resides in the forest ecosystem (Eswaran *et a*l., 1999). The Indian Himalayas, characterized by the tremendous variation in altitude, slope, aspect and vegetation, results in a change in micro-climate influencing the SOC stock markedly. Thus, forests are one of the most significant storehouses of carbon and play a crucial role in reducing atmospheric CO_2 levels through the process of photosynthesis and also by increasing the soil organic carbon content by maintaining carbon balance in the globe. The Himalayas, with dense forest vegetation, covers nearly 19% of India and contains 33% of the SOC reserve of the country (Bhattacharyya *et al*., 2008). The presence of smectites with more surface area is responsible for better water storage capacity resulting in more organic matter retention in the soil towards the formation of Mollisols.

Forest ecosystem contributes carbon pool to global carbon budget and serves in mitigation of global climate change for sustainable agriculture (Lal, 2004, Smith, 2004). Soils in cooler and moist climates usually contain more organic carbon due to slower mineralization rates (Bhattacharyya *et al*., 2008; Banerjee, 2014). Vegetation also has a marked influence on SOC concentration and is the primary carbon source from biomass decomposition. Thus, the sequestration potential of soil depends on the existing vegetation (IPCC, 2000, Houghton, 2003, Grace, 2004).

Due to dense forests with new and phyto-geographically interesting taxa, Sikkim is a botanical paradise. Generally, deciduous species are primarily found in the lower hill areas, whereas coniferous species are mostly found in the middle and upper hill ranges. Coniferous species occupy the maximum areas in the middle hill (900 to 1800m). Other species found are broad-leaf species, namely *Bucklandia populnea, Schima wallichii, Michelia champaca,* and *Jambosa formosa,*with undergrowth of cardamom. Soil organic carbon (SOC) is high at higher altitudes, and within the profile, it is more on the surface and decreases with the increase in soil depth. With the rise in altitude, there is an increase in soil organic carbon pool, which virtually reduces the bulk density of soil (Gangopadhyay *et al*., 2020). The increasing tendency of carbon density with the increase in altitude indicates its better stabilization at cooler temperatures and higher precipitation with lesser microbial activity. The forest soils of Sikkim supporting different types of vegetation at different altitudes differ in SOC stock at all the depths (0-15, 15-30 and 30-60 cm). The carbon stock up to 60 cm soil depth under the forest cover of South and West Sikkim combined was 213.39 million tons (Gangopadhyay *et al*., 2020). Comparing the forest soil carbon of Sikkim Himalayas with other Himalayan regions revealed that the SOC of the forest soils of Sikkim Himalayas is higher at high altitudes. Within the profile, it is more on the surface and decreases with the increase in soil depth. The distribution of soil organic carbon stock in the Mollisols of Sikkim is given in Fig. 3.

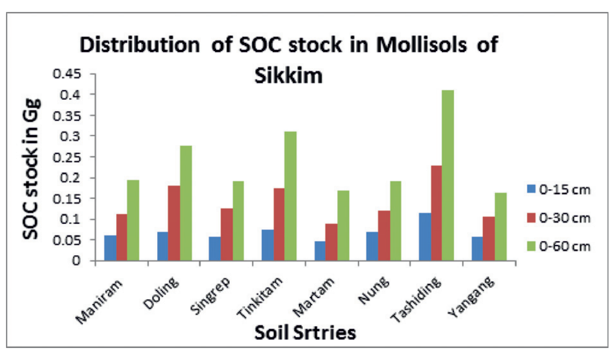

Fig. 3. SOC stock in Mollisols of Sikkim

The data indicate that soils of the Tashiding series show the highest SOC stock at 0-15 cm depth (0.115 Gg), showing their capabilities for restoring more soil organic carbon and the Martam series the least at 0-15 cm depth (0.046 Gg) reflecting their inability to restore soil organic carbon. At 0-30 cm depth, the Tashiding series shows the highest value of SOC stock (0.229 Gg), while the Martam series shows the least (0.09 Gg). At 0-60 cm depth, the Tashiding series shows the highest value of SOC stock (0.411 Gg) while the Yangang series has the lowest value of SOC stock (0.163 Gg). Thus, there is a wide variation in SOC stock among the Mollisols of Sikkim at various soil depths mainly due to the variation in elevation, slope, aspect and vegetation.

