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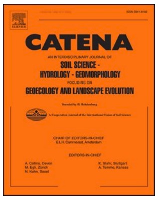

Taxonomy and genesis of soils in contrasting ecosystems of Southern Western Ghats, India

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ABSTRACT

Clay minerals formed during soil formation are imprints of ecosystem functioning and pedogenic processes in landscapes. The study evaluated the variations in taxonomy, soil weathering and pedogenic changes in contrasting forest soils in the Southern Western Ghats, India. Three different forest systems with comparable soil-forming factors vis-a-vis evergreen, moist deciduous and a man-made system (rubber plantation) were evaluated for physical, chemical, morphological, and pedogenic characteristics of the related soils. Soil profiles were dug up to 1.50 m in the selected ecosystems and horizon-wise soil samples were collected. All the pedons were classified in the soil order of Ultisols and subclassified as Ustic Palehumult (evergreen forest), Ustic Haplohumult (moist deciduous forest) and Typic Haplustult (rubber plantation), respectively. The soil pH was found to be acidic in all the ecosystems ranging from 4.6 to 5.8. Chlorite, hydroxyl interlayered vermiculite (HIV), mica, kaolinite, feldspars, gibbsite and quartz dominated the mineral assemblages in the clay fractions of soils of natural forest systems. The losses of SiO_2 in the non-clay fraction and corresponding enrichment of the component in the clay-sized fraction in all horizons indicated an active continuous weathering process in all the systems of this region. Clay accumulation by way of formation and translocation was highest in the lower horizons of the soils of evergreen (Bt2 at a depth range of 28–57 cm) and moist deciduous (Bt3C at a depth range of 23–150 cm) forest, whereas it was highest at Bt1 at a depth range of 15–28 cm in the plantation soil. The depth variations in the clay formations in natural and manmade forest systems provide insights into ecosystems regulated profile development under natural and man-made systems in the humid tropics, a vital information gap hitherto in soil pedogenesis of the humid tropics. Such pedogenic assessments along with the factors responsible for such modifications would provide important inputs in developing soil health management strategies in the humid tropics.

1. Introduction

Geomorphological and pedogenetic interactions fundamentally ties soils and landforms at the landscape scale (Vanwalleghem et al., 2013). This notion was present since the early models of soil (Hilgard, 1914; Glinka, 1927; Milne, 1936; García-Gamero et al., 2021), and implied that distinct soil types are associated with different landforms (Gerrard, 1992). The earliest models took an empirical approach that considered soil formation as a product of state factors (climate, organisms/biota, relief, parent material and time) or processes such as erosion, mineral dissolution and soil organic matter decomposition. As such, quantitative evaluation of soil formation processes allows one to assess the long-term impact of vegetation, climate, and human activities on soil systems in landscapes.

Pedogenic characteristics, a subject of intense debate, could be influenced by state factors. Though pedogenic characteristics in the early stages are greatly influenced by the mineralogical and chemical peculiarities of the geologic parent material, factors such as climate and vegetation would be relatively more influential over time (Maniyunda et al., 2014). Climate would have a strong influence on soil properties by way of its regulations on biological (both plant and soil) and hydrological processes and affects soil physical, chemical and biological properties, including clay formation and pedogenesis (Smith et al., 2002; Lin, 2010; Bojko and Kabala, 2016). Similarly, vegetation affects soil properties by way of root exudation, root activity and surface litter composition (Quideau et al., 2001; Onweremadu and Peter, 2016) and

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exerts influences on the soil morphology, biochemistry, mineralogy and sustainability of soil resources (Quideau et al., 2001; Abril et al., 2013; Vazquez et al., 2013). Biosequences create microclimates through shading of soil surface (Buol et al., 1997), regulate soil biota (Coleman and Crossley, 1996), wind movement and water cycling and as such the vegetation type, age and landforms can create contrasting soil and pedogenic characters (Upadhaya et al., 2008; Onweremadu and Peter, 2016).

Besides climate and vegetation, the topographic position of soils is regarded as an essential factor in soil formation. The soil arrangements into the catenary sequence in accordance with their position on the slope have been a major guiding tenet in pedogenetic research since Milne et al. (1936) established the consistency and regularity of these sequences in landscapes. Subsequently, catenas have been considered as a combination of slope and spatial flux of materials (solutes, colloids and particles) wherein the soil properties gradually change depending on the geomorphic, geological, biological or atmospheric processes (Wysocki and Zanner, 2006; Bojko and Kabala, 2016). For example, Khomo et al. (2011) showed that there occurs an increase in the intensity of redistribution of clay from top to bottom in hillslopes with an increase in rainfall and thereby influencing most of the other soil properties (Amundson et al., 2007; Scholten et al., 2017). Another factor, the slope aspect also affects the microclimate with its influences on soil temperatures and moisture (Carletti et al., 2009; Barbosa et al., 2015; Zhao and Li, 2017).

