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Brown Forest and Organic Soils: Rich Carbon Reserves to Provide Soil Ecosystem Services

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Abstract

Soils' ecosystem services, with special reference to soil carbon reserves, are immense in food production and maintaining ecosystems and biodiversity for prosterity. Among most of the soils, brown forest soils mostly formed in the forest under cooler climates or supported by soil conditioners in the humid tropics, store relatively high levels of organic carbon. Besides. organic soils mainly found under peats and marshy areas also reserve sizeable amounts of organic carbon. The role of these two types of soils in ecosystem services is discussed in this paper.

Key words: Ecosystem services, brown forest soils, organic soils, soil carbon

Introduction

Soil ecosystem services include carbon sequestration in soils as one of the important engines for boosting soil quality and health. Soil carbon sequestration is important for registering soil carbon footprint as a negative C emission strategy. Among many other soils, brown forests (Mollisols) and organic soils (Histosols) show more soil organic carbon (SOC) sequestration, thus offering greater scope to mitigate global warming and climate change. A few examples of these two types of soils and their contribution to reserving SOC in India are prescribed. This effort might create awareness among natural resource managers about preserving these valuable natural resources.

Land provides the principal basis for human livelihoods and well-being including the supply of food, fresh water and multiple other ecosystem services, as well as biodiversity (IPCC, 2019). People currently use one-quarter to one-third of land's potential net primary production for food, feed, fibre, timber and energy. Land provides the basis for many other ecosystem functions and services, including cultural and regulating services, that are essential for humanity (Bhattacharyya, 2022). To adapt and mitigate the climate change effects, a few response options have immediate impacts, while others take decades to deliver measurable results. Examples of response options with immediate impacts include the conservation of high-carbon ecosystems such as peatlands, wetlands, range lands, mangroves and forests (IPCC, 2019). Interestingly, peatlands and wetlands in many cases represent organic soils (Histosols), while the forests represent Mollisols (brown forest soils). Some response options of soil carbon management are potentially applicable across a broad range of land use types, whereas the efficacy of land management practices relating to organic soils, peatlands and wetlands depend on specific agroecological conditions (Paul et al., 2022).

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Brown-forest Soils and Soil Ecosystem Services

Brown forest soils (Mollisols) have vast reserves of organic carbon and hence demand special attention from natural resource managers (Soil Survey Staff, 2014). These soils are generally characterized by the thick, dark, humus-rich surface horizon (mollic epipedon) developed by the process of darkening of the soil by organic matter additions (melanization). The addition, decomposition, and accumulation of a relatively large amount of organic matter in the soil pedon, with the presence of calcium, forms the central concept of brown forest soils. The high base saturation (>50%) is another important criterion for brown forest soils. Due to their typical characteristics, these soils are considered abundant and precious organic carbon resources and require special global attention for conservation to mitigate global warming and climate change (Gangopadhyay and Bhattacharyya, 2022). Brown forest soils occupy about 916 million ha, representing 7% of the world's ice-free land surface. They are most prevalent in the mid-latitudes of North America, Eurasia, and South America. Mollisols in tropical climates are not uncommon (Bhattacharyya et al., 2006).

Brown forest soils, rich in organic carbon, indicate healthy soils, since they provide a microbe-healthy soil environment with improved soil structure and porosity, enhancing water and nutrient holding capacity, more 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 & animal populations by restoring the soil and water for agriculture, which should be protected against degradation.

The role of high amount of organic matter in Mollisols of these soils towards ecosystem services includes 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 i) adopting conservation-based cropping methods to reduce erosion; ii) precise nutrient application in cropping systems to reduce nutrient loss from agricultural systems; iii) land-use changes that promote nutrient conservation and removal in the terrestrial system to reduce export to aquatic ecosystems; and iv) 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. The representative brown forest soils (Mollisols) are shown in **Figures 1** and **2**. The distribution of Indian brown forest soils and organic soils is shown in **Tables 1**. A few selected parameters of brown forest

