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Ultisols with Unique Soil Properties and their Implications in Carbon Enhancement Strategies for Indian Tropical Soils

D.K. Pal [1*], P. Chandran [1], Ranjan Paul[1] and Ashim Datta [2]

[1]Division of Soil Resource Studies, ICAR-National Bureau of Soil Survey and Land Use Planning, Amravati Road, Nagpur - 440 033
2 ICAR-Central Soil Salinity Research Institute, Karnal, Haryana - 132001

Abstract: Million years old Ultisols, developed as an end stage of advance soil weathering on base-poor rock systems under forest and plantation crops of the Indian sub-continent, are enriched with organic carbon (OC). Despite their remarkable acid chemical reaction, they show an upward increase in extractable bases (EB) and base saturation (BS) in the pedon, and on some occasion BS > 35% in surface horizons. Recent research suggests that the litter falls from forest species provide bases on soil surface, which causes similar depth distribution of EB and BS in Andisols of Nilgiri Hills of humid tropical southern India, developed on pre-weathered lateritic materials consisting primarily of Fe and Al oxides/ hydroxides. Under similar humid tropical (HT) climate in protected rain forest, million years old OC rich soils of Andaman and Nicobar Islands, developed on base-poor rock systems, have similar chemical and clay mineralogical properties of Ultisols except however their EB and BS, which are more than 10% and much above 50%, respectively and therefore, they are acidic Alfisols. Formation of Alfisols on the Island is a unique example on the formidable role of vegetation in soil formation, suggesting that if inland Ultisols are kept under natural protected forest ecosystem, they may phase towards Alfisols thereby facilitating OC sequestration and perform other ecosystem functions. The preservation of natural or semi-natural ecosystems is thus essential to raise the OC stocks of soils, which would help to gain various ecological benefits.

Keywords: *Ultisols of tropical India; natural forest system; high OC status; bases enrichment through litter falls; hydroxy-interlayered clay minerals; phasing of Ultisols towards acidic Alfisols.*

Introduction

Ultisols, the important soil order of red ferruginous (RF) soils of tropical India, occur in association with acidic Inceptisols, Alfisols, and Mollisols. These soils are developed mostly on granite, granite-gneiss, ferruginous sandstone and schist of Achaean Period (Sehgal *et al*. 1998; Bhattacharyya *et al*. 2009) under humid tropical (HT) climates in many Indian states (Assam, Arunachal Pradesh, Tripura, Kerala, Goa, Karnataka, Tamil Nadu, Manipur, Meghalaya, Nagaland, and Mizoram) (Pal *et al*. 2014). Ultisols, of Indian sub-continent are popularly known as 'laterites' (Pal *et al*. 2014). However, in US Soil Classification System, the term 'laterite' is generally conceived to be equivalent to Oxisols (Buol and Eswaran 2000), which are expected to have an oxic horizon with low CEC and ECEC, and less than 10% weatherable

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*Corresponding author: (Email: paldilip2001@yahoo.com) minerals. It is however paradoxical that despite having favourable conditions in many above mentioned states in HT climate of India, the soils of these geographical areas do not qualify to be Oxisols (Bhattacharyya *et al.* 1993, 2009: Pal *et al.* 2014). Under Indian HT climate, the most weathered RF soils recorded by Indian pedologists, belong to Ultisols, which are predominant under dense forest vegetation, plantation crops and agriculture (Pal *et al.* 2014). The exclusive formation of Ultisols under HT climate finds a support from the evolutionary pathways of soil formation for millions of years, especially in zeolitic Vertisols (Pal *et al.* 2012a). Studies on soils evolution in different parts of India such as southern India (Chandran *et al.* 2005; Pal *et al.* 2014); HT parts of the Western Ghats (Bhattacharyya *et al.* 1993, 1999; Pal *et al.* 2012a; Pal 2017a) and north-eastern hills (NEH) areas (Bhattacharyya *et al.* 2000a; Sahoo *et al.* 2020) depict that with time, Vertisols (Typic Haplusterts) of HT does not transform to any other soil orders as long as the zeolites continue to supply bases, thereby preventing the total transformation of smectites tokaolin. However, upon complete depletion of zeolite stocks, the soils would gradually turn to acidic and kaolinitic and point towards Ultisols through a transitional stage of non-vertic Alfisols. Complete transformation of smectite to kaolinite is unlikely as silica is insoluble in acidic soil environment leading to unaltered Ultisols with kaolin (0.7 nm mineral interstratified with hydroxy-interlayered smectite, Sm–K) as the dominant mineral (Bhattacharyya *et al.* 1993; Chandran *et al.* 2005; Pal *et al.* 2012 a, 2014; Sahoo *et al.* 2020). This soil genesis model is justified when the published literature on Oxisols is critically re-examined. In PuertoRico Oxisols (Beinroth 1982), higher extractable acidity was observed, which is not in agreement with the predominance of kaolinite and gibbsite (Jones *et al.* 1982) because the extractable acidity is linked to the hydroxy-interlayered 2:1 layer silicate mineral (HIM). Therefore, report on the unavailability of HIM appears to be misleading because such soils adsorb moderate amount of added K (Fox 1982). K adsorption in soils can happen only when they contain vermiculite and/or hydroxy-interlayered vermiculite, HIV. Further examination of chemical data of Oxisols in Brazil (Macedo and Bryant 1987) indicates that the clay CEC of these soils is > 16 cmol (p+) kg^{-1}, thus the basic criteria of an oxic horizon is not fulfilled, and their placement in Oxisols soil order is therefore not well defined. (Buurman *et al.* 1996) and (Muggler 1998) reported pH (5.0 to 5.5)and CEC (4 to 6 cmol (p+) kg^{-1}), and zero amount of the exchangeable bases and extractable Al of selected Oxisols suggesting a zero value for the ECEC and base saturation, which is incompatible with the siliceous nature (30–50% SiO_2)of soils that sustain maize cultivation. It is also envisaged that Ultisols with time frame would phase towards Oxisols (Smeck *et al.* 1983; Lin 2011). But in view of contemporary pedogenesis of millions of years old Ultisols in HT environment of tropical India (Bhattacharyya *et al.* 2000a; Chandran *et al.* 2005; Pal *et al.* 2014; Sahoo *et al.* 2020), it will be highly improbable that Indian Ultisols would ever phase towards Oxisols. Therefore, consideration of Ultisols as the end stage of advanced soil weathering in HT climate has been a wise decision.