In recent times, attempts have been increasingly made to assess these complex processes and interactions in soil formation in specific landscapes (Doula and Sarris, 2016). The parent materials in a profile would comprise of a variety of materials, hence assessment of the initial state of the soil may be considered the most important prerequisite in any profile development study. Evaluating the mineralogical, physical, chemical and morphological changes would further aid in establishing the sequence of pedogenic processes in these systems. Soil development as a major product of weathering would proceed through specific stoichiometric relations of non–clay fractions (as the reactant) and clay-sized fractions (as the product) and such estimations would provide clear indications of the amount of parent material weathered and the type of minerals formed thereupon. However, such studies relating profile characteristics, mineral distribution, vegetation characteristics and their interrelations in humid tropical soils are still scarce.

The Southern Western Ghats cover an area of 7000 km^2 and form a block forest cover that includes a diversity of natural ecosystems (ranging from tropical wet evergreen forests to montane grasslands) and agricultural systems. Being the base matrix, soils sustain these forests and agricultural ecosystems with a continuous and adequate supply of nutrients by weathering of minerals (Mukesh et al., 2011; Moghimi et al., 2013; Ramady et al., 2014). Though the area has a tropical humid climate and had a conducive weathering environment for millions of years, there have been no reports of extremely weathered soils satisfying taxonomical criteria to place them in the soil order of Oxisols (Varghese and Byju, 1993; Velayutham and Bhattacharyya, 2000; Chandran et al., 2005), posing pertinent questions on pedogenesis and transformation in the tropics. The present study hypotheses that contrasting forest types in a landscape would have distinct imprints on soil profiles and attempts to assess the taxonomy, pedogenesis and mineralogical variations in three different ecosystems in the southern Western Ghats.