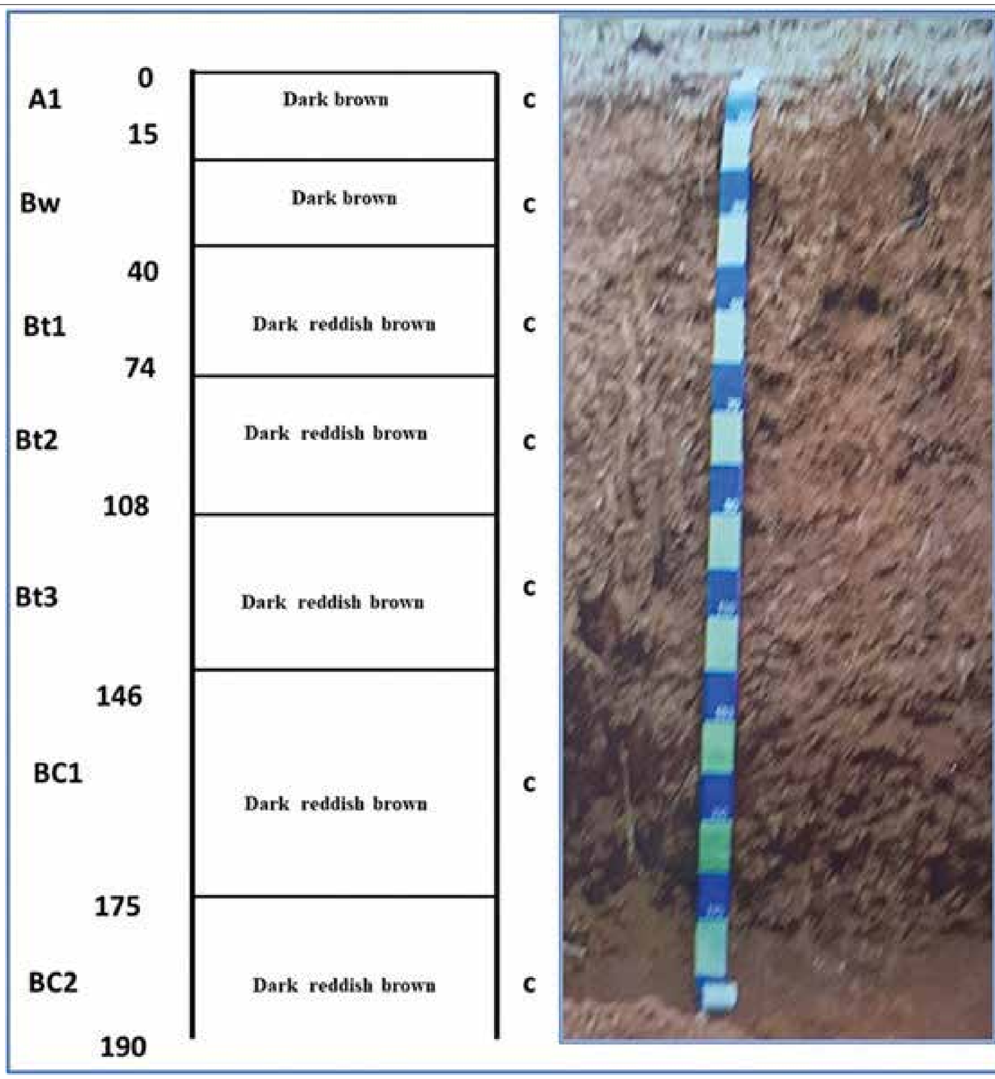

Figure 1. Brown forest soils (Mollisols), Maharashtra, India showing the profile - Vertic Argiudolls (Source: Bhattacharyya et al., 2006).
Note: The schematic diagramme shows the soil depth in cm, horizon designations as A (surface), B and BC (subsurface and near parent materials); c in right side means texture as clay