Ultisols are not chemically degraded

It is often conceived that acidity in Ultisols is a sign of chemical degradation that causes decline in fertility. While estimating the area degraded by acidity, soils with strong (pH <4.5) and moderate acidity (pH 4.5–5.5) only were considered and with this assumption, about 6.98 m ha area is affected by soil acidity, which constitute 9.4% of the total geographical area of the country (ICAR-NAAS 2010). Additionally, physical degradation in terms of soil loss of Ultisols is also reported in a menacing proportion. But the recent review clearly indicates that the soil loss from Ultisols (with clay enriched B horizons) is not at an alarming stage. However, they require improved management practices developed by researchers to upgrade and maintain their nutrient status and make efficient use of soil water to sustain crop productivity at an enhanced level (Pal 2017 b, c).It is evident when the OC rich Ultisols do respond to management interventions and support luxuriant forest vegetation, horticultural, cereal crops, tea, coffee and spices (Sehgal 1998). In view of such reality, it would not be prudent to class them as chemically degraded soils (Pal 2017c). This suggests that a mechanistic review of some pedochemical and mineralogical properties of Ultisols, is warranted to highlight some unique soil properties that actually support the above-mentioned successful land use enterprises.

Some unique chemical properties of Ultisols under forest vegetation/plantation crops

A recent review by (Pal 2021) indicates that the kaolin dominated Ultisols exhibit some unique chemical and mineralogical properties effecting higher OC stabilization, favourable retention and release of N, P and K and in arresting Al -toxicity problem of Ultisols, suggesting that Ultisols of India are neither less fertile nor chemically degraded soil substrate. On the contrary, these soils act as ecosystem providers to various economically profitable land uses in almost 33% of total geographic area of the country, and are capable of producing sufficient food stocks for a large Indian population (Pal 2021). Uniqueness of some soil properties that have really made Ultisols very thought provoking especially in view of formation of OC rich and acidic Alfisols and Mollisols instead of Ultisols under prolonged tropical weathering under HT climate in the Deccan basalt areas due to the constant supply of Ca-ions from Ca-Zeolites (Bhattacharyya *et al.* 1993, 1999, 2005, 2006).The abundance of Ca-ions in soluble and on soil exchange sites prevent the formation of Ultisols but it is difficult to reconcile the formation of OC rich and acidic Alfisols on base poor and non-zeolitic rock systems (schist and ferruginous quartzite) under well protected and natural forest ecosystem in similar HT climates of Andaman and Nicobar Islands (Chandran *et al.* 2021). Questions remain how the abundance of Ca-ions that creates base saturation (BS) > 35%, was ensured in the formation of acidic Alfisols in these islands? Does the microbial decomposition of huge litter fall from profuse rain forest vegetation provide enough Ca-ions? This intriguing situation needs some discussions especially in view of implications of these unique soil properties on the issues such as factors of OC enrichment in Ultisols, and possibility of phasing of Ultisols to acidic Alfisols if such soils are kept under protected and uninterrupted forest vegetation.