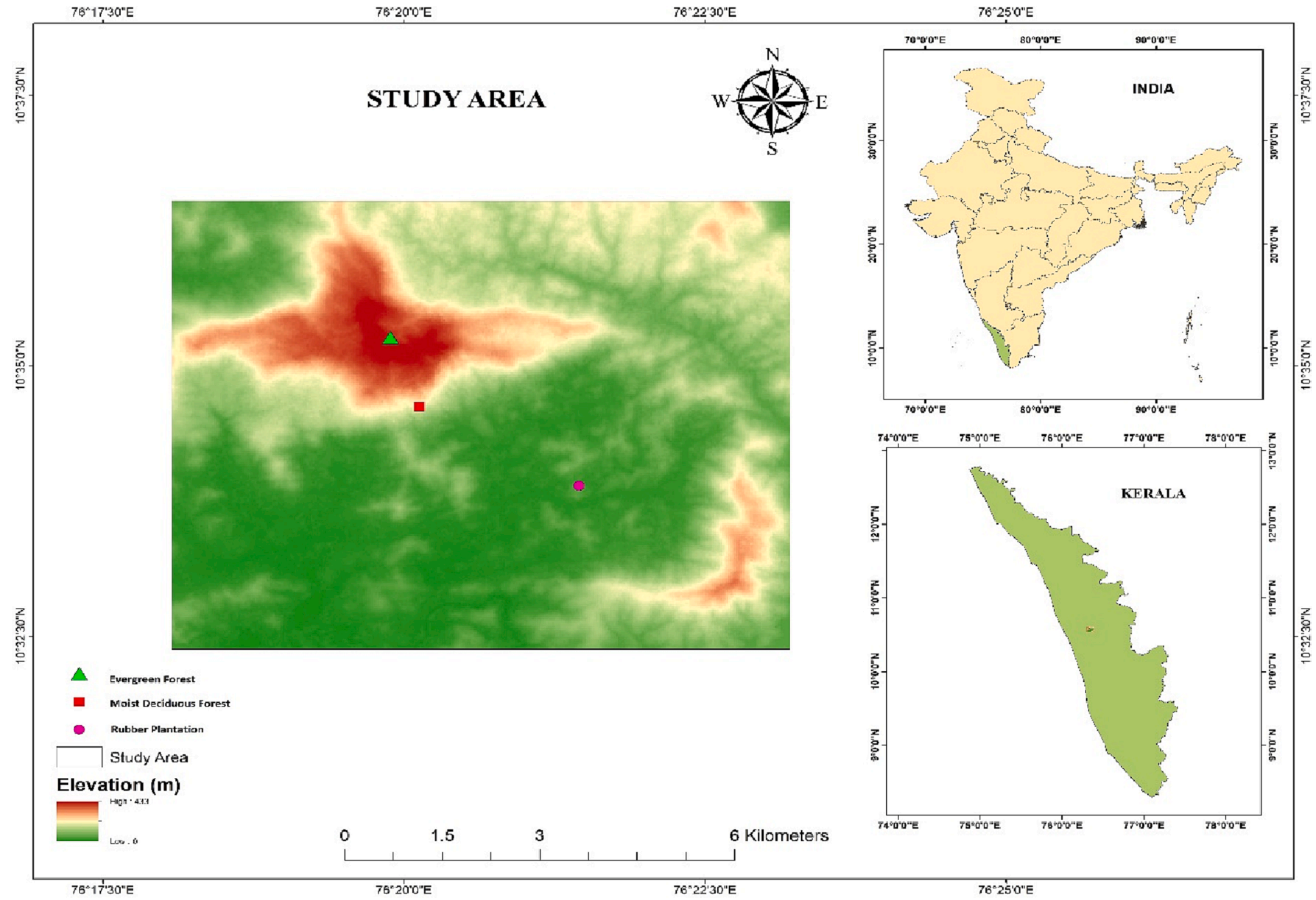

Fig. 1. - Study area in the southern Western Ghats.

2. Materials and methods

2.1. Study area and sample collection

Three contrasting forest types – evergreen forest (76.331455°E, 10.587632°N; 479 m a.s.l), moist deciduous forest (76.33549°E, 10.577061°N; 259 m a.s.l), and a rubber plantation (76.357565°E, 10.56485°N; 60 m a.s.l) - were selected for soil sampling in the northern high hills landscape of Southern Western Ghats (Fig. 1). The selected systems represent the major natural forest and man-made plantation types in the Western Ghats. In evergreen forest, *Euvodia lunuankenda, Artocarpus heterophyllus, Calophyllum elatum, Bischofia javanica, Hopea ponga, Mesua ferrea, Mangifera indica*, and *Myristica dactyloides* were found as the dominant species. In moist deciduous forest, tree species such as *Tabernaemontana heyneana, Dillenia pentagyna, Strychnos nux-vomica,* and *Xylia xylocarpa* were observed. The rubber plantation (*Hevea brasiliensis*) was located at a lower elevation when compared to the other two forest systems. The rock type of the selected region was charnockite (an orthopyroxene granite). The annual mean temperature and rainfall were 25 °C and 2900 mm, respectively. The three soil profiles were dug up to 1.5 m keeping as many soil-forming factors as constant and samples were collected horizon-wise from the profiles (Fig. 2a–c).

2.2. Analytical methods

Soil samples collected from the horizons were processed by removing the root fragments, air-dried, powdered, sieved (2 mm sieve), and used for physico-chemical and mineralogical analysis. Soil texture was determined using the hydrometer method (Bouyoucos, 1936) and the core method (volumetric cylinder method) based on mass–volume relationship was used to determine soil bulk density (Jackson, 1973). pH was assessed with water and KCl in a soil: suspension ratio of 1:2.5 by potentiometry (Jackson, 1973). Organic carbon was estimated by the wet combustion method (Walkley and Black, 1934). Cation exchange capacity (CEC) was determined by the neutral normal NH_4OAc (pH 7.0) saturation method, and percent base saturation (BS) was estimated as the ratio of basic ions to CEC (Chapman, 1965). The neutral normal NH_4OAc extracted Ca and Mg were estimated using atomic absorption spectrophotometry (Varian AA240), while K and Na were determined using a flame photometer (ELICO CL 378). The total exchangeable acidity of the soil is constituted of exchangeable H^+ and Al^{3+}. They were extracted using 1.0 N of KCl solution. Titration with a standard alkali was used to calculate the total exchangeable acidity. The Al^{3+} in the titrated solution was determined in the same extract by adding 1 N potassium fluoride solution followed by titration of released alkali with standard acid (Sarma et al., 1987). CEC, sum of cations (Ca + Mg + Na + K + TEA acidity), Effective Cation Exchange Capacity (ECEC = Ca + Mg + Na + K + Al), and total exchangeable bases/ CEC as sum of cations were also calculated.

For mineralogical studies, sand (coarse 2–0.6 mm and fine 0.6–0.02 mm), silt (0.02–0.002 mm) and clay (<0.002 mm) fractions were separated by sedimentation after sodium citrate-bicarbonate-dithionite treatment (Jackson, 1979). The separated sand and silt fractions were subjected to randomly oriented powder X-ray diffraction (Bruker AXS D8 Advance) with a Ni-filter and Cu-Kα radiation at a scanning speed of 2°2θ/min. Clay samples were saturated with (1) Ca and solvated with ethylene glycol, (2) K at 25 °C and heated to 110 °C, 300 °C, and 550 °C. Identification of clay minerals in different fractions were done following the criteria laid down by Jackson (1979) and estimated semi- quantitatively with standard samples (Dixon and Weed, 1989). The morphology of the clay-sized particles was determined with a scanning electron microscope (JEOL Model JSM-6390LV) (Bhattacharyya et al., 1994; Chandran et al., 2005; Rajkumar et al., 2014; Islam et al., 2022).