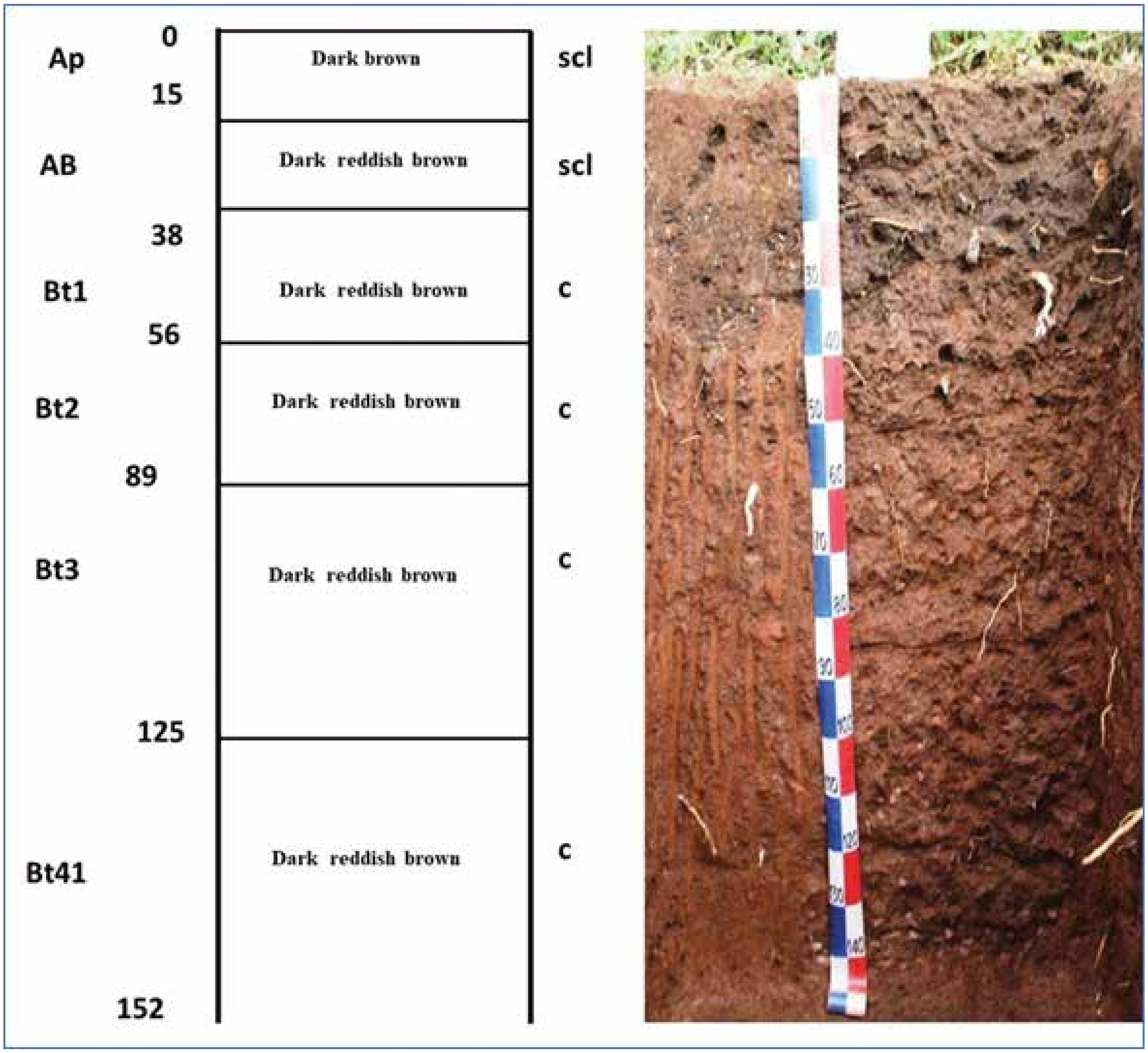

Figure 2. Brown forest soils (Mollisols) in Kerala foothill - Pachic Paleustolls (Source: Anil Kumar et al., 2016).
Note: The schematic diagramme shows the soil depth in cm, horizon designations as A and AB (surface and intersection of subsurface), Bt as textural subsurface with sizeable amount of clay enrichment; scl and c in right side means texture as sandy clay loam and clay, respectively

soils in World and India are given in **Table 2**.

The total SOC stock of Indian brown forest soils is estimated to be 0.82 petagram-Pg (1 Pg = 10^{15} g) (0-150 cm soil depth), corresponding to 0.33 Pg per million (M) ha (0-30 cm soil depth). This value is high as compared to the threshold limit of 0.05 Pg Mha^{-1} for identifying areas of soils as a green belt (Bhattacharya et al., 2008). This shows that brown forest soils have a considerable reserve of SOC compared to other soils, which demand their preservation.

Organic Soils

Organic soils (Histosols), in general, occur in the peat and marshy lands. Peat consists of spongy materials derived from partially or fully decomposed organic matter, primarily plant material in wet lands such as swamps, muskegs, bogs, fens and moors. The colour of peat varies from dark brown to black depending upon its degree of decomposition (Huat et al., 2014). Peat lands cover around 423 Mha of the Earth, representing 2.8% of the total land surface area (Xu et al., 2018). Further, it has its expanse in Asia (38% of peat lands) and in North America (32%), followed by Europe (12%) and South America (11%). Peat is a versatile geo-material that has extended its domain to many aspects such as engineering, horticulture, environment and energy, etc. (Paul et al., 2022). The quantitative assessment of peat deposits in India as per the Indian Council of Agricultural Research (ICAR) is approximately 88,756 km^2 (2.17%), which extended from coastal areas surrounding the Bay of Bengal and the Arabian Sea to the foot hills of Himalaya (Rieley, 2007). The researchers also

Table 1. Distribution of brown forest (Mollisols) and organic soils (Histosols) in India