SOC enrichment in Ultisols

In the first 1.5 m soil depth, SOC stock of Indian soils is 29.92 Pg and soils of HT climates contain >1% OC and Ultisols have a share of about 1% (Bhattacharyya *et al.* 2000b). For organic carbon sequestration of Indian soils, some factors were identified. They are (1) profuse vegetation with adequate rainfall (>>1000mm) under HT climate and few months of cooler temperature, (2) presence of geogenic Ca-zeolites that enhances soil moisture by retaining smectite in humid tropical soils, (3) active inorganic part of soil builds the SOC through clay-organic matter complexation, (4) large specific surface area of smectites and vermiculites that helps in accumulation of greater amounts of OC than the non-expanding minerals (Pal *et al.* 2015). Soil substrate quality in terms of quality and quantity of expanding clay minerals is generally considered to be of fundamental importance in OC sequestration in HT climate with few winter months aided by profuse vegetation. But, higher build-up of OC is not observed even in smectitic semi-arid tropical (SAT) soils (Pal *et al.* 2015). Smectitic soils of SAT climate contain << 1% OC in the 0–30 cm depth. In contrast, zeolitic and acidic Vertisols (Typic Haplusterts) and Mollisols (Vertic Haplustoll/ Argiudolls) of HT climate show a similar value or an increase in OC content ~1% and 2.0%, respectively (Bhattacharyya *et al.* 2006) even in the dominance of kaolin mineral. (Barre *et al.* 2014) and (Pal 2019) point out the impact of phyllosilicate mineralogy on SOC protection, and therein highlight the importance of short-range order (SRO) minerals, metallic oxides and hydroxides and carbonates in SOC protection. In HT climate, due to predominance of H^+ and Al^{3+} ions, low amount of KCl extractable acidity is observed in many acid soils and their clay cation exchange capacity and effective cation exchange capacity values are less than 16 and 12 cmol (p+) kg^{-1}, respectively. Thus, according to the mineralogical criteria of (Smith 1986), kaolinitic mineralogy class is assigned to them (Bhattacharyya *et al.* 2009). This is however, not compatible with their unique capacity to sequester OC (Pal 2019). The total acidity of these soils as determined by $BaCl_2$-TEA shows a much higher values than determined by 1 N KCl. The CEC of soils and their clays as determined by the sum of total acidity and extractable bases measured by 1 N NH_4OAc (pH 7) show values much higher than 16 and 12, respectively (Chandran *et al.* 2005; Pal 2017b, 2019). Such greater values indicate their mixed mineralogy class and thus justify the unique role of clay minerals with hydroxy-interlayering in OC sequestration in soils. This fact becomes more explicit from the OC enhancement (weighted mean of the 0–0.3m soil profiles depth) with lower clay CEC values (as determined by soil CEC, NH_4OAC, pH 7), which are caused due to the increase of hydroxy-interlayering in the interlayers of 2:1-layer silicates(Figure 1). This unique relation strongly suggests a need to revise our current understanding on the role of layer silicate minerals in SOC stabilization (Barre *et al.* 2014).Thus, even a 0.7 nm mineral (kaolin) shows an enormous capacity to sequester more OC under acidic pedochemical environment caused by profuse vegetation under HT climate, than by fairly well crystalline smectite. Therefore, both acidity and interstratified clay minerals are important factors of OC sequestration in Ultisols of India. Enrichment of OC in Ultisols of western Amazon regions under tropical rain forest is also associated with hydroxy-interlayered 2:1 clay mineral (Marques *et al.* 2002). The million years old Ultisols of NEH areas (Bhattacharyya *et al.* 2000a; Manpoong and Tripathi 2019; Sahoo *et al.* 2020) and southern India (Chandran *et al.* 2005; Shamsudheen *et al.* 2007; Nair *et al.* 2019; Vasundhara *et al.* 2020) are enriched with OC (~1% to 3.1%) in the 0–30 cm depth, which manifests a quasi-equilibrium value under natural forest cover and also under plantation crops.

Recent research suggests that a better turnover rate of OC in Ultisols of tropical ecosystems is because of the interaction between the disproportionally large amount of organic matter and reactive species of Al oxides and hydroxides (Souza *et al.* 2017). However, a significant role of Fe and Al oxides/hydroxides in hydroxy-interlayering of smectite and vermiculite is evident from the predominance of hydroxy-interlayered smectite (HIS) and vermiculite (HIV) and kaolin in Ultisols (Pal 2017b, 2019). Therefore, the simultaneous formation of HIV, HIS and kaolin through hydroxy-interlayering, and retention of high amount of OC by such oxides and hydroxides is fascinating. In order to have a better understanding on this issue, Andisols developed from secondary Al and Fe oxides of earlier lateritic weathering cycle under the HT climate of the Nilgiri Hills situated in southern India (Caner *et al.* 2000), is a suitable reference to discuss. These authors explained that more recent climate change-induced complexation of organic acids with Al and Fe oxides favours the higher accumulation of organic matter in these soils. The production of enough metal-humus complexes induced the andic properties in soils. The clayey Andisols are highly acidic and have very high content of OC (8 to 14% in the 0–30 cm of soil profile). Such soils have considerable amounts of HIV clay minerals with moderate to high clay CEC > 30 but <65 cmol (+) kg^{-1} (Caner *et al.* 2000). These authors explained the OC enrichment even in presence of HIV, which is basically due to metal-humus complexes because in acidic soil conditions, Fe and Aloxides serve as a good source of positively charged metal cations for metal-humus complexation (Oades 1989; Chatterjee *et al.* 2014; Kleber *et al.* 2015; Shimada *et al.* 2022). SOC sequestration in some of the Indian non-acidic smectitic Vertisols and Inceptisols with predominance of mica has also been linked to amorphous Al and Fe oxides (Chatterjee *et al.* 2013) and poorly crystalline layer silicate minerals (Datta *et al.* 2015) like in Andisols. During the acidic tropical weathering of soils, Fe, and Al hydroxides are released and remained as positive cations (Barnhisel and Bertsch 1989). These positively charged hydroxides then enter the interlayer spaces of smectite and vermiculite when the pH is 5.0–6.0 and 4.5–5.0, respectively (Rich 1968; Pal *et al.* 2012b). Such small hydroxyl ions are produced at low pH (Rich 1960; Vinnet *et al.* 2016). For SOC sequestration, soil acidity is one of the major factors (Rasmussen *et al.* 2018; Malik *et al.* 2018) as acidity would dissolve primary and layer silicate minerals to form SRO and hydroxy-interlayered material (HIM) that are essential for SOC stabilization.