The classification of the soils was determined according to the protocols stipulated by Soil Survey Staff (2014). Total elemental analysis for clay and non-clay fractions was done using ICP-AES (Perkin Elmer Model: Aveo 200) after digesting the samples using hydrogen fluoride and nitric acid mixture in a micro digester (Perkin Elmer-Titan MPS). Using these results, the amount of clay formed in any horizon from 100 g of non-clay of the parent material (f), the amount of clay formed in the horizon which resulted in the present amount of non-clay in 100 g of soil

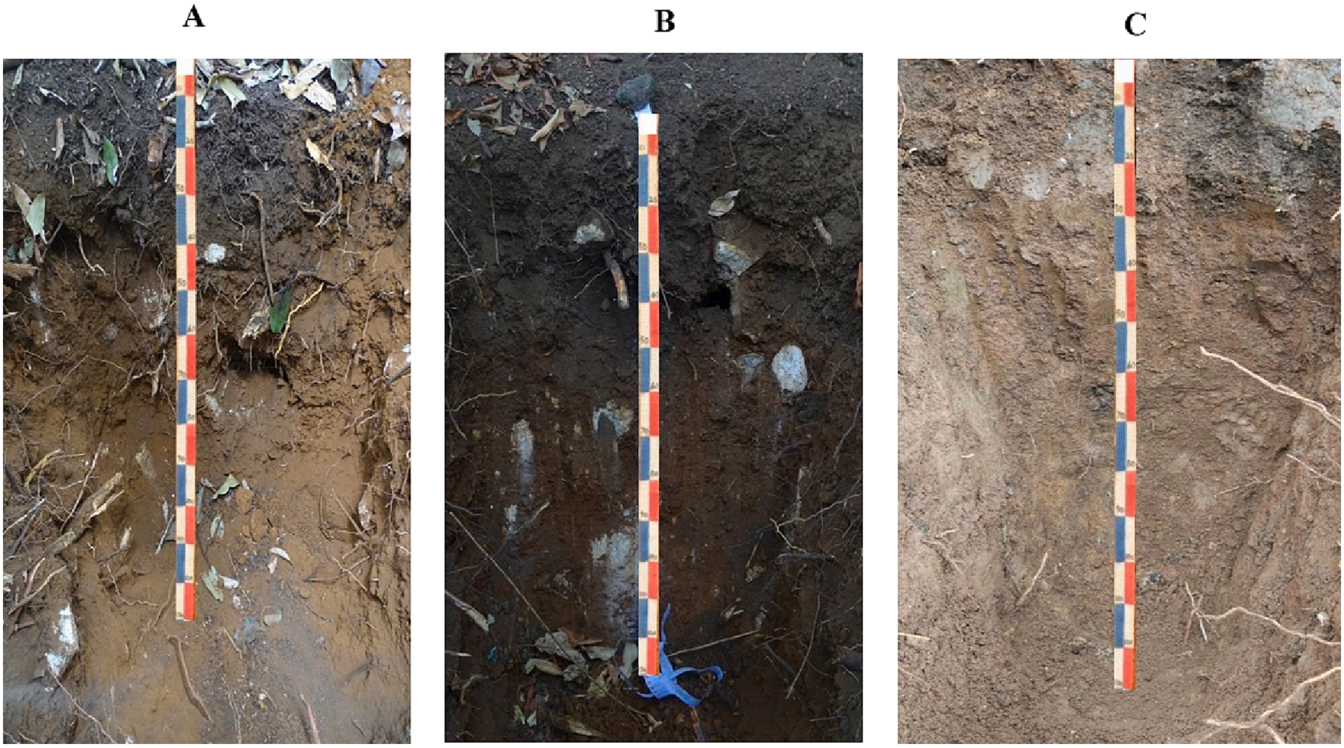

Fig. 2. Soil profiles of contrasting forest systems in the southern Western Ghats. (A) Evergreen forest, (B) moist deciduous forest, (C) plantation.

(F), the original amount of non-clay at the parent material before clay formation occurred in the horizon (O), amount of clay originally present and loss or gain of clay were calculated as below (Bear, 1964).

$$f = 100\ (a1 - Bb1)/(a2 - Bb2)$$

a1 = % SiO_2 in sand + silt of C horizon.
a2 = % SiO_2 in clay of assessed horizon.
b1 = % Fe_2O_3 in sand + silt of C horizon.
b2 = % Fe_2O_3 in clay of assessed horizon.
a3/b3 = B = % SiO_2 of (sand + silt) in assessed horizon/% Fe_2O_3 of (sand + silt) in assessed horizon.

$$O = (100/f) \times F$$

$$F = (f/(100 - f) * k)) \times (100 - d)$$

k = proportionality factor affecting the SiO2 content of the non-clay of assessed horizon due to losses/gains other than clay formation.
d = clay content of assessed horizon.

Amount of clay originally formed (g/horizon) = {(Amount of clay formed in profile- present clay in profile)/Amount of non-clay in profile} × Amount of non-clay originally present in each horizon.

Amount of clay formed = (F/100) × weight of present soil.
Amount of non-clay originally present = (O/100) × weight of present soil.