States	Area		References
	ha	%*	
Brown forest soils (Mollisols)			
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	1638000	0.5	Bhattacharyya et al., 2013
Organic soils (Histosols)			
Tripura	2400	0.00073	Bhattacharyya et al. 1996
Kerala	200000	0.06	Nair et al,. 2011
A&N Islands	—	—	
West Bengal	—	—	
Goa	—	—	
Manipur	13460**	—	Khoiyangbam, 2021
Assam	—	—	

*Of geographical area of India; —: not available;
** Area under wetland in Loktak Lake representing organic soils (Histosols)

highlighted the occurrence of the peat land domain in the country, both zonal and state-wise. Yet, the quantitative incidence of this peat land domain, specifically as per their respective location, has not been done. The peat deposit studied in the South-Western part of India indicated its significant prominence. Thomas et al. (1974) mentioned 47 locations of peat deposits in the Nilgiri region of Tamil Nadu state. Mascarenhas (1997) noted the widespread occurrence of peat on the Western Continental Shelf of India. Narayana et al. (2002) and Kumaran et al. (2016) reported the presence of peat deposits around Vembanad Lake and flood plains of the Greater Pamba Basin of Kerala. Singh (2016) indicated the peat swamps at the Barmer basin in Rajasthan. The total wet land area is estimated to be 15.26 Mha, around 4.63% of the country's total geographical area (Anonymous, 2020). Organic soils, occurring mostly in the wetlands, have diagnostic horizons with more than 20% organic matter and essentially reside in marshes, bogs and swamps, where anaerobic soil conditions support a low rate of organic matter decomposition relative to the rate of organic matter production. Thus, organic soils are observed to have a carbon input rate that is initially greater than the carbon loss rate, resulting in an annual carbon accumulation. Then, over time, the rate of carbon input approximately equals the carbon loss rate and an organic carbon quasi-equilibrium is attained.

These soils are thicker than 18 inches, with significantly less mineral matter occurring mainly in the wetlands. Organic soils are ecologically important since they contain high organic carbon. These soils are valuable for various uses, including agriculture and as a source of fuel (Soil Survey Staff, 2014). These organic soils (Histosols) are comprised of soils formed in organic materials. These soils contain >20% organic matter (by weight) and globally occupy about 325-375 Mha. Structurally, these are loose soils and lighter weight (bulk density of organic materials varies from 0.05 to 0.15 Mg m^{-3} (Anonymous, 2023). A few selected parameters of organic soils in World and India are given in **Table 3**.

The key characteristics of these soils include i) organic peat lands or boggy soils, ii) layered organic materials

Table 2. A few selected parameters of brown forest (Mollisols)

Parameters	Mollisols	References
World		
SOC	1.1%	Khakipour et al., 2012
	2.7%	Liu et al., 2012
SOC stock (Pg)	301	Anonymous, 2023
Area (Mha)	668.70	Liu et al., 2012; Khakipour et al., 2012; Aydinalp, 2003
	548	Eswaran et al., 1993
India		
SOC	2.0-3.5%	Bhattacharyya et al., 2006
SOC stock (Pg)	0.82 (0-150 cm)	Bhattacharyya et al., 2000, 2017
Area (Mha)	1.64	Bhattacharyya et al., 2013

Table 3. A few selected parameters of organic soils (Histosols)

Parameters	Histosols	References
World		
SOC	77 kg cm^{-2} (0-100 cm)	
SOC stock (Pg)	330 (0-100 cm)	Batjes, 1996
Area (million ha)	174.5	Eswaran, 1993
	325-375	Anonymous, 2023
India		
SOC	28.9% (0-150 cm)	Nair et al., 2011; Anil Kumar et al., 2016 *
SOC stock (Pg)	6.91 (0-150 cm)	Nair et al., 2011; Anil Kumar et al., 2016 *
Area (Mha)	0.0024 (only Tripura state)	Bhattacharyya et al., 1996

*Represents organic soils (Terric Sulfihemists) in Kerala

Table 4. Selected physical and chemical properties of certain brown forest and organic soil in India (Source: Bhattacharyya et al., 2006; Anil Kumar et al., 2016; Nideesh et al., 2021; Kalaiselvi et al, 2023; Karthika et al., 2024)