Higher accumulation of OC in acidic soils as compared to non-acidic soils under forest highlights an important role of HIV, HIS and kaolin in OC sequestration than partially hydroxy-interlayered and expanding crystalline clay minerals (Pal 2019). Finally, this suggests that acidity in soil environment plays the key role in carbon sequestration (Kleber *et al.*2015).

Acidity, clay illuviation, exchangeable cations and base saturation

Indian Ultisols are acidic with pH (in water) ranging from 4.0 to 5.8, and thus, they are less saturated with basic cations as evidenced from their base saturation (BS) at < 35%. Occurrence of Ultisols on base rich rock system like the Deccan basalt, calc-gneiss rock and limestone, even after prolonged weathering for millions of years under HT climate, is very rare. Such prolonged weathering however ends with the formation of OC rich and acidic Alfisols and Mollisols with BS > 35 under agricultural land uses and natural forests (Pal *et al.* 2014). Many Ultisols have clay-enriched B-horizon (Table 1): however, identification of their argillic horizons as reflected in the presence of clay skins is seldom straightforward while identifying them in the field of tropical India (Bhattacharyya *et al.* 1994; Sen *et al.* 1994) and elsewhere (Beinroth 1982; Eswaran 1972; Rebertus and Buol 1985). In situations, where identification of clay skins is difficult, the clay illuviation process can be confirmed by the appearance of pure void argillans in soil thin section study (Pal *et al.* 1994). However, the presence of pure void argillans, if any in Ultisols is not a result of current pedogenesis (Kooistra 1982; Eswaran and Sys 1979), suggesting that clay illuviation as a current pedogenic process in Ultisols is not possible (Pal *et al.* 2014).Only under slightly acidic to moderately alkaline pH conditions and very low electrolyte concentration dispersion of the clay particles takes place (Eswaran and Sys 1979). Therefore, at the initial stage of soil formation the downward movement of the dispersed clay particles in Ultisols occurred under moderately alkaline pH (Pal *et al.* 2014). Because of doubtful presence of clay skins such soils were often inappropriately placed in the US Soil Taxonomy by undermining possibly the major pedogenetic process on a stable geomorphic surface. To resolve this enigmatic issue, the US Soil Taxonomy introduced the 'Kandic'concept (Soil Survey Staff 1990), thereby providing a scope to drop the requirement for argillic horizon in Ultisols. But this way pedogenic reasons for the formation of clay enriched B-horizons still remain elusive in many Ultisols of Arunachal Pradesh, Assam, Meghalaya, Nagaland, Tripura (Sen *et al.*1997 a,b) and Manipur (Sen *et al.* 1994; Sahoo *et al.* 2020) in the NEH regions and in the southern peninsular states Karnataka (Eswaran *et al.* 1992; Kharche 1996; Shiva Prasad *et al.* 1998), Tamil Nadu (Natarajan et al. 1997), Kerala (Eswaran *et al.* 1992; Krishnan *et al.* 1996). Therefore, there is a need for a comprehensive micro-morphological study of Ultisols in India to unravel the pedogenic processes that would better explain the cause of the development of the clay enriched B-horizons rather than solely depending on the inductive reasons for the presence/absence of clay skins (in field mostly identified by 10x hand lens)(Pal 2022). It can be reasoned that the enrichment of clay in the B-horizons of Ultisols is the result of movement of clay particles at the early stage of soil formation under alkaline pH condition. With the advancement in weathering under HT climate, basic cations from such horizons were leached downwards, and the resultant acidic solum is preserved with BS < 35%. In view of such pedogenic processes, content of both EB and BS in Ultisols would be the least in surface horizons likewise in many acidic Alfisols developed on zeolitic Deccan basalt (Bhattacharyya *et al.* 1993, 1999, 2005).In contrast, depth distribution of EB, BS, $BaCl_2$-TEA exchange acidity and OC% in Ultisols show an upward increase, in general (Table 1). Such observation is not uncommon in many Ultisols under forest and plantation crops in southern India (Shamsudheen *et al.* 2007; Nair *et al.* 2019; Vasundhara *et al.* 2020) and NEH regions (Sen *et al.* 1997a-c) where BS is > 35% (based on NH_4OAC CEC method) and more EB (especially of Ca ions)in their surface horizon. Enrichment of BS little > 35% in the surface horizons is often observed in Indian Ultisols (Chandran *et al.* 2005; Sen *et al.* 1997 a-c), likewise in Ultisols of the western Amazon regions under tropical rain forest (Marques *et al*. 2002). Microbial decomposition of huge plant biomass under profuse forest vegetation of HT climate, release carbonaceous acidic exudates, which cause acidity in the immediate rhizosphere. Such exudates also act as a source of carbon (Chatterjee *et al*. 2013; Velmourougane *et al*. 2017; Panchal *et al*. 2022) and influence carbon sequestration by partially breaking the crystalline clay structure to form SRO minerals with higher carbon sequestration potential (Chatterjee *et al*. 2013; Souza *et al.* 2017). It is thus evident from considerable OC enrichment of Ultisols (Table 1). In acidic soil environment, SRO minerals (Fe and Al oxides / hydroxides) as positively charged cation cause hydroxy-interlayering of smectites and vermiculites, which on further weathering transform to kaolin (Pal *et al*. 2014). Because of formation of hydroxy-interlayered layer silicates, Ultisols show considerable amounts of exchange acidity by $BaCl_2$-TEA extraction method (Table 1).However, such pedochemical environment fails to explain the typical depth distribution of EB and BS in Ultisols. Explanation so far proposed (Nayak *et al*. 1996; Reza *et al*. 2018) suggests the contribution of bases from the decomposition of forest litter falls. Therefore, a major role of vegetation (bio cycling)among the other soil forming factors creates unique soil properties like acidity with concomitant increase in OC content and EB and BS in the surface horizons of Ultisols (Miller 1983). Superior role of vegetation under forest is quite evident in enriching EB and OC in surface horizons of Andisols of Nilgiri Hills of southern India even when these soils are developed primarily on base poor Fe and Al oxides (Caner *et al*. 2000; Paul 2023).On base poor rock systems, similar role of forest vegetation in enriching EB and OC in surface horizons of acidic soils is also evident in OC rich and acidic Alfisols of Andaman and Nicobar Islands (Chandran *et al*. 2021). It is an intriguing issue in pedological parlance and thus, in the following section the development of acidic Alfisols are discussed to showcase the superior role of vegetation in preventing (a) the formation of Ultisols, (b) a possibility of phasing of Ultisols to acidic Alfisols under undisturbed forest system, and (c) providing hints for C enhancement strategies for Indian tropical soils.