Loss or gain of clay (g/horizon) = (Amount of clay formed + clay originally present)- Amount of clay present.

Relative clay loss or gain (g/cc/horizon) = Loss or gain of clay/ original volume.

The assessed clay contents in the horizon contain the clay formed in situ from parent material and non-clay fractions, clay originally present in the parent material, and the clay gained by accumulation from outside sources and can be considered as the clay remaining in a particular soil after losses by depletion.

3. Results

3.1. Soil properties

The colour was found to range from 2.5YR to 7.5YR hue in all the collected soils (Tables 1–3). Sandy clay loam was the most common texture in the soil horizons of evergreen and moist deciduous forests, while in the rubber plantation soil, it varied from sandy loam to sandy clay loam. Analysis of the particle size distribution in different horizons of the profile showed that the sand-size fractions decreased with a concomitant increase in the clay content from top to bottom horizons in both the natural forest systems. The sand and clay contents varied from top to bottom horizons as 76–62% and 16–34%, respectively, in the evergreen forest and from 68 to 62% and 22 to 26%, respectively, in the moist deciduous forest. On the other hand, rubber plantation had an uneven distribution of sand and silt fractions along the profile.

Soil pH was found to be acidic in all the selected ecosystems and the values ranged from a minimum of 4.6 (Bt1 in the moist deciduous forest soil) to a maximum of 5.8 (Bt2 in the rubber plantation soil). KCl - pH was less than H_2O - pH in the soils of all the systems. The KCl - pH values of Bt2 in moist deciduous and Bt1 in rubber plantation exhibited distinctive values which were contrary to the trend of higher KCl - pH than its succeeding layers in the evergreen forest. In moist deciduous forest, the KCl - pH values were 4.0 and 4.2 in Bt2 and Bt3C horizons, respectively, and the rubber plantation gave values of 4.6 and 4.8 in Bt1 and Bt2, respectively. The Δ pH values indicated that the evergreen system soil had relatively larger amounts of amorphous materials (Δ pH range: − 0.7 to −1.3) among the selected forest systems, while the manmade rubber plantation had the least of these materials (Δ pH range: −0.3 to −1.0).

The organic carbon contents decreased from the top to bottom layers and varied as evergreen forest > moist deciduous forest > plantation in all the layers. The evergreen forest had the highest organic carbon content among the three systems and the values varied from 9.46% in the top A horizon (0–9 cm) to 1.74% at a depth of 57–150 cm (Bt3C horizon). In rubber plantation, there was a 60% variation in the organic carbon between the surface (0–15 cm) and subsurface (15–28 cm) layers.

3.2. Soil classification

Classification of the soil pedons was done based on their physical–chemical and morphological characteristics by referring to the Keys to Soil Taxonomy (Soil Survey Staff, 2014). In the evergreen forest, dark brown colour (7.5YR 4/1) was observed in the A horizon, which varied to light yellowish-red colour (5YR 4/6) in the Bt3C horizon. The presence of roots was observed up to the Bt2 horizon. Undecomposed organic debris was observed in A horizon. The percentage of clay in the evergreen forest pedon increased from BA (26 %) to Bt1 (30 %) horizon. The texture of the Bt1 horizon was sandy clay loam indicating clay illuviation with the presence of clay films, hence classified as an argillic horizon. In the Bt2 horizon of this system, organic carbon% was found to be lower than the preceding upper horizon (Bt1), cation exchange capacity was less than 16 cmol (+) kg^{-1} soil, ECEC less than 12 cmol (+)

Table 1
Selected morphological and textural properties of different forest system from northern high hills.

Depth (cm)	Horizon	Colour	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Texture class**	**Bulk density (g/cm^3)**	**Roots**
Evergreen forest								
0–9	A	7.5YR 4/1	76	8	16	sl	0.92	c m
9–20	BA	5YR 3/3	66	8	26	scl	0.92	c m
20–28	Bt1	5YR 5/3	64	6	30	scl	1.02	f m
28–57	Bt2	5YR 4/4	60	6	34	scl	1.09	f f
57–150	Bt3C	5YR 4/6	62	4	34	scl	0.95	–
Moist deciduous forest								
0–4	A	5YR 3/2	68	10	22	scl	1.21	c m
4–15	Bt1	5YR 3/3	66	8	26	scl	1.01	c m
15–23	Bt2	2.5YR 3/4	66	8	26	scl	1.21	f m
23–150	Bt3C	2.5YR 4/6	62	12	26	scl	1.02	–
Plantation								
0–15	A	5YR 5/4	80	4	16	sl	0.98	c m
15–28	Bt1	5YR 4/4	68	6	26	scl	1.26	c f
28–62	Bt2	5YR 5/8	70	6	24	scl	1.29	f vf
62–150	Bt3C	7.5YR 5/6	74	8	18	sl	1.27	–

sl- sandy loam, scl- sandy clay loam, c m- common medium, f m few medium, f f- few fine, f vf- few very fine.

