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Soil Carbon Stock in Non-traditional Black Soils of North Eastern India: Tripura as Example

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Abstract: Tripura state in the north-eastern region (NER) of India, by its geographic location and richness in biodiversity, well supported by complementary climatic factors, more particularly high rainfall for luxuriant phyto-biomass (both above and below ground) in the form of forests and allied sources of vegetation, are known as non-traditional black soil area. Studies conducted on the soils of Tripura indicate that about 18.20 per cent area of the State consists of black soils. The study attempts to identify the important factors responsible for the formation of black soils even in the non-traditional black soil area of the north-eastern region in general and Tripura state in particular. These black soils are deep to very deep and are mostly dominated by smectitic clays. Such soils resembled the Vertisols mapped elsewhere in other parts of the country concerning texture, periodical opening and closing of cracks and sub-surface colour but have dissimilarity for slickenside development, wedge-shaped structure and colour on the surface. The CEC of these soils indicate the dominance of low-activity clays (LAC). However, the clay CEC of these soils are more than 30 and it has been extended up to 60, indicating mixed mineralogy and dominance of smectites or hydroxy interlayered smectites in the clay fraction, which holds more nutrient and moisture and thus converts these areas as the granary of the State. Therefore, besides the dominating effect of humid climate with cooler winter months with profuse vegetation, the soil substrate quality (quality and quantity of expanding clay minerals) is of fundamental importance in the sequestration of OC in the soil.

The study indicated that within the 0-30 cm soil depth, black soils of Tripura has got the capabilities to store 0.01Pg soil organic carbon stock which is about 20 per cent of the SOC stock of whole Tripura and 0.01 per cent of SOC stock of India. These soils are more fertile, holding more nutrients and moisture and are still in the weathering stage and show the presence of HIS and HIV in their mineralogical makeup. Therefore, the present information will be helpful for developing appropriate land use plans and conservation planning to ensure the green belt in northeastern India in general and Tripura state in particular to protect natural ecosystems.

Key words: *Tripura, black soil, soil organic carbon stock, north-east India.*

Introduction

Tripura is the smallest state in North-East India and the third-smallest state in the country (0.32 per cent of the total geographical area of India). The State is surrounded by Bangladesh in the south, west and south-east, Mizoram in the east and Assam in the north-east (Fig. 1). The terrain in Tripura consists of parallel hills and ridges alternated with narrow valleys. The geology of the state is represented by sedimentary rocks which range in age from Miocene to loosely consolidated sediments of recent age. The climate is humid subtropical

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characterized by high rainfall. The variety of landforms starting from hills to flood plains of the state gives rise to different types of soil (Bhattacharyya *et al.* 1996, 2003, 2010; Gangopadhyay *et al.* 2001, 2008).

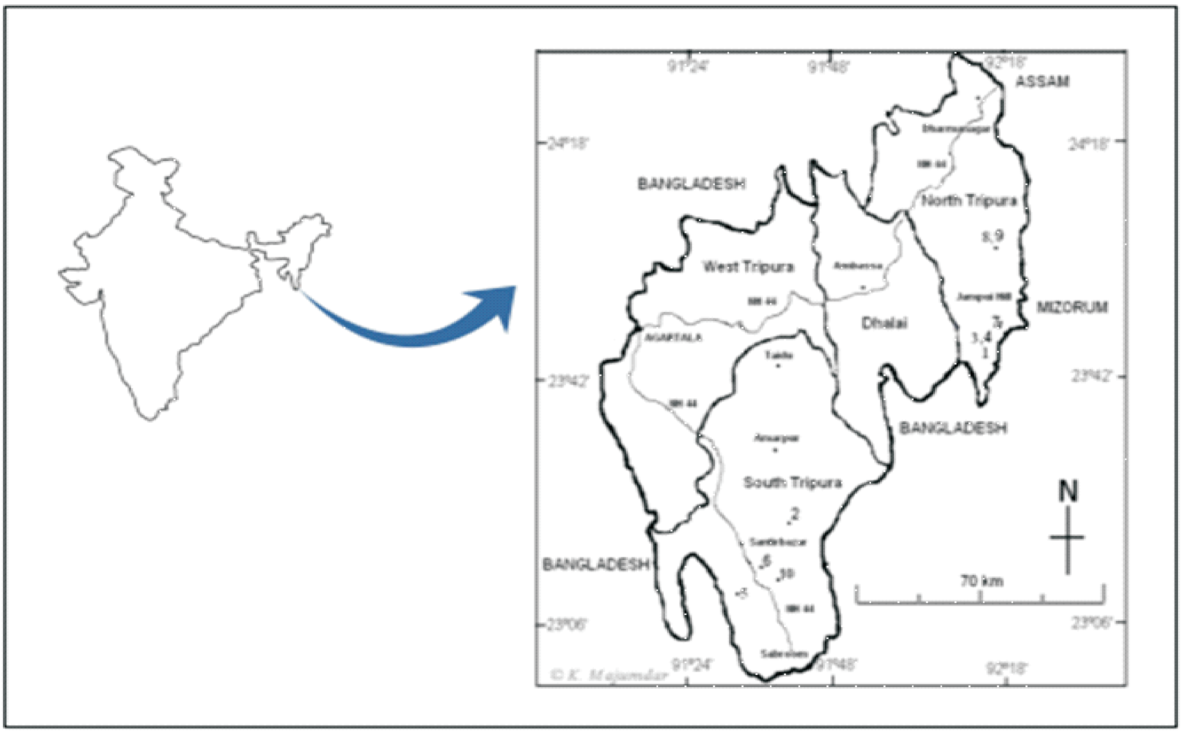

Fig. 1. Location map of Tripura

The Land use pattern in the State (Fig. 2). indicates that ~52 % area in Tripura is occupied by the dense forest and 11 per cent is under open forest. About ~13 per cent area is crop land, ~5 per cent is under plantation and ~3 per cent is under shifting cultivation (Choudhury *et al.* 2013). These variations in land-use land cover also results in the development of a varying type of soils.