Formation of acidic Alfisols on base poor rock systems under protected rain forest area of Andaman and Nicobar Islands: an example of superior role of vegetation in pedogenesis and C enhancement

Under intense weathering of base poor metamorphic and sedimentary rock system under forest vegetation of HT climate, formation of OC rich Ultisols with more EB and BS in their surface horizons is possible because of availability of basic cations through the microbial decomposition of litter falls of forest species. In contrast, weathering of base rich rock system like Deccan basalt results in the formation of only acidic Alfisols/ Mollisols due to the abundance of basic cations available through base rich rock system, and prevents the formation of Ultisols under similar HT climate continued even for millions of years. In such Alfisols and Mollisols developed on zeolitic Deccan basalt show an increasing BS with soil depth (Bhattacharyya *et al.* 2005, 2006; Pal 2017a). Thus, the occurrence of million-year-old OC rich and acidic Alfisols on base-poor metamorphic rocks under forest vegetation of Andaman and Nicobar Islands, which remained undisturbed by human interference in HT climate (Das *et al*. 1996; Chandran *et al.* 2021), is a unique case in pedology. The acidic Alfisols of the islands have similar chemical and clay mineralogical characteristics of Ultisols (acidic pH, high OC content, considerable amounts of $BaCl_2$-TEA exchange acidity and hydroxy-interlayered layer silicate minerals) except their high EB and BS (> 50%). However, the depth distribution of EB and BS is in contrast to those observed in acidic Alfisols and Mollisols of the Deccan basalt (Table 1).Formation of such soils provides a distinctive example in pedology as their pedogenic processes are primarily influenced by vegetation under forest ecosystem in alliance with well distributed precipitation, which enhances OC status, creates high acidity and make highly base saturated soils (> 35%) by adding metal cations through litter falls. Acid pedo-chemical reaction produced Al and Fe oxides/ hydroxides by breaking the crystalline clay minerals, which later got trapped in the interlayers of 2:1 clay mineral making clay minerals as HIV and HIS, however, with much less amounts of kaolin (Fig. 2) unlike in Ultisols of southern India and NEH regions where kaolin is either a dominant (Chandran *et al.* 2005; Bhattacharyya *et al.* 2000a, Figure 3) or sub-dominant (Sahoo *et al.* 2020) clay mineral (Fig. 4). The relative abundance of HIV and kaolin in million-year-old acidic Alfisols and Ultisols, indicates that more enrichment of basic cations in Alfisols than in Ultisols through litter falls, prevented the total transformation of HIV/HIS to kaolin in Alfisols. The superior role of vegetation in persistence of acidic but base rich Alfisols of Andaman and Nicobar Islands prompts us to envision how inland Ultisols under prolonged and protected forest vegetation (like in Andaman and Nicobar Islands) with clay enriched B-horizons (with > 30% clay), could phase towards Alfisols after gaining bases from leaching in the surface horizons.