Table 2
Chemical properties of different forest system from northern high hills.

Horizon	Organic carbon (%)	pH		EC (ds/cm)	Exchangeable bases				CEC	BS (%)	CEC/Clay
					(cmol (+) kg^{-1} soil)						
		H_2O	KCl		Na	K	Ca	Mg			
Evergreen forest											
A	9.46	5.5	4.8	1.1	0.13	0.49	5.05	1.17	17.8	38.44	1.11
BA	4.92	5.7	4.4	0.23	0.11	0.38	2.25	1.41	31.0	13.38	1.19
Bt1	3.74	5.4	4.4	0.19	0.10	0.42	1.15	1.10	18.4	15.07	0.61
Bt2	2.25	5.2	4.3	0.21	0.09	0.33	0.32	0.65	15.0	9.32	0.44
Bt3C	1.74	4.8	4.0	0.19	0.10	0.42	0.25	0.78	13.2	11.71	0.39
Moist deciduous forest											
A	6.17	5.3	4.4	0.78	0.12	0.55	0.33	0.22	24.0	5.05	1.09
Bt1	4.13	4.6	4.4	0.37	0.09	0.24	0.61	1.10	26.2	7.83	1.0
Bt2	3.09	5.1	4.0	0.18	0.09	0.15	0.25	0.10	15.6	3.78	0.6
Bt3C	1.39	4.7	4.2	0.15	0.10	0.12	0.20	0.54	20.0	4.75	0.77
Plantation											
A	2.0	5.4	4.9	0.07	0.23	0.22	3.19	1.54	21.6	23.98	1.35
Bt1	0.78	5.0	4.6	0.01	0.12	0.02	3.23	1.77	17.8	28.9	0.68
Bt2	0.45	5.8	4.8	0.02	0.20	0.03	3.31	1.75	23.8	22.19	0.99
Bt3C	0.38	5.0	4.7	0.01	0.20	0.02	2.93	2.26	23.4	23.13	1.3

Table 3
Cation exchange properties of different forest system from northern high hills.

Horizon	$BaCl_2$-TEA acidity	H^+	Al^{3+}	CEC (Sum of cations)	ECEC	Total Exchangeable bases/CEC, sum of cations (%)
	(cmol (+) kg^{-1} soil)					
Evergreen forest						
A	63.0	0.91	1.10	69.84	7.84	9.80
BA	39.0	0.90	4.21	43.15	8.15	9.61
Bt1	47.0	0.89	4.20	49.77	6.77	5.57
Bt2	42.0	0.85	9.0	43.40	10.40	3.22
Bt3C	49.0	0.82	9.10	50.55	10.55	3.06
Moist deciduous forest						
A	36.4	0.89	7.30	37.62	8.22	3.23
Bt1	39.5	0.89	11.21	41.55	13.05	4.94
Bt2	32.5	0.86	12.01	33.09	12.59	1.78
Bt3C	34.0	0.83	13.20	34.95	13.95	2.72
Plantation						
A	38.0	1.0	3.0	43.18	8.18	11.99
Bt1	38.0	0.91	2.1	43.14	7.14	11.92
Bt2	35.0	0.91	2.1	40.28	7.28	13.11
Bt3C	25.5	0.90	3.1	30.91	8.41	17.51

kg^{-1} soil and base saturation was less than 35% in all horizons. These unique features place the soil pedon of the evergreen forest in the order of Ultisols. At the sub-order level, it was classified into the Humults, as the profile had 9.46% organic carbon in the upper 15 cm of the argillic horizon. With increasing depth, the horizons did not show a clay decrease of 20% or more, enabling it to be placed in the great group Palehumults. The soil of this natural forest had mixed mineralogy with ustic soil moisture regime and an isohyperthermic temperature regime, hence, the soil in the evergreen system can be described as fine-loamy, mixed, acid, active, isohyperthermic, Ustic Palehumult.

In the moist deciduous forest soil, fine roots were present up to the Bt2 horizon. The soil was sticky in the Bt3C horizon and clay films were observed. The clay percentage was found to be stabilized at 26% in Bt1, Bt2, and Bt3C horizons. The presence of argillic horizon in the Bt horizon enabled it to be classified in the order Ultisols of and suborder Humults. Further, the moist deciduous forest with mixed mineralogy, ustic soil moisture regime, CEC/clay ratio > 0.6, and isothyperthermic temperature regime was classified as loamy, mixed, acid, superactive, isohyperthermic, Ustic Haplohumult.

In the rubber plantation, clay illuviation with the presence of clay films were observed in Bt horizon was designated as the argillic horizon. The clay percentage was found to decrease to 18 in the Bt3C from 24 percent in Bt2 horizon. The base saturation was less than 35% in all the horizons enabling the pedon to be classified as Ultisol and the presence of an ustic soil moisture regime facilitated the classification of this soil in the sub-order Ustults. As per the soil taxonomy protocols, the pedon was defined as a coarse loamy, mixed, acid, superactive, isohyperthermic, Typic Haplustult.