Depth (cm)	Bulk Density (Mg kg^{-3}) (dry)	pH (water)	Soil organic carbon (%)	Cation exchange capacity (cmol (+) kg^{-1})
Brown forest soils (Maharashtra: Mollisols: Vertic Argiudolls)				
0-15	1.20	5.7	2.0	18.6
15-40	1.34	5.7	1.2	18.5
40-74	1.42	5.7	0.7	18.7
74-108	1.47	6.1	0.4	18.6
108-146	1.49	6.1	0.3	18.7
146-175	1.54	6.1	0.1	20.0
175-190	1.54	6.1	0.1	19.5
Brown foot hill soils (Kerala: Mollisols: Pachic Paleustolls)				
0-15	1.23	5.89	1.61	12.87
15-38	1.21	6.00	1.57	12.60
38-56	1.47	6.03	0.95	12.69
56-89	1.47	5.91	0.69	13.23
89-125	1.37	5.96	0.56	14.58
125-152	1.42	6.07	0.31	15.03
Trissur *Kole* organic soils (Kerala: Histosols: Terric Sulfihemists)				
0-12	1.40	4.23	3.42	17.49
13-33	1.47	4.46	2.66	13.82
34-49	1.27	4.66	4.66	27.43
50-66	0.57	4.22	14.22	39.98
67-99	0.80	3.62	46.22	102.71
100-133	0.71	4.47	45.86	106.72
134-164	0.62	4.78	50.75	107.14
Kuttanad *Kari* organic soils (Kerala: Histosols: Typic Sulfohemists)				
0-19	0.51	3.11	50.18	79.00
19-50	1.47	3.45	49.62	66.23
50-73	1.26	3.91	42.02	66.46
73-97	1.12	4.61	32.59	67.37
97-127	1.56	5.30	11.51	43.66
127-166	1.79	3.20	11.43	23.94

BD estimated by pedo-transfer function (Tiwary et al., 2014)

(more than 20% organic materials by mass), iii) cool and wetland environments, and iv) no permafrost (Anonymous, 2023a). Organic soils are an endless source of organic carbon controlling soil health and quality. These soils have not been reported in India except for Tripura (Bhattacharyya et al., 1996). Besides Tripura, Manipur and Kerala have organic rice-growing soils.

Selected physical and chemical propeties of brown foest and organic soils in India are enumerated in **Table 4**. The representative organic soils (Histosols) are shown in **Figures 3** and **4**.

Discussion

While estimating SOC stock globally (Sombroek et al., 1993; Eswaran et al., 1995; Batjes, 1996) and in India (Bhattacharyya et al., 2000, 2017), the brown forest soils and the organic soils (Histosols) were also