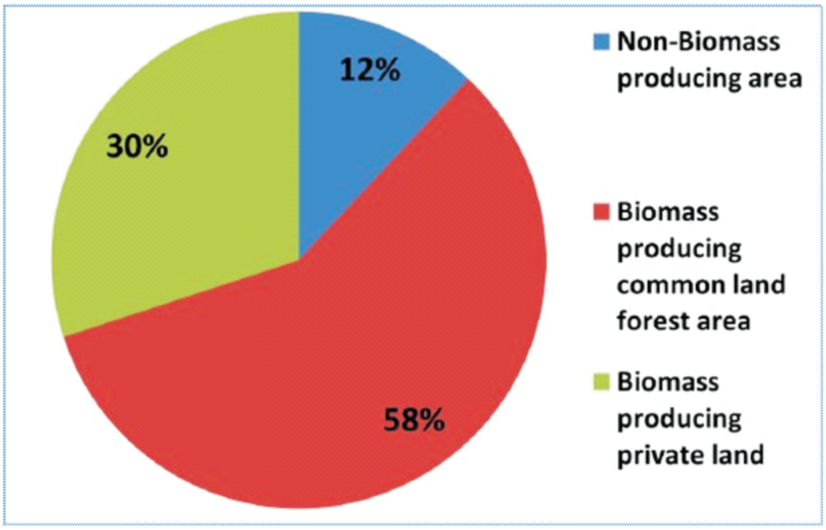

Fig. 2. Land use pattern in the State

Source : Saha *et al.* 2017

Agriculture is the main livelihood of the State offering the largest avenue of employment to its workforce. But the State has been facing some serious problems of undulation, soil degradation, and water logging because of its topographical situation. The major food crops of the region are cereals, pulses, oilseeds and potatoes. Rice is the main crop, followed by maize in this region. The agro-climatic conditions of the region are suitable for the production of temperate to sub-tropical fruits such as pineapple, citrus, mango, litchi, guava, banana, jackfruit and plantation tree like rubber (Bhattacharyya *et al.* 1996).

So far as the black soil is concerned, Tripura state in the north-eastern region is known as a non-traditional area as it has not been developed from any basic parent materials dominated with Ca^{2+} instead it has been developed from acidic sedimentary rocks in the humid tropical climate with high precipitation and cooler temperature. However, the Soil Resource information of Tripura indicates the presence of black soils in significant areas of the State. Hence, the present study is an attempt to identify the major factors responsible for the development of black soils in a non-traditional black soil area like Tripura state in the north-eastern region. Again, these black soils have got the potential to stock high organic carbon and helps in mitigating climate change through organic carbon stock providing ecosystem services to society.

Materials and Methods

Soil Resource Mapping of Tripura (1:250,000 scale) has identified different soils *viz.,* Inceptisols (80%), Entisols (9%), Ultisols (7%), Alfisols (5%) and Histosols (0.2%) (Bhattacharyya *et al*. 1996) (Fig.3).

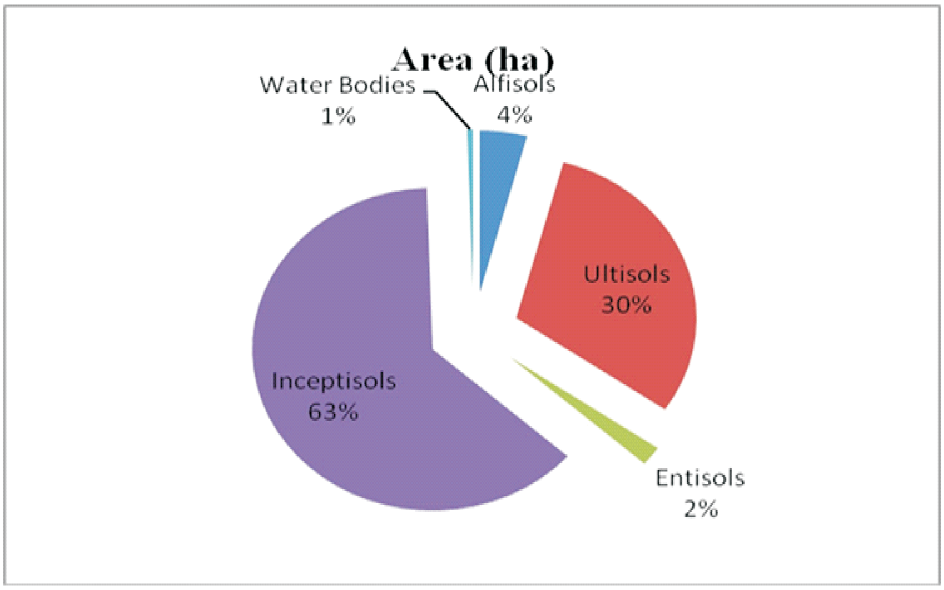

Fig. 3. Distribution of soils in Tripura

The study was conducted to those soil series which shows the swell shrink characteristics of black soils. From each representative soil series, horizon-wise soil samples were collected. 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 and 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. The soils were classified following the standard methods (Soil Survey Staff 2014).