Way forward for enhancement strategies of OC sequestration

The basic knowledge in pedology as discussed above, provides a way forward how the forestry species under the least human disturbances can help in building enhancement strategies for OC sequestration even in Ultisols of tropical India to curb the ill effects of climate change by arresting the emission of CO_2 through decomposition of soil OC. This suggests that possible phasing of Ultisols to Alfisols under protected profuse forest vegetation may become an equal or a better ecosystem service provider than typical Ultisols. This suggests that changing land use from agriculture to forestry under protection and plantation crops may lead to large SOC accumulations by doubled or trebled in a little over a century (Poulton *et al.* 2018). Under natural sparse forest vegetation, red ferruginous Alfisols (Chandran *et al.* 2009) and Vertic Inceptisols (Naitam and Bhattacharyya 2004) even in the Indian SAT climate, show OC concentration of 1.78% and 0.81% (in 0–30 cm soil depth) over a century's time, respectively. But the land use change from agriculture to forestry would cause an uncertainty in food security goals of the Indian sub-continent. It is modelled that to feed the burgeoning human population, by 2050, global natural ecosystems of 10^9 ha require to be brought under agriculture (Tilman *et al.* 2001), especially by the farmers in the tropics through crop rotation, agroforestry and mulching (Woomer *et al.* 1994). A loss of biodiversity in Ultisols and acidic Inceptisols areas of southern India (Nair *et al.* 2016) is recently observed when natural forests are converted to coffee plantation. Such conversion resulted in lowering of OC content and available nutrients, which made soils in medium quality class whereas earlier natural forests had higher soil quality index (Karthika *et al.* 2020). (Powlson *et al.* 2022) are of the opinion that to maintain sustainable soil health in arable soils, it is essential to maintain SOC as high as practically feasible. These authors concluded that in the vast majority of situations under arable land it would not be wise to expect to maintain pre-clearance OC levels under forest system and to maintain global SOC stocks, it is more vital to reduce current rates of land clearance to produce necessary food from existing agricultural land in a sustained manner. This practice would however demand stringent measures to reduce expansion of agriculture through deforestation, tilling of natural grasslands or draining of peats and wetlands (Powlson *et al.* 2022). This way of preservation of natural or semi-natural ecosystems with their large SOC stocks along with various ecological benefits would be possible only when a reversal of the decades' long trends in unwise utilization of various lands happens (Noon *et al.* 2021). (Powlson *et al.* 2022) thus emphasised that the proposed strategy is more pragmatic than a flawed understanding that SOC stocks under natural forest conditions can be reproduced in soils presently engaged for food production even by following appropriate management protocols.

Table 1. Some selected soil properties of representative Ultisols and Alfisols of tropical humid climate of India

Horizon	Depth (cm)	pH (H_2O)	Organic Carbon (%)	Extractable bases (NH_4OAC) (Cmol(+)/kg)	Exchange acidity ($BaCl_2$-TEA) (Cmol(+)/kg)	Base saturation (NH_4OAC) (%)
Pedon 1: Kanjirapally Series-Ustic Kandihumults- under rubber plantation in Kerala – on gneissic rock system [1]						
Ap	0-13	4.8	2.35	0.98	11.2	21.7
Bt1	13-32	4.4	1.86	0.61	10.4	17.1
Bt2	32-56	4.5	1.50	0.52	9.9	14.0
Bt3	56-83	4.5	0.90	0.54	8.9	13.2
Bt4	83-112	4.4	1.11	0.51	6.6	13.2
Bt5	112-150+	4.7	1.22	0.67	7.0	16.8
Pedon 2: Suongpeh Series-Typic Hapludults – under forest cover in Manipur-on weathered shale/colluvium[2]						
A	0-17	4.9	2.5	4.67	Not available	34
Bt1	17-35	4.9	0.8	2.70	Not available	24
Bt2	35-50	4.8	0.4	2.89	Not available	22
Bt3	50-70	5.0	0.4	2.46	Not available	22
Bt4	70-110	5.0	0.4	1.29	Not available	13
Pedon 2: Bench mark Ultisols-under forest cover in Meghalaya on gneissic rock system[3]						
A1	0-11	5.0	4.1	2.4	Not available	40
B1	11-38	5.1	0.3	1.9	Not available	70
Bt2	38-70	5.1	0.2	1.0	Not available	34
Bt3	70-136	5.1	0.3	1.0	Not available	34
C	136-190	4.9	0.1	1.4	Not available	28
Pedon 1: Basantipur Series - Hapludalfs – under forest cover in Andaman & Nicobar Islands on schist and ferruginous quartzite [4]						
A	0-7	5.3	4.10	16.34	11.51	97
Bt1	7-29	4.9	1.40	12.22	10.66	50
Bt2	29-50	4.7	1.74	13.05	16.41	52
B3	50-75	4.9	0.72	15.63	17.63	84
C	75-100	5.0	0.41	17.80	14.75	77

[1] Adapted from (Chandran *et al.* 2005); [2] Adapted from (Chandran *et al.* 2013); [3] Adapted from (Bhattacharyya *et al.* 2000a); [4] Adapted from (Chandran *et al.* 2021)

[1] Adapted from (Chandran *et al.* 2005); [2] Adapted from (Chandran *et al.* 2013); [3] Adapted from (Bhattacharyya *et al.* 2000a); [4] Adapted from (Chandran *et al.* 2021)