Soil Classification

Soils are classified into soil series based on their physical and chemical characteristics by following the normal set by the Soil Survey Staff (2014). The soils are classified in the order Mollisols due to the presence of Mollic epipedon (dark-coloured surface horizon with greater than 50 percent base saturation as determined by the ammonium acetate method) or have a surface horizon that, after mixing to a depth of 18 cm meets all requirements for a mollic epipedon except thickness and also has an upper sub horizon that is greater than 7.5 cm thick in an argillic or natric horizon that meets the colour, organic carbon, base saturation and structure requirements of a mollic epipedon but is separated from the surface horizon by an albic horizon. Soils of Pedons 1,4,6 and 9 were classified as Hapludolls in the great group level due to the udic moisture regime and its initiation for forming Mollisols. The Typical concept of the great group classifies the soil as Typic Hapludolls at the subgroup level. The loamy-skeletal textural class of the control section, along with the thermic temperature regime and mixed mineralogy classes, qualifies the soils of Pedon 1 as loamy-skeletal, mixed, thermic, Typic Hapludolls at the family level. Similarly, the soils of Pedon 2 are similar to Pedon 1 except for the control section textural class, which is coarse-loamy and hence qualifies for coarse-loamy, mixed, thermic, Typic Hapludolls.

The soils of Pedons 6 and 8 are classified as fine-loamy, mixed, thermic, Typic Hapludolls due to the fine-loamy control section textural class. The soils of Pedon 3 do not have a cambic horizon. They do not, in any part of the mollic epipedon below 25 cm from the mineral soil surface, meet the requirements for a cambic horizon, except for the colour requirements and hence classified as loamy-skeletal, mixed, thermic, Entic Hapludolls. Soils of Pedons 2 and 7 have been classified as fine-loamy, mixed, thermic, Typic Argiudolls due to the presence of argillic subsurface diagnostic horizon. The soils of Pedon 5 is classified as fine, mixed, thermic, Typic Paleudolls because within 150 cm of the mineral soil surface, a clay decrease, with increasing depth, of less than 20 percent (relative) from the maximum non-carbonate clay content and in 50 percent or more of the matrix of one or more sub horizons in its lower half, the hue of 7.5YR or redder and chroma of 5 or more.

Ecosystem function

Ecosystem function is the capacity of natural processes and components to provide goods and services that satisfy human needs either directly or indirectly (de Groot *et al.*, 2002). The ecosystem's services are the goods and services that biodiversity provides. These include soil formation, the provision of food and shelter, air quality and climate regulation, water supply and quality and the cultural and aesthetic value of particular plants and species. Biodiversities, such as nutrient cycling, carbon sequestration, pest regulation and pollination, sustainable agricultural production and cultural such as spiritual and recreational benefits, provide many essential ecosystem services.

The Mollisols of Sikkim developed mainly on the slopes of hills and mountains under dense forest cover. With more agriculture in these areas, natural resource managers need to protect these valuable soils to maintain the ecosystem in this fragile Himalayan environment. As the Mollisols are rich in organic carbon and exchangeable bases, they can provide Ecosystem services better by giving a higher crop yield without adding commercial fertilizers. Hence it can perform ecosystem services by providing a better soil physical environment, soil fertility, nutrient and water holding capacity and protect the environment from global warming through carbon sequestration.

Soil in Ecosystem

Soil is composed of five essential components such as mineral matter, organic matter, air, water and microorganisms, all of which are important and, when present in proper amounts, is the backbone of all terrestrial plant ecosystems. Regarding Earth's carbon cycle, soil is an important carbon reservoir and is the most reactive to human disturbance (Pouyata *et al*., 2002) and climate change (Davidson and Janssens, 2006). Soils are complex, dynamic bodies that form from interactions among the Earth's various spheres (atmosphere, biosphere, lithosphere, hydrosphere) within the ecosphere, which is modified by the anthroposphere (the realm of human influence) (Mikhailova *et al*., 2021). The concept and measures of soil diversity/ pedodiversity (variability of soils) are complex as because pedodiversity (biotic + abiotic) results from atmospheric diversity (abiotic + biotic), biodiversity (biotic), hydrodiversity (abiotic + biotic), and lithodiversity (abiotic) within the ecosphere, which is modified by the anthroposphere. Pedodiversity is influenced by intrinsic (within pedodiversity itself) and extrinsic factors (environmental factors from the atmosphere, biosphere, lithosphere, hydrosphere, ecosphere, and anthroposphere that control and influence pedogenesis).

Soil is by far the most biologically diverse part of Earth. A wide variety of organisms provides checks and balances to the soil food web through population control, mobility and survival from season to season. The soil food web includes beetles, springtails, mites, worms, spiders, ants, nematodes, fungi, bacteria and other organisms. These organisms improve the entry and storage of water, resistance to erosion, plant nutrition and the break down of organic matter. The diversity of organisms living within the soils is critical to all earth ecosystems because soil organisms are essential for the cycling of nutrients and increase the porosity of soil by adding organic matter, which allows and improves the entry of water in the soil and its storage in the soil and also provide resistance to erosion.