Results and Discussion

The black soils were mostly identified in the soils of interhill valleys, valleys and flood plains showing the redoximorphic features with varying degrees of hydromorphism.

The hydromorphic soils of Tripura

The hydromorphic soils of Tripura developed on gently to very gently sloping flood plain under humid tropical climate represents the granary of the State. They are deep to very deep with varying texture and drainage classes and have some common characters during pedogenesis under impeded drainage conditions (Gangopadhyay *et al*. 2015). The soils are characterized by the redoximorphic features such as mottles and gley with varying degrees of hydromorphism. Translocation of clay and free iron oxide is generally prominent in these soils. These low-lying areas with high groundwater levels support primarily paddy cultivation, especially in Tripura which is an exception among the other paddy growing sites in north-east India in respect of varying degrees of hydromorphism,

Under submerged condition, the decomposition of organic matter is slow, and the higher primary productivity of wetlands, contribution by biological nitrogen fixation and decreased humification of organic matter enhance the preferential accumulation of organic matter in wetland soils and sediments (Sahrawat *et al*. 2005). Thus, the relatively higher accumulation of organic matter in wetland paddy soils leads to the sequestration of organic C for increasing the fertility of these soils and at the same time mitigating greenhouse emissions. The presence of smectitic clay minerals further aids in more accumulation of OM due to high surface charge densities (Bhattacharyya *et al.* 2014; Bhattacharyya 2022).

Black soils

Indian black soils, popularly known as black cotton soils or "Regur" are usually classified to Vertisols and Vertic intergrades of other soil orders (Inceptisols, Entisols and Alfisols). Traditionally, these soils were believed to be confined to the Peninsular region, but now a days, their presence has been reported in other parts of the country as well. The black soils are deep to very deep and are dominated mainly by smectitic clays. They are characterized by the presence of either slickensides or wedge-shaped peds, $\geq$30% clay and cracks that open and close periodically. These soils are grouped as Vertisols and include other soil orders possessing the characteristics of black soils showing linear extensibility (LE) of 6.0 cm or more. High LE values are caused by smectitic clays that allocate these soils to vertic sub-group. Revised estimation indicates that black soils occupy nearly 76.4 m ha (Fig. 4).

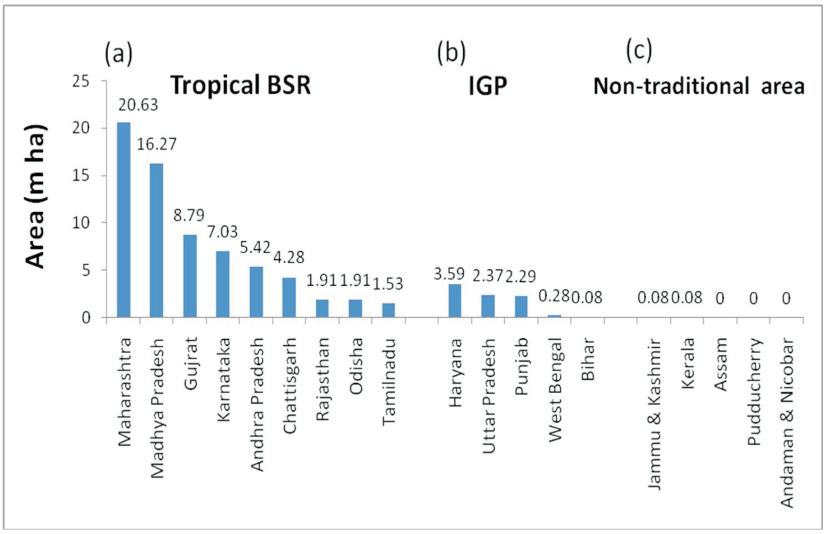

Figure 4. Black soils (m ha) in different states of India. (a) Tropical BSR (Maharashtra, Madhya Pradesh, Gujarat, Karnataka, Andhra Pradesh, Chhattisgarh, Rajasthan, Odisha, Tamil Nadu); (b) Black soils in the IGP (Haryana, Uttar Pradesh, Punjab, West Bengal, Bihar); (c) Non-traditional area (Jammu & Kashmir, Kerala, Assam, Puducherry and Andaman & Nicobar Islands) occupying 0.0072, 0.0000146 and 0.0000071 m ha respectively). Source: Modified from Bhattacharyya *et al*. (2013).

Unlike the traditional areas, black soils were also reported in IGP. Black soils were also reported from Kerala, J&K, Andaman and Nicobar Islands (Fig. 4). The occurrence of shrink-swell soils in Kerala appears to be related to the fluvial deposit by rivers. The presence of such soils in J&K may be due to the presence of basic rocks in the complex rock system in the Himalayan regions (Bhattacharyya *et al.* 2013).