3.3. Mineralogy of soils

The XRD patterns of the coarse sand fractions in the different soil horizons of the natural forest systems (evergreen and moist deciduous forests) and rubber plantation showed the presence of dominant peaks at 0.48 nm, 0.42 nm and 0.33 nm indicating the presence of gibbsite, feldspars and quartz as the major minerals. Besides gibbsite, feldspars and quartz, the subsurface horizons of evergreen forest (BA, Bt1 and Bt3C horizons) contained kaolinite (5–10%) in the fine sand and silt fractions. The subsurface horizons of the other natural system, moist deciduous forest, lying at the mid-slope (between evergreen forest and rubber plantation) showed the presence of mica (<5%) along with kaolinite in the fine sand and silt fractions of Bt2 and Bt3C horizons. Micas were conspicuously absent in the fine sand fractions of the surface layers of all natural systems.

The fine sand and silt fractions in the rubber plantation showed the presence of a 1.0 nm peak of mica and a 1.2 nm peak of mixed layer minerals along with gibbsite, quartz and some feldspars in all the horizons. The broadening of 0.72 nm peak base in the silt fractions of A and Bt2 horizons of rubber plantation indicates the discrete amounts kaolinite-Illite (K-I) and a similar pattern for the 1.2 nm (HIV mineral) points to a Kl-HIV interstratified mineral. The mixed layer minerals were absent in the fine sand and silt fractions of all horizons in the evergreen and moist deciduous forests. The sharpness of the 0.48 nm peak indicates that gibbsite in all these systems is well crystallised and the SEM images show it may be pseudomorph of feldspars. The presence of appreciable amounts of gibbsite along with layer silicates in the fine sand fractions of rubber plantation suggests that there is a high possibility of a co-genesis of gibbsite along with layer silicates, thereby presenting evidence against the 'anti – gibbsite effect' in the humid tropical soils (Ndayiragije and Delvaux, 2003).

The clay-sized fractions in the studied systems exhibited significant differences in their mineralogical composition with well-defined XRD maxima showing the presence of mica, vermiculites, kaolinite, gibbsite and interstratified mineral assemblages such as kaolinite–illite (K-I), mica – hydroxy-interlayered vermiculites (M-HIV) and K-I - hydroxy-interlayered vermiculites (K-I–HIV). The Ca-saturated sample showed sharp peaks at 1.4 nm, 1.0 nm, 0.72 nm and 0.48 nm. (Fig. 6). The unaltered 1.0 nm peak under Ca – saturation, Ca – EG (Calcium saturated and ethylene glycol solvated), K – saturation, K-saturated and heating confirms the presence of mica in the natural forest, which was conspicuously absent in the rubber plantation. Kaolinite was established in all the systems by the disappearance of 0.72 nm peak following K-saturation and heating at 550 °C. The reinforcement of the 1.0 nm peak with the concomitant disappearance of the 1.4 nm and 0.72 nm at 550 °C, along with the broadening of the base of the 0.72 nm peak on heating from 25 to 300 °C suggests an interstratification of kaolinite – illite and possibly a K-I–HIV in the natural forest systems. On the other hand, such interstratifications were relatively lesser diverse in the rubber plantation. In the clay-sized fractions of the rubber plantation soils, the peak at 1.4 nm shifted to 1.0 nm on saturation with K and heating to 550 °C, indicating the presence of M-HIV. The presence of traces of vermiculite in the rubber-planted soil was established by a non-prominent peak at 1.4 nm in Ca saturated and Ca – EG which shifted to 1.0 nm on K-saturation and heating from 110 to 550 °C. *(Minerals are represented as the following letter codes in figures and tables: C – chlorite, ML – mixed layer minerals, V – vermiculite, M – mica, K – kaolinite, G – gibbsite, F – feldspar, Q – quartz)* (Figs. 3–9 and Tables 4–6).

3.4. Quantitative pedogenesis

The number of horizons in the pedons of the forested systems varied as five in evergreen forest (A, BA, Bt1, Bt2, Bt3C), four each in moist deciduous forest (A, Bt1, Bt2, Bt3C), and plantation (A, Bt1, Bt2, Bt3C). The proposed method assumes that along with profile development, the clay formed is proportional to the loss in the non-clay fraction. The amount of clay formed from 100 g of non-clay (f) throughout profile development in the evergreen forest varied from 28.69 to 70.67 g (Table 7). The f values in any horizon of the moist deciduous forest (0.16–40.90 g) and plantation (0.08–52.13 g) were lower than evergreen forest (Tables 8 and 9), indicating lesser in situ clay from non-clay fractions in these systems compared to the evergreen system. In evergreen forest system, there was a gradual increase in the f value with depth up to Bt1 (70.67 g) whereas the values lowered in Bt2 (54.49 g) showed restricted weathering and soil formation in this horizon. Unlike the evergreen system, the moist deciduous and plantation system showed abrupt manifold rises between Bt1 (0.16 g) to Bt2 (40.90 g) and Bt1 (0.08 g) to Bt2 (45.83 g), respectively, attributed to clay migrations.