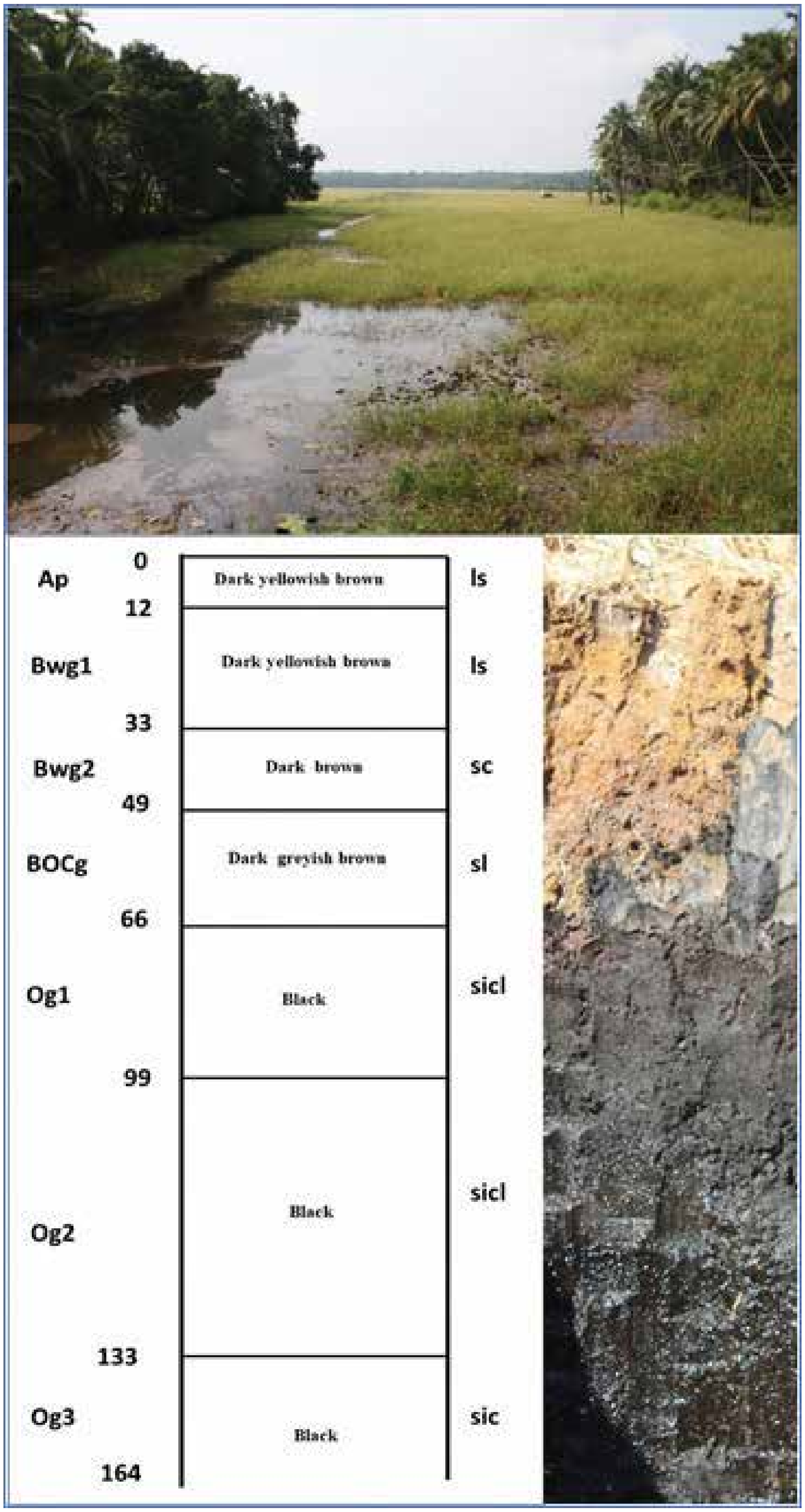

Figure 3. Trissur *Kole* Organic soils (Histosols), Kerala, India, showing the landscape and profile -Terric Sulfihemists (Source: Nideesh et al., 2021)

Note: The schematic diagramme shows the soil depth in cm, horizon designations as A [surface], Bwg as structural gleyed subsurface, Og as gleyed organic layers typical of organic soils; ls, sc, sicl, and sic in right side means texture as loamy sand, sandy clay, silty clay loam and silty clay, respectively