Black soils of Tripura

During soil resource inventory of Tripura, it was reported that Inceptisols were the major soil order followed by Entisols. However, studies of some of the low-lying hydromorphic soils shows an increase in clay content with the increase in soil depth indicating the illuviation of clay due to heavy rainfall. Due to high clay content, these soils develop deep and wide cracks in the surface during summer, which extends up to few centimeters of depth. Such soils resembled to the Vertisols mapped elsewhere in other parts of the country concerning texture, periodical opening and closing of cracks and sub-surface colour but have dissimilarity for slickenside development, wedge-shaped structure and colour on the surface. The CEC of these soils indicates the dominance of low-activity clays (LAC). However, the clay CEC of these soils are more than 30 and it has been extended up to 60, indicating mixed mineralogy and dominance of smectites or hydroxy interlayered smectites in the clay fraction, which holds more nutrient and moisture and thus converts these areas as the granary of the State.

Genesis of black soils in Tripura

Considering the agro-ecological sub regions (AESRs), the soils vary in terms of soil reactions, base saturation, nutrient-holding capacity, organic matter content and length of growing period (LGP) to support a host of agricultural and horticultural crops (Bhattacharyya *et al.* 2013a). The smectitic parent materials are the building block of black soils (Vertisols and their associates), and their retention in tropical Vertisols of the Western Ghats has been possible because of the presence of unique mineral like Ca-zeolites. In Tripura, under humid tropical weathering environment, vermiculite/low charge smectites in clay fractions are not weathered to reach the stage of kaolinite suggesting mixed mineralogy class for these soils.

During humid tropical weathering, huge quantity of Al^{3+} ions are liberated to cause higher acidity (H^+), which was estimated about 149 kg ha^{-1} (Bhattacharyya *et al.* 2010). These vermiculites adsorb Al^{3+} ions as hydroxy-cations to form HIV/HIS. The vermiculite minerals thus act as a natural sink to sequester Al^{3+} ions. This is the reason why Tripura soils show relatively higher proportion of hydroxy interlayered vermiculites effecting lower concentration of Al^{3+} ions in the soil solution (Bhattacharyya *et al.* 2010) reducing Al^{3+} toxicity hazards in soil.

The soils in the uplands in Tripura are highly acidic and show the dominance of kaolinite minerals, while the low-lying flood plains/ valleys, mostly remain saturated with water and show the dominance of vermiculite/ low charge smectites. The persistence of these shrink-swell minerals in the poorly drained conditions (Bhattacharyya *et al.* 1993, 1999, 2006) make the formation of black soils possible even in the present-day humid conditions.

While explaining the formation and persistence of black soils (Vertisols and their intergrades) in the Western Ghats, smectites in soils are still persisting. In spite of prolonged weathering since the early Tertiary period, the dominance of smectite/ kaolin interstratified minerals in the clay fractions of black soils formed in the Deccan basalt have not yet reached the kaolinitic and/or oxidic mineralogy due to the presence of Ca-zeolites which prevents the formation of kaolinitic and/or oxidic clay minerals (Bhattacharyya 2021).

The genesis of Vertisols indicates that in the initial stage of soil formation by landscape reduction process, smectite-rich products of weathering from the hills were deposited in micro-depressions, as is evident from the lithic/paralithic contacts of such Vertisols. Over time, these sites gradually flattened, and internal drainage dominated over surface run-off. After peneplanation, the red soils (Alfisols) of the present (Bhattacharyya *et al.* 1993, 1999, 2006) and the past

(Pillai *et al.* 1996) HT climates on relatively stable surfaces continued to weather, forming Sm–K (Pal *et al.* 2012). In contrast, Vertisols continued to exist in the micro-depressions even in HT climates because of the continuous supply of bases from Ca-rich zeolites that helps to stabilize the smectite (Bhattacharyya *et al.* 1993). Zeolites can indeed provide sufficient bases to prevent the transformation of smectite to kaolinite, thus making the formation and persistence of Vertisols possible even in a humid tropical climate (Bhattacharyya *et al.* 2005), as zeolites can maintain the base saturation of soils well above 50% (Bhattacharyya *et al.* 1993, 1999, 2006; Pal *et al.* 2006b).

Clay mineralogy

Out of the 48-soil series identified in Tripura, 7 soil series were identified (Table 1) belong to Vertisols and their intergrades showing mixed mineralogy class with smectite as a dominant mineral (Bhattacharyya *et al.* 2004). Ideally, black soils (Vertisols and their intergrades) commonly occur in the Deccan Plateau extending to central, western and southern part of India. North eastern India represented by Tripura in this study is non-traditional area so far as black soils are concerned (Bhattacharyya *et al.* 2013). There is as such no parity of climate, vegetation, parent materials, soil reaction, Organic carbon content and soil CEC and clay CEC in soils of Tripura state under humid tropical climate with the traditional black soils in the Deccan Plateau extended to central, the western and southern part of India (SAT). In the humid tropical climate, the prevalence of high temperature and adequate moisture in the weathering environment should have nullified the effect of the parent rock composition of the Deccan basalt by resulting in kaolinite and/or oxidic mineral assemblages consistent with either residua (Chesworth 1973) or Haplosol model of soil formation (Chesworth 1980). On the contrary, the dominance of smectite/kaolin interstratified minerals in clay fractions indicates that in spite of prolonged weathering since the early Tertiary, products of weathering of Deccan basalt have not yet reached the kaolinitic and/or oxidic mineralogy due to the presence of Ca-zeolites. Presence of Ca-zeolites creates a chemical environment sufficiently rich in bases, which prevents the formation of kaolinitic and/or oxidic clay minerals.