Again, the soil is closely related to human health, directly or indirectly. As plants grow or animals are rare, the nutrients taken up by them from soil enter their food chain, and plants are also a part of human food articles. Soil supplies essential elements to humans and can cause harm in different ways through malnutrition, disease and toxic elements. Depending on the type of soils, the presence of toxic elements varies, which may cause health hazards (Bhattacharyya, 2021).

Advances in the watershed, natural resources and environmental sciences have shown that soil is the foundation of primary ecosystem function. Soil filters our water, provide essential nutrients to our forests and crops and helps regulate the Earth's temperature and many important greenhouse gases.

Soils are the environment in which seeds grow. They provide heat, nutrients and water to nurture plants to maturity (Haygarth and Ritz., 2009). In fine, the main ecological functions of soil include nutrient cycling, C storage and turnover, water maintenance, the soil structure arrangement, regulation of above-ground diversity, biotic regulation, buffering and the transformation of potentially harmful elements and compounds.

Mollisols, rich in organic carbon, are an indicator for healthy soils and the environment by improving soil structure and porosity, enhancing water and nutrient holding capacity, carbon sequestration and SOC stock. As these soils contain a high amount of organic matter, they also act as a storehouse of organisms which help decompose the organic matter and are capable of sequestering CO_2 from the environment, considering themselves as the carbon sink and are treated as the most valuable soils of the world. Increasing fertility enhances crop production, mainly consumed by the human and animal populations by which the nutrients enter the food chain of living beings, including the human population. Thus, the ecosystem benefits the environment and human and animal populations by restoring the soil and water for agriculture and, therefore should be protected against degradation.

The role of a high amount of organic matter in Mollisols of these soils towards ecosystem services is listed below:

i) Anthropogenic soil degradation affects 20% of vegetated land;

ii) Shelters seeds and provide plants with physical support;

iii) Retains and delivers nutrients to plants;

iv) Plays a crucial role in the decomposition of organic matter with the support of microorganisms;

v) Recycles nutrients and

vi) Regulates carbon, nitrogen and sulphur cycles

The soil ecosystem services will require conserving soil for sustainable production of raw materials that human lives depend on; adopting conservation-based cropping methods to reduce erosion; precision nutrient application in cropping systems to reduce nutrient loss from agricultural systems; land-use changes that promote nutrient conservation and removal in the terrestrial system to reduce export to aquatic ecosystems; and conversion of marginal agricultural lands to more natural systems that conserve soil, water, nutrients and biodiversity. The abundance, diversity, activity and composition of soil biota regulate many ecosystem functions that underpin ecosystem services provided by soil (Wagg *et al*., 2014). Knowledge of the diversity and redundancy within the soil biota is needed to predict their role in promoting the resilience of ecosystem services provided by soil in the face of many global environmental changes. To meet the global food requirement by 2050, there must be at least a 70% increase in agricultural production (FAO, 2009), which can only be achieved by agricultural intensication of existing cropland and marginal lands.

Soil Information System

This soil information system involves collecting and storing huge soil and land databases to implement and monitor various projects on land resource management. It is the need of the hour to protect and conserve precious natural resources like soil and water for better information on spatial variation and trends in the conditions of soils and landscapes. Such information would undoubtedly improve our understanding of biophysical processes regarding cause–effect relationships in the pedo-environment (Bhattacharyya, 2021a, 2021b).

Mollisols in the temperate climate in Sikkim is a unique type of soil developed mainly on the steep to very steep hill slope on granite gneiss parent materials, presently under agriculture (previously under forest) plays a very crucial role for agricultural developments. As this soil is most valuable and occurs in patches, it is the need of the hour to store all the databases, including climate, soil, crop and management strategies relating to the formation and persistence of Mollisols which the natural resource manager can use in some other areas of the state having the similar environmental condition. The forest ecosystem contributes to the global carbon budget's carbon pool and serves to mitigate global climate change for sustainable agriculture. Comparing the forest soil carbon of Sikkim Himalayas with other Himalayan regions revealed that SOC of the forest soils of the Sikkim Himalayas are higher at high altitude; and within the profile, it is more on the surface and decreases with the increase in soil depth. The increasing tendency of carbon density with the increase in altitude indicates its better stabilization at a cooler temperature and higher precipitation with lesser microbial activity.