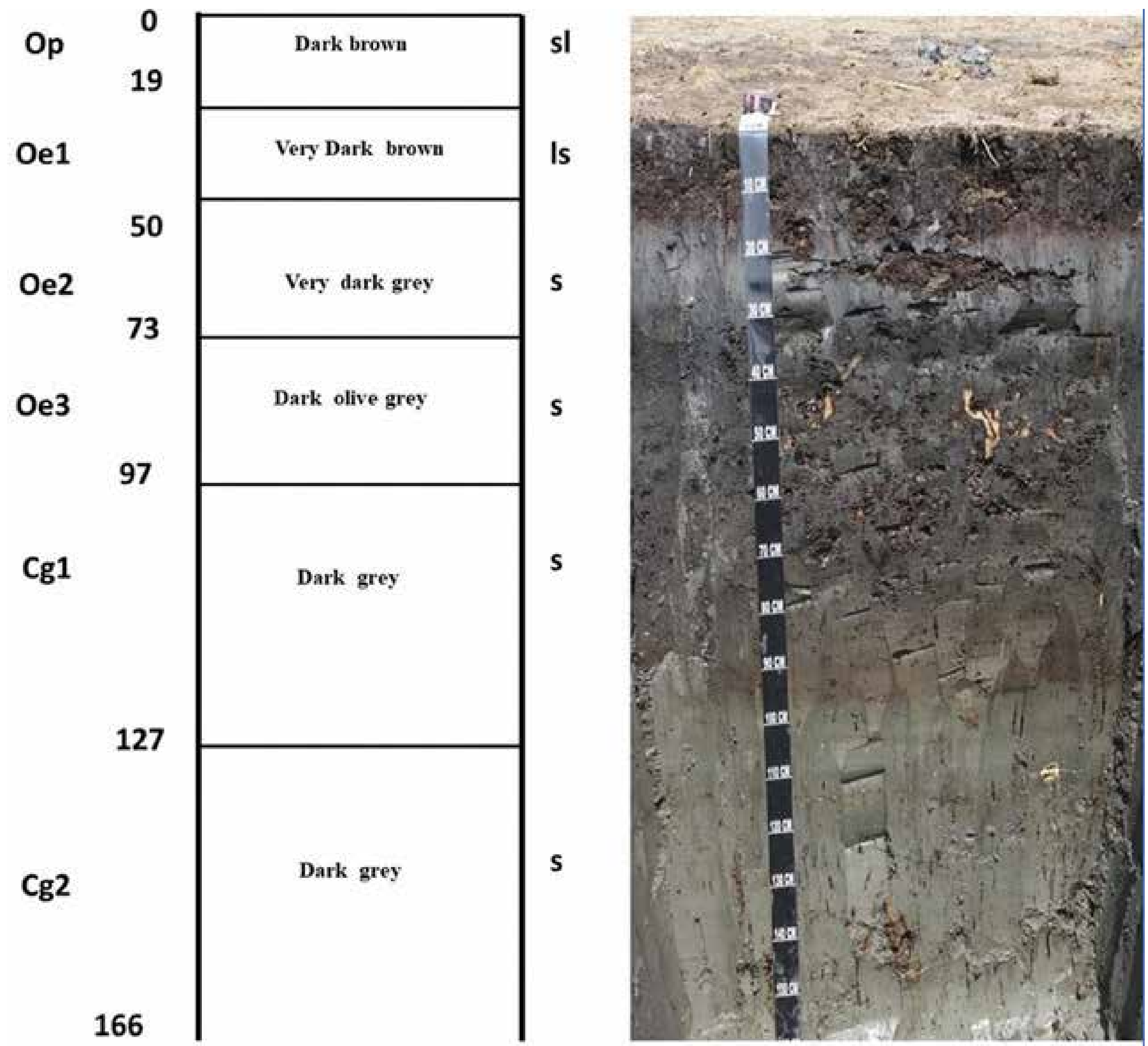

Figure 4. Typical *Kari* soils (organic soils: Histosols) of Kuttanad - *Typic Sulfohemists* (Source: Karthika et al., 2024)

Note: The schematic diagramme shows the soil depth in cm, horizon designations as Op (surface organic layer), Oe as eluvial organic layer, Og as gleyed organic layers typical of organic soils; sl, ls, and s in right side means texture as sandy loam, loamy sand and sand, respectively

analyzed simultaneously. Soil organic carbon stocks of organic soils (Histosols) and brown-forest soils (Mollisols) in the world have been assessed as 330 and 301 at 0-150 cm soil depth (Batjes, 1996; Anonymous, 2023). The SOC stock for the brown forest soils (Mollisols) in India was assessed after revision (Bhattacharyya et al., 2000; 2017) as 1 Pg at 0-150 cm soil depth. There is a reference to organic soils (Histosols) from Tripura (Bhattacharyya et al., 1996). These soils from Kerala, Manipur, Andaman & Nicobar Islands may not be uncommon (Personal communications). However, precise data on these soils are unavailable. The SOC stock has been tentatively assessed from a selected profile as 4 Pg per million ha. The relative share of SOC stock at the global and Indian levels indicates that these two types of soils reserve at least 20-25% SOC (**Figures 5** and **6**). These soils need conservation through appropriate management strategies.

Conclusion

Broadly, two categories of soils are found, namely mineral and organic soils. Among mineral soils, Mollisols or brown forest soils are generally capable of storing more organic carbon than other mineral soils. The organic soils occur mostly in the wetlands (peats/mucks and swampy areas). The total wetland area is estimated to be 15.26 Mha, around 4.63% of the country's geographic location (Anonymous, 2020). There are examples of organic soils/ presence of the