In Tripura, mineralogy class of major soils indicates that kaolinite is the dominant clay mineral particularly in the hills, flat topped denuded hills and undulating uplands. However, conversion of soil CEC into clay CEC suggests that these are no more low-activity clay (LAC) soils. The knowledge of clay mineral composition of soils is of paramount importance in fertilizer use, crop management and for various land uses since the soil properties such as water retention and release, nutrient adsorption and desorption, and shrink-swell behaviour are significantly influenced by the nature and content of soil clay minerals.

On the basis of the mineral makeup of different soil series, it was observed that tilla lands mostly used for rubber and horticultural crops are dominated by soils with less than 10% HIS, less than 17% HIV and with less than 35% KI/HIV. High hills (forests) are dominated by soils with less than 10-20% HIS, less than 17-20% HIV and less than 35-50% KI/HIV and interhill valleys (agricultural crops) are dominated by soils with more than 20% HIS, more than 20% HIV and more than 50% KI/HIV (Bhattacharyya *et al.* 2010).

While estimating the minerals in various clay fractions using soil CEC, we presume that CEC is largely contributed by clay and organic matter, and the CEC of humic acid, mica/hydroxy-inter-layered smectite (M/HIS), HIS, hydroxy-interlayered vermiculite (HIV), M/HIV and K/HIV were considered as 300, 40, 25, 30, 15 and 5 cmol(+)kg^{-1}, respectively (Bhattacharyya *et al.* 2013). Based on the clay CEC value of the soil series under mixed mineralogy classes, seven soil series were found in Tripura (Table 1) covering an area of 1,91,030 ha (18.20% of TGA) with clay CEC of more than 30, and it goes to maximum 60 indicating the dominance of mica/hydroxy-interlayered smectite (M/HIS) and HIS in the clay fractions (Table 1). Hence, the study indicates that black soils occupy ~ 18 per cent area of Tripura and 0.06 per cent of the country which represents 0.01 Pg of SOC stock at 0-30 cm depth and constitute 20 per cent of the SOC stock of Tripura (11.397 Pg) and 0.08 per cent of the SOC stock of the country. Mandal *et al.* (2014) while revisiting the Agro-ecological sub-regions in the IGP also reported the presence of black soils in Tripura indicating the presence of black soils in non-basaltic terrain under humid environment.

Table 1. Soil series of Tripura with the dominance of mica/hydroxy-interlayered smectite (M/HIS) and HIS in the clay fractions.

Sl. No.	Soil Series	Texture	Mineralogy	Subgroup	Greatgroup	Clay CEC	Area (ha)
1.	Dharaichherra	Fine	Smectitic	Aeric	Endoaquepts	49-60	7,250
2.	Nayanpur	Very fine	Smectitic	Typic/ Vertic	Endoaquepts	56-64	43,106
3.	Paschim Manu	Fine	Smectitic	Oxy-aquic	Dystrudepts	26-42	29,190
4.	Netajinagar	Fine	Smectitic	Fluventic	Dystrudepts	36-42	35,156
5.	Bagbassa	Fine	Smectitic	Typic	Dystrudepts	27-33	49,747
6.	Chhailengta - II	Fine	Smectitic	Typic	Paleudults	23-34	10,343
7.	Manpui	Clayey	Smectitic	Lithic	Dystrudepts	32-44	16,238

These soils are deep to very deep and are dominated by smectitic clays. They are characterized by the presence of wedge-shaped structure, pressure phases, more than 30 % clay, cracks that open and close periodically and resemble black soils of Peninsular region except the slickenside and the colour of the surface soil. These soils belonging to other soil orders possess the characteristics of black soils. In the absence of linear extensibility (LE) value, we consider the clay CEC value of the soils to other soil orders possessing the characteristics of black soils. The high smectite content allocated these soils to vertic subgroup. These soils assume importance due to similar characteristics and land management practices for agriculture and allied uses by Vertisols. Recent studies show that Vertisols and their intergrades can also possess red colour (Kolhe *et al*. 2011).Thus, the term black soils for Vertisols and vertic intergrades are technically not correct. Bhattacharyya *et al.* (2013) estimated the extent and distribution of black soils in India and accordingly Madhya Pradesh, Maharashtra, Rajasthan, Puducherry, Tamil Nadu, Uttar Pradesh, Bihar, Odisha, Andhra Pradesh, Gujarat states covering 16.6 per cent area of the country contains black soil under the various soil orders like Vertisols, Mollisols, Inceptisols, Entisols, Aridisols. Considering the smectite content in the clay fractions, these soils of Tripura may be included in the black soils.