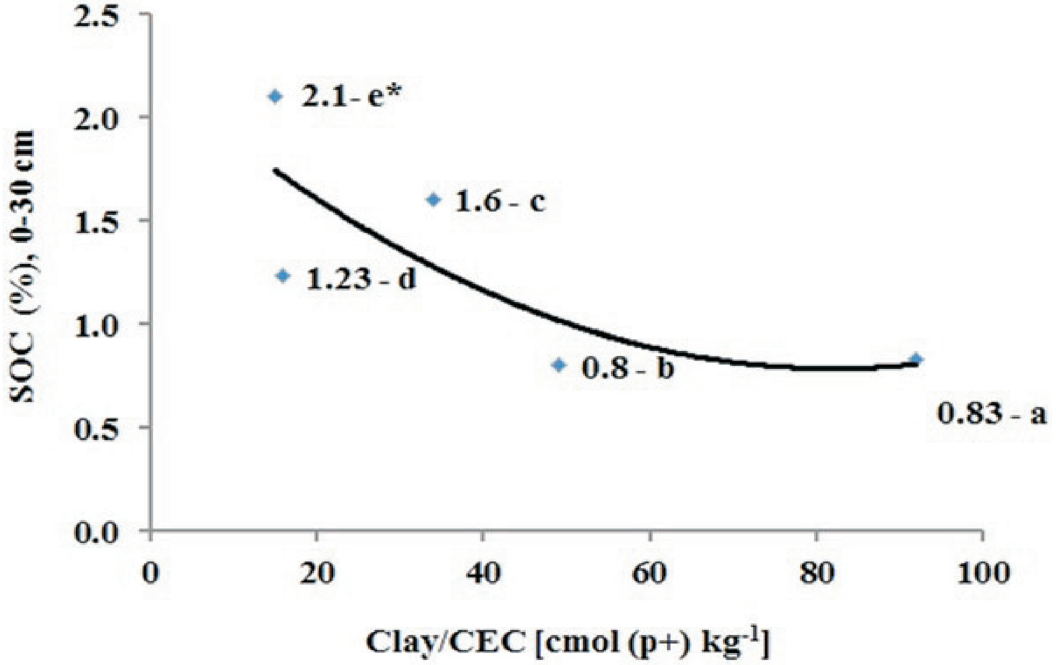

Fig. 1. Relation between OC (%) and clay CEC (cmol (p+) kg^{-1}) in the 0–30 cm of pedon depth ∗(a) Typic Haplusterts of SHM climate, (b) Typic Haplusterts of HT climate, (c) Vertic Argiudolls of HT climate, (d) Typic Haplustalfs of HT climate and (e) Ustic Kandihumults of HT climate. a, b Adapted from (Pal *et al.* 2009); c, d Adapted from (Bhattacharyya *et al.* 2005); e Adapted from (Chandran *et al.* 2005).

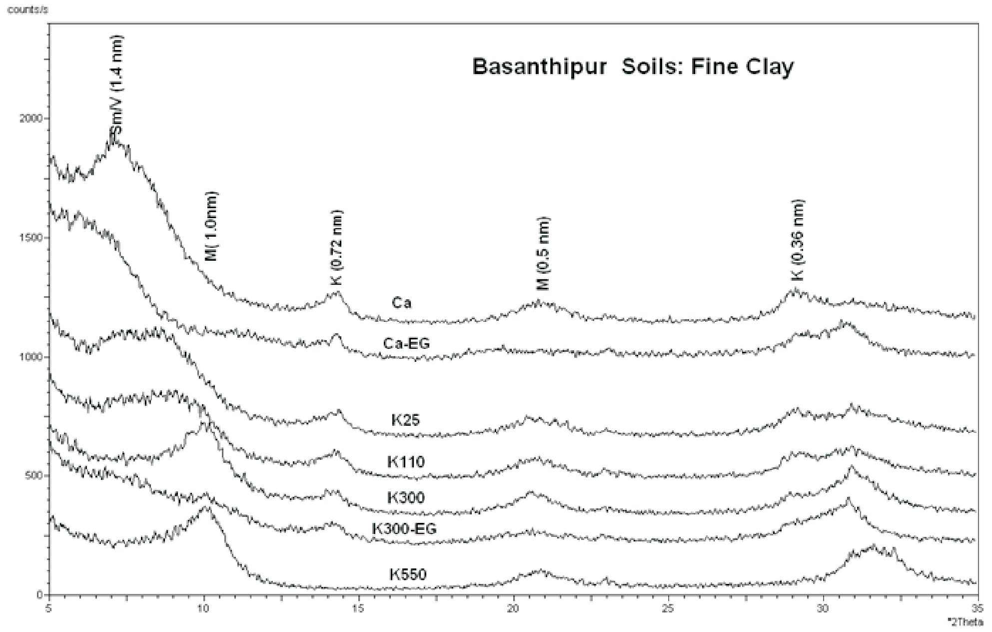

Fig.2. Representative X-ray diffractogram of fine clay fractions of Basanthipur soils, A&N Islands (P1): Ca, Ca-saturated; CaEG, Calcium saturated and ethylene-glycol-solvated; K25, K110, K300, K550, K saturated and heated to 25°C, 110°C, 300°C, 550°C, respectively; K300-EG, K saturated and heated to300 ° C and glycolated; V-vermiculite, Sm-smectite, M mica, K-kaolin. Adapted from (Chandran *et al.* 2013).