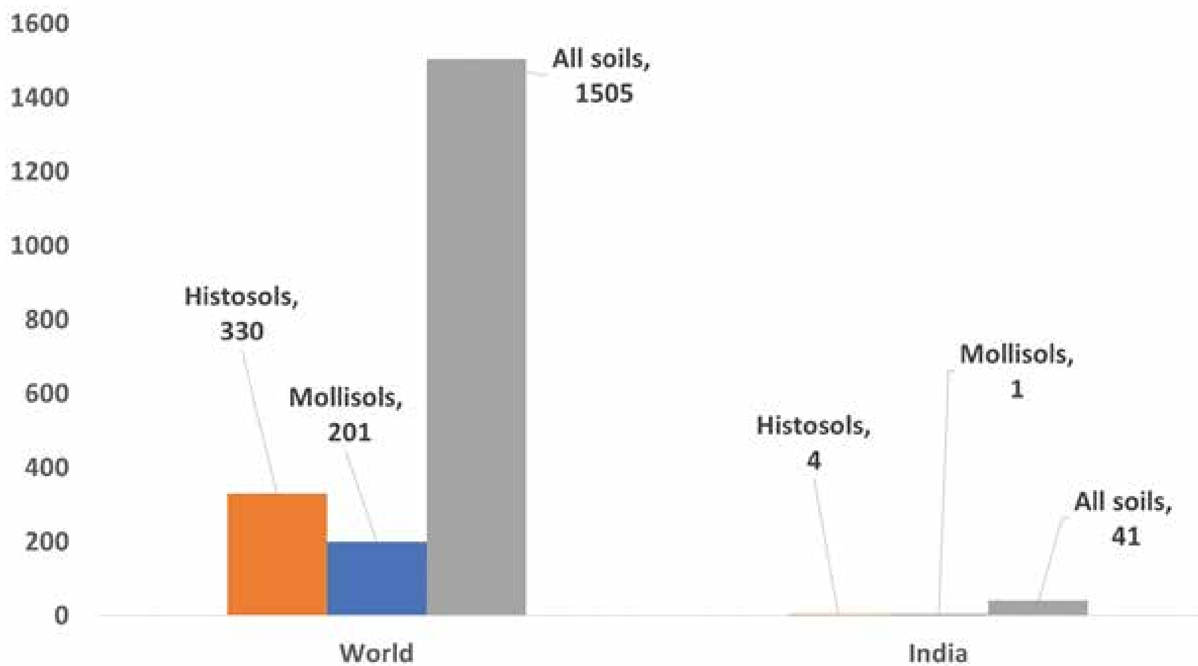

Figure 5. Soil organic carbon stock (Pg: Petagram) of organic soils (Histosols) and brown forest soils (Mollisols) in the world and India
Note: For Histosols, the value is in Pg per million ha

floating vegetative mat, locally called *phumdi* in Manipur, and some other parts of the northeastern region in India (Paul et al., 2022; Khoiyangbam, 2021).

Soils containing higher organic matter in either mineral or organic soils help mitigate climate change through a negative carbon emission strategy with more soil carbon footprints (Bhattacharyya, 2024; Bhattacharyya et al., 2024 a, b). Brown forests and organic soils are the two examples discussed in this paper. It is hoped that similar soils will be identified using modern soil inventory techniques at a relatively large scale. Besides the ecological services, including agriculture and horticulture, these soils, with special reference to organic soils, are also being explored as a probable energy source (Khoiyangbam, 2021; Paul et al., 2022). The lands representing these soils are extremely important for the soil ecosystem services, namely provisioning, regulating, cultural, and supporting services. Thus, the lands representing these valuable soils demand appropriate conservation measures from resource managers.

IPCC (2019) discussed the adaptation and mitigation response options with special reference to the degree of impacts in a time scale. While some response options

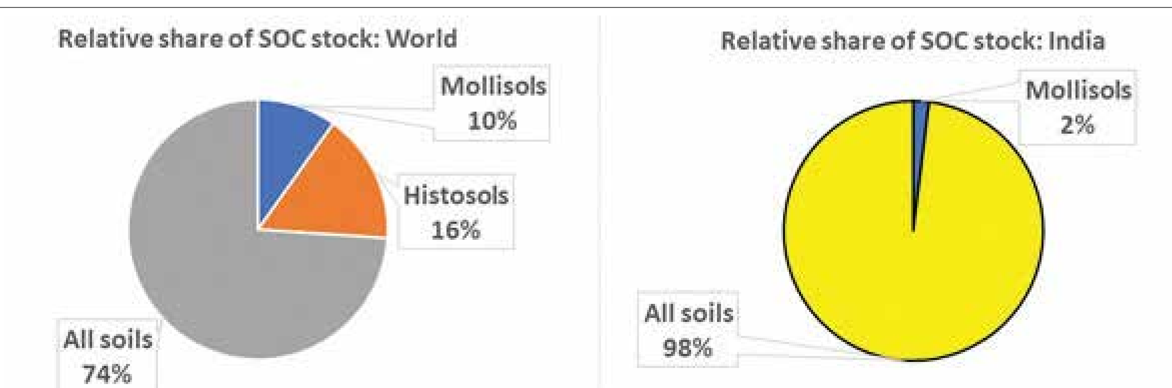

Figure 6. The relative share of soil organic carbon stock in organic soils (Histosols) and the brown forest soils in the world and India
Note: The India share of Histosols is not shown in the absence of data on areal extent

have immediate consequences, others take decades to deliver measurable results. The first one includes the conservation of high-carbon ecosystems such as peat lands, wet lands, range lands, mangroves (mostly organic soils) and forests (brown forest soils). IPCC also stressed the importance of successfully implementing response options for climate change adaptation, considering local environmental conditions. These may include soil carbon management, potentially applicable across a broad range of land use types, whereas the efficacy of land management practices relating to organic soils (Histosols) in the peatlands and wetlands representing specific agroecological conditions. This might further help land resource managers to map such areas using large-scale mapping.

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