Soil Fertility

As Tripura is predominantly a hilly area and characterized by the varied soil type and geographical situations, the fertility status is widely varied across the climatic gradients. Single soil factor that mostly determine the abundance of plant nutrient in soil is pH or soil reaction. It is very important particularly for soils of Tripura where more than 49.2 per cent of the soils are strongly acidic in reaction, causing deficiency and toxicity of a number of nutrients. Climatic factors like, temperature, rainfall tremendously regulates nutrient availability through decomposition of organic matter of soil. Carbon stock in Tripura soil showed wide variability, thus nutrient availability varies accordingly. Both macro and micronutrients showed low to medium status across the length and breadth of the State. With soil being the source of nutrients to the crops, proper assessment of its nutrient status is required for each and every crop before application of any additional nutrient sources. Judicious use of external resources is one of the main criteria to raise agricultural productivity in the soils of the State. The clay mineralogical data of Tripura shows the dominance of hydroxyl interlayered vermiculite (HIV), mica (M) and kaolinite (KI) in fine and total clay fractions. Presence of hydroxyl interlayered smectite (HIS) was also noticed. Interestingly mica and kaolinite clay minerals are also present as interstratified minerals with HIV as M/HIV and KI/HIV (Bhattacharyya *et al*. 2010). The Soil information system *vis-a-vis* clay mineralogy and land use in Tripura is presented in table 2.

Table 2. Soil information system *vis-a-vis* clay mineralogy and land use in Tripura

Physiographic position	HIS[a] (%)	HIV[b] (%)	KI/HIV[c] (%)	Land Use	Elevation Ranges (m amsl)	KCl–Al cmol (+) kg^{-1}
High hills	10–20	17–20	35–50	Forest	> 400	1.5–2.5
Tilla lands	< 10	< 17	< 35	Horticulture, plantation, agriculture	400–250	2.0–4.0
Valleys	> 20	> 20	> 50	Agriculture	< 250	< 1.0

Note : [a]HIS, Hydroxy-interlayered smectites; [b]HIV, Hydroxy-interlayered vermiculites; [c]Kl/HIV, Kaolin interstratified with HIV.

Source: Bhattacharyya *et al*. (2010)

Soil organic carbon

Soil organic matter (SOM) is both a source and a sink of plant nutrients that promote the formation of soil aggregates and thus influences soil physical properties and soil moisture; it is an energy substrate for soil microbes and macro fauna. The primary way that carbon is stored in the soil is as soil organic matter (SOM) which is a complex mixture of carbon compounds consisting of decomposing plant and animal tissues, microbes and carbon associated with soil materials. In addition, the sequestration potential of soil also depends on its physical and chemical characteristics, mineralogical composition, depth of the solum, soil drainage, the availability of water and air and the temperature of the soil environment (Bhattacharyya *et al*. 2000, 2008).

The role of soil C in the global C cycle and in the mitigation of atmosphere levels of GHGs, with special reference to CO_2 is of global importance. Soils with low base saturation with almost similar values of pH and CEC are mostly found in the states of Tripura, Kerala and Karnataka (southern states) under humid tropical climate. However, the OC content of soils of Tripura is highest than Kerala and Karnataka reflecting the influence of cooler temperature in Tripura for a fewer months (November, December, January and February) than the other states with a conclusion that cooler temperature is responsible for high accumulation of OC in soil. Further studies indicate that cooler temperature alone may not be able to influence accumulation of OC as observed in the soils of Punjab and Haryana states, which are low in SOC (<1 %) (Bhattacharyya *et al.* 2004a), although the minimum temperature of these geographical areas varies between 6 and 8°C in winter months. Thus, cooler temperature along with high precipitation *i.e.*, the overhead climate may possibly be the factor of formation of high organic matter content in soil.

The major portion of SOC is retained through clay–organic matter complex formation, indicating the importance of the inorganic part of the soil as a substrate to build the SOC. Generally, phyllosilicates such as smectites are more intimately associated with retaining and increasing SOM than the other clay minerals, mainly due to their high specific surface area. The sequestration of organic carbon is achieved through various mechanisms which include the formation of clay-humic complexes, sorption of organic matter on clay particles, fixation of organic carbon in the crystal lattices of clays and the formation of organo-metallic compounds such as Ca, Fe and Al humates through humification processes. Ultimately, after a lot of debates by several scientists working on several mineralogically contrasting soils in different parts of the world regarding the retaining and increasing of organic matter in the soil, it was suggested that smectitic soils tend to have more OM content than kaolinitic ones due to higher specific surface area and a quantitative relationship between clay mineralogy and OC which can be used to deduce possible effects of clay mineralogy on the OC contents of organic-mineral clay fractions in the soils of Tripura (Table 3).

Table 3. Effects of clay mineralogy on the OC contents of organic-mineral clay fractions

Clay content (%)	Clay Type	OC (%)	Soil Type
39	Kaolinite and Montmorillonite	1-2	Alluvial soils
17-18	Kaolinite	2-3	Merredin Sandy Loam (Ustalfs)
69	Smectite	1-2	Dystric Gleysol (Tropaquepts)
28	Smectite / Vermiculite	2-5	Typic Paludalf, Typic Hapludalf

Source : Kome *et al*. 2019

The importance of expanding 2:1 clay mineral in the accumulation of SOC is well demonstrated in the ferruginous red soils (Alfisols and Ultisols) of the north-eastern, eastern, western and southern parts of the country (Chandran *et al*. 2021). It has been observed that even in the Ultisols of Kerala (Chandran *et al*. 2005) and Meghalaya in the north-eastern regions of India (Bhattacharyya *et al*. 2000) the presence of smectite and/or vermiculite either in the form of interstratifications or in a discrete mineral form is quite common. The presence of these minerals favours the accumulation of OC in the soil. Therefore, besides the dominating effect of a humid climate with cooler winter months with profuse vegetation, the soil substrate quality (quality and quantity of expanding clay minerals) is of fundamental importance in the sequestration of OC in the soil. The factors affecting SOC (soil organic carbon) accumulation as influenced by rainfall, temperature and soil substrate quality is presented in fig 5.