Discussion

Mollisols developed on the steep to very steeply sloping hill slopes of Sikkim are very strongly acidic, rich in organic matter and, at the same time, highly weathered. Generally, Mollisols developed in the world under temperate climates were reported to be slightly acidic to alkaline and mostly with $CaCO_3$. In that respect, Mollisols of Sikkim are a new addition. These Mollisols explain its formation and persistence through the continuous replenishment of bases in soils from the upper niches (enriched with the decomposed organic matter and the addition of the decomposed leaves/litters from the forest vegetation) releasing the exchangeable bases, significantly Ca^{2+} ions.

The subdominant amount of smectite in these soils holds enough moisture to maintain a pedo-environment for the accumulation of organic matter resulting in the formation of mollic epipedon even in the humid temperate climate. Again, the steep hill slopes, along with high rainfall and agricultural practices, cause severe soil degradation losing most of the fertile top soils and exposing part of upper B horizons. Besides the accumulation of leaves/litter and their decomposition on the soil surface, the huge amount of organic matter carried by the runoff water from the upper hills is also deposited in the middle and lower hill areas, enhancing the soil organic matter content. Over time, these sites gradually become rich in organic matter.

In this physiographic situation, the high amount of bases in the soil is a concern. As per the geochemistry of the soils of Sikkim Himalayas, the presence of basic volcanic lava in the form of basic rocks in the upper Paleozoic (Lower Gondwana) sequences in Sikkim Himalayas plays an essential role in continuously supplying the required base saturation (>50%) of soil to qualify for Mollisols even in the humid temperate climate of Sikkim.

The Mollisols of Sikkim are a significant source of soil organic carbon, which helps to increase the SOC stock in soil and, 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 and also provide better ecosystem services by providing healthy soils with low bulk density, high infiltration capability with higher SOC stock. With more agriculture in these areas, natural resources become vulnerable.

To protect these valuable soils to maintain the ecosystem in this fragile Himalayan environment, much more attention should be given to preserving organic matter against erosion, which may be supplemented by organic farming for crop production. The high SOC content of Mollisols is a boon for agriculture in Sikkim because of two reasons (1) the Mollisols in Sikkim are rich in in-built organic matter, and (2) if the organic matter is added in the soil in the form of farm yard manure (FYM), the loss of organic matter will be less due to cooler temperature which will be more beneficial in growing crops justifying the declaration of the state as organic state.

- For preserving this valuable natural resource, erodibility indices help plan appropriate treatment measures in areas where the generation of soil erosion is a constraint.

- As the terrain is very steep (average >30% slope), conservation structures such as check dams may be planned on 2nd and 3rd-order streams located in downstream areas.
- Vegetative measures may also be encouraged and can enhance infiltration, thereby reducing the erosive surface runoff and increasing interception losses.

Soils provide essential ecosystem services at local and global levels and are the mainstay for crop production. Reducing atmospheric CO_2 by sequestration has been reported to have a great potential for shifting greenhouse gas (GHG) emissions to mitigate climate change. As an ideal reservoir, soil can store organic carbon to a great extent (Wang *et al*., 2010). Soil carbon (SOC plus SIC) is a significant determinant of agroecosystem functions; it dramatically influences soil fertility, water-holding capacity, and other soil quality parameters that influence overall productivity and sustainability (Bhattacharyya, 2014). Soil C sequestration can improve soil quality and reduce the contribution of agriculture to CO_2 emissions.

Conclusion

The soils of temperate India in the Himalayas require greater attention. At places these hills/ mountains develops brown forest soils (Mollisols) as shown in this paper. These soils need careful attention since they store high quantity of organic matter in this forest vegetation (Gangopadhyay *et al*., 2021). The preservation of the existing vegetation in this part of the Himalayas shall protect these precious soils and shall continue to provide ecosystem services (Bhattacharyya, 2021b) to us in plenty.

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Conflict of interest

I, S.K. Gangopadhyay on my behalf and on behalf of my co-author, Dr. T. Bhattacharyya, hereby declare that none of the authors have any Conflict of Interest for the publication of the Research Paper entitled, “Mollisols of Sikkim : The Unique Soils of the Humid Temperate Zone of India” authored by S.K. Gangopadhyay, Dr. T. Bhattacharyya in Clay Research.

Authors Contribution

The Research Paper cited above has been prepared by myself, Dr. S.K. Gangopadhyay, Former Principal Scientist and Head, ICAR-NBSS & LUP, Regional Centre, Kolkata, West Bengal along with Dr. T. Bhattacharyya’, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli 415 712, Maharashtra, India, helped to interpret the X-ray Duffractograms of the clay samples, and also edited the manuscript’ after clay samples.

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