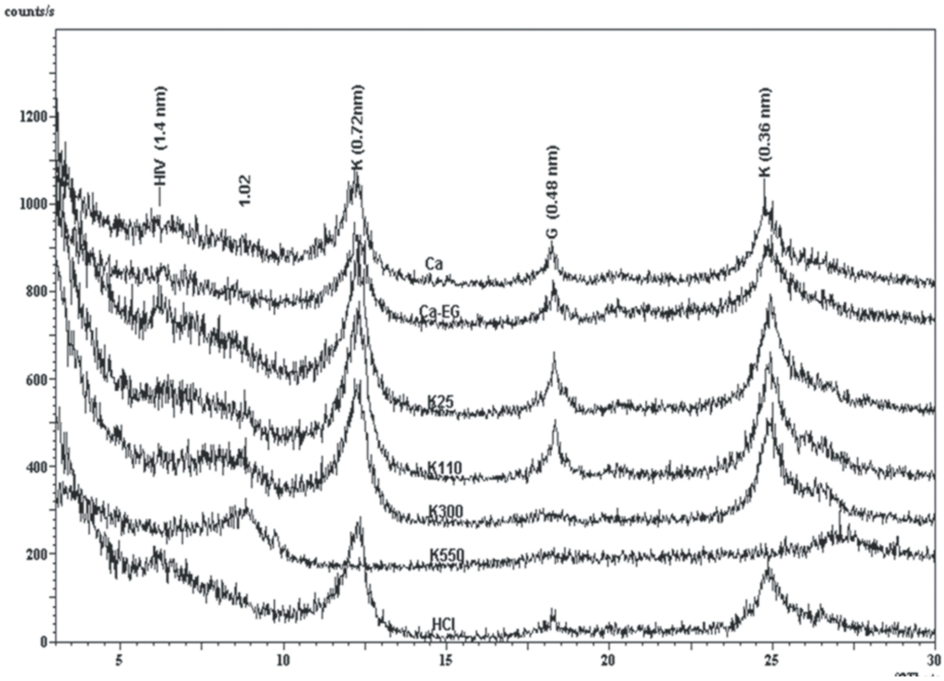

Fig. 3. Representative XRD diagrams of fine clay fractions of Kerala Ultisols of HT climate: Ca, Ca–saturated; Ca-EG, calcium saturated and ethylene glycolated; K25, K110, K300, K550, K-saturated and heated to 25^0,110^0,300^0,550^0 C, respectively; HCl, treated with 6N HCl for 30 minutes at 90^0C. HIV, hydroxy-interlayered vermiculite; M-HIV, mica-HIV minerals; M, mica; K, kaolin; G, gibbsite. Adapted from (Chandran *et al.* 2005).

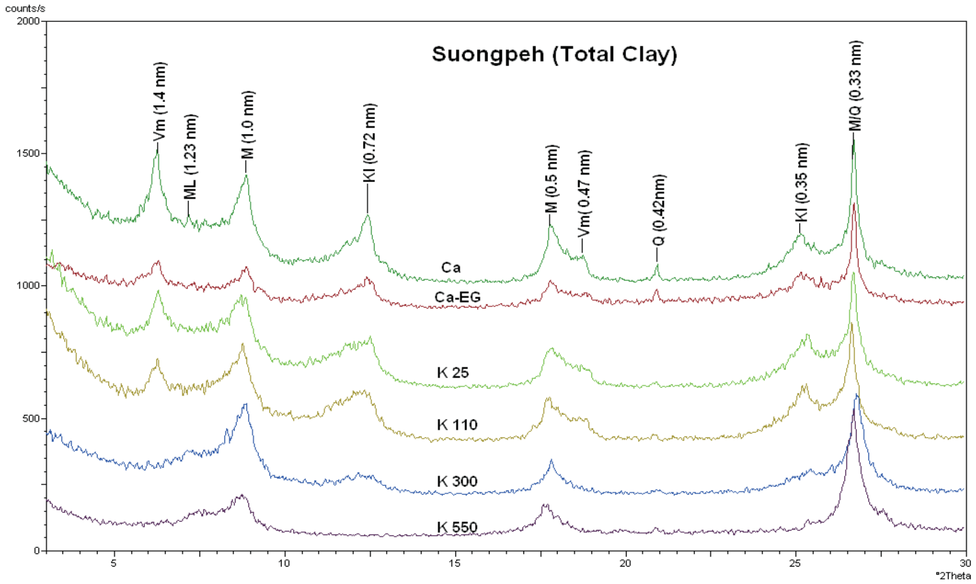

Fig.4. Representative X-ray diffractogram of total clay of Ultisols (Suongpeh series) of Manipur: Ca, Ca-saturated; CaEG, calcium saturated and ethylene-glycol-solvated; K25, K110, K300, K550, K saturated and heated to 25°, 110°, 300°, 550°C, respectively; Vm-vermiculite, ML-mixed layer, M-mica, KI-kaolin, Q-quartz. Adapted from (Chandran *et al.* 2013).

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Author contributions

Dilip K. Pal: Conceptualization; Writing-original draft; Writing, review and editing.
Padikkal Chandran: Data curation: Formal analysis: Writing, review and editing.
Ashim Datta: Formal analysis; Writing, review and editing.
Ranjan Paul: Formal analysis; Writing, review and editing.

Conflict of interest

The authors declare no conflict of interest.

ORCID

*Dilip K. Pal:*Orcid Id: https://orcid.org/0000-0002-7048-9812
Padikkal Chandran: https://orcid.org/0000-0003-3287-117X
Ashim Datta: https://orcid.org/0000-0002-1843-9981
*Ranjan Paul :*https://orcid.org/0000-0001-6928-3799

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