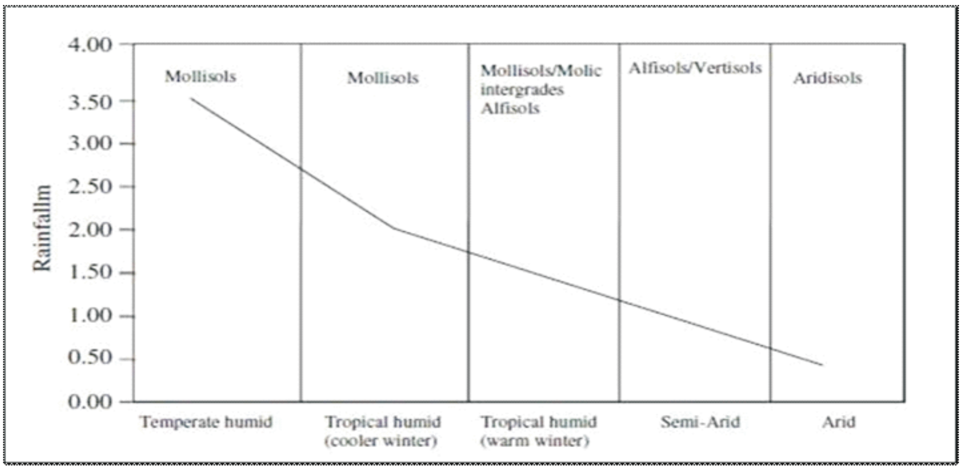

Fig. 5. Factors influencing SOC (soil organic carbon) accumulation. SOC as influenced by rainfall, temperature and soil substrate quality. Soils contain 2:1 mineral either in the form of interstratifications or in a discrete mineral form. Source : Goswami *et al*. (2000)

In Tripura, SOC content varies from 0.34% to 1.88%. It has been found that about 7.55 per cent of the total geographical area of the State contains 0.5 to 1.0 per cent SOC, 89.03 per cent area under 1.0 to 1.5 per cent SOC and 3.42 per cent under 1.5 to 2.5 per cent SOC (Choudhury *et al*. 2013). Relatively high SOC is found in deep to very deep, well to excessively drained loamy hill soils. The Soil Information System (SIS) of Tripura helps to estimate SOC stock. The data showed that nearly 58% area in Tripura has more than 45 kg ha^{-1}SOC stock in the first 30 cm depth of soils (Bhattacharyya *et al*. 2010). Estimation of SOC stock under different land-use system indicates that highest amount (20.5 Tg: I Tg= 10^{12} g) SOC stock was found in dense forest while crop land and open forest shows 4.0Tg SOC stock in each system. Plantation and shifting cultivation show SOC stock of 1.6 and 0.8 Tg respectively (Chaudhury *et al.* 2013). The total estimated SOC stock in India and Tripura is 9.55 Pg and 0.05 Pg, respectively. It shows that SOC stock in Tripura is maintained at 0.046 Pg ha^{-1} compared to the all-India average of 0.029 Pg ha^{-1} (Gangopadhyay *et al*. 2021). Earlier, using the 14 agro-climatic zones (ACZs) of the Planning Commission, ACZ 2, representing the entire NER was found to store organic carbon @0.064 Pg/m ha of soils (Bhattacharyya *et al*. 2008). Such threshold values of SOC stock ranging from 0.05 to 0.06 Pg/m ha should, therefore, be maintained in areas declared as the green belt to protect natural ecosystems.

The SOC stock data of selected black soils of Tripura shows that in the surface (0-30 cm) Nayanpur series of flood plain has got highest SOC stock (3.640 Tg) followed by Bagbassa of low relief structural hills and ridges (1.971 Tg), Paschim Manu of flood plain (1.449 Tg), Chailengta-II soil series of medium relief hills (1.055 Tg) and least SOC stock in Dharaichherra soil series of flood plain (0.509 Tg), totaling an amount of SOC stock by the selected soil series at 0-30 cm depth is 10.289 Tg (Fig. 6).

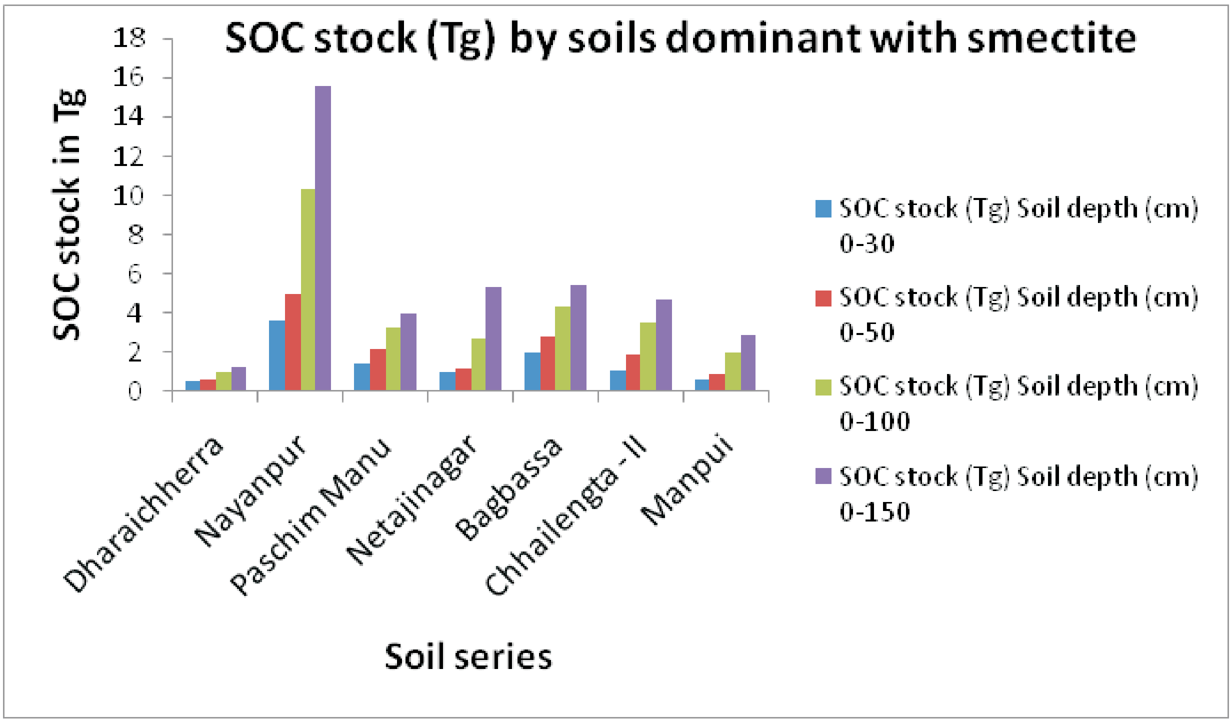

Fig. 6. SOC stock (Tg) of black soils in Tripura.

The study revealed that 18.20 per cent area of Tripura state represents black soil and within the 0-30 cm soil depth, black soils of Tripura has got the capabilities to store 0.01Pg soil organic carbon stock which is about 20 per cent of the SOC stock of whole Tripura and 0.01 per cent of SOC stock of India. These soils are more fertile holding more nutrients and moisture and are still in the weathering stage and show the presence of HIS and HIV in their mineralogical make-up. Therefore, the present information is the need of the hour and will be useful for developing appropriate land use plan and conservation planning to ensure the green belt in north eastern India to protect natural ecosystems. Roth *C*, Century, DNDC, and InfoCrop models were used to model the organic matter decomposition rate and the fate of OM in future in Indian black soils (Bhattacharyya *et al.* 2011; Bhattacharyya 2022). It is a good suggestion, and we hope others will undertake studies with black soils in Tripura. In the present article, we did not mention carbon modelling.

Conclusion

Tripura state in the north-eastern region, is mainly characterized by varied physiography and climate, developing varying types of soils endowed with various land use types and agricultural systems. The soils are Inceptisols (80%), Entisols (9%), Ultisols (7%), Alfisols (5%) and Histosols (0.2%). The land use classification of the State shows that more than 58% of the total geographical area is covered by forest. Only 26% of the total geographical area is available for agricultural purpose. Agriculture is the main stay of the people of Tripura.

Black soils, especially the Vertisols occur in a wide range of climatic environments of India. North eastern India represented by Tripura is a non-traditional area so far as black soils are concerned (Bhattacharyya *et al*. 2013). In the humid tropical climate of Tripura, swell-shrink soils occupy more than 18 per cent of the total geographical area of the State. Unlike traditional black soil, the non-traditional black soil possesses seasonal swelling and shrinking, pressure phases in the sub-surface with high clay content developing deep and wide cracks in the summer, seldom shows the presence of slickenside and varies completely in the colour of the surface soil and also represents the granary of the State. These are mainly developed over alluvium of the weathering Deccan trap basalts. The shrink-swell soils require huge amount of smectitic clay for their formations. These Vertisols and vertic intergrades are more or less similar in land management practices**.** Since carbon storage potential lies in the quality (and quantity) of clay, it is evident that black soils with smectitic clay shall provide better environment for organic carbon stock build up as compared to other soils due to the formation of clay-humus complex. The clay-humus bonding through Calcium Bridge which binds the organic matter with clay, would depend upon the quality of both clay and organic compounds in soil.

These soils are more fertile, holding more nutrients and moisture and are still in the weathering stage and show the presence of HIS and HIV in their mineralogical makeup. Therefore, these soils will be helpful for developing appropriate land use plans and conservation planning to ensure the green belt in northeastern India to protect natural ecosystems. Mitigating climate change through organic carbon sequestration in soils is one of the ecosystem services the soils provide to the society.

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