Although the changes in non-clay fractions in any horizon are mainly due to clay formation, this could also be altered by losses or gains of elemental components strictly not associated with clay formations. The proportionality factor (k) indicates processes other than clay formation leading to non-clay losses in the soil profiles (Tables 7–9). Analysis showed that evergreen forest soil (0.68–2.47) had the most clay accumulation or losses by way of processes other than clay formation followed by moist deciduous forest soil (1.00–1.36) and plantation soil (0.79–1.23) which had the least k values. Accordingly, the non-clay fractions in the evergreen forest soil may be considered highly vulnerable to losses either by way of conversion to clay-sized fractions or other losses. The amount of non-clay minerals of the parent material responsible for clay formation as indicated by F values, further confirms that among the different analysed systems, pedons in the evergreen forest still retain appreciable amounts of weatherable reactants in all the horizons. Moist deciduous forest soil was found to have appreciable non-clay fractions only in the Bt2 horizon with a value of 37.65 g/100 g soil. In the plantation, the F values were as low as 0.06 g/100 g soil in Bt1 showing very low amounts of weatherable minerals in the active plant root zones. This would have a direct impact on the soil's nutrient replenishing and buffering capacities.

In evergreen forest soil, there was an incremental gain of clay with depth indicating a uniform transformation and deposition of clay

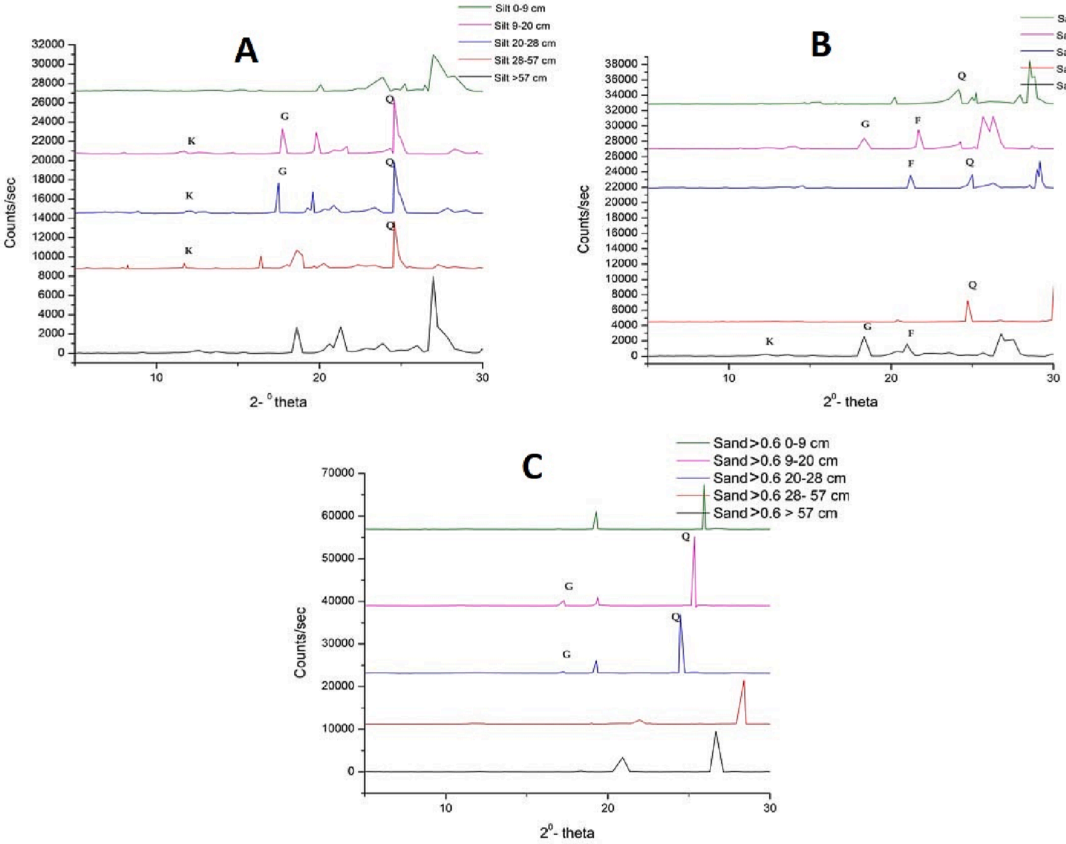

Fig. 3. - Random oriented XRD spectra of soil particles from the evergreen forest soil in the southern Western Ghats: (A) Silt, (B) sand less than 0.6 mm, (C) sand above 0.6 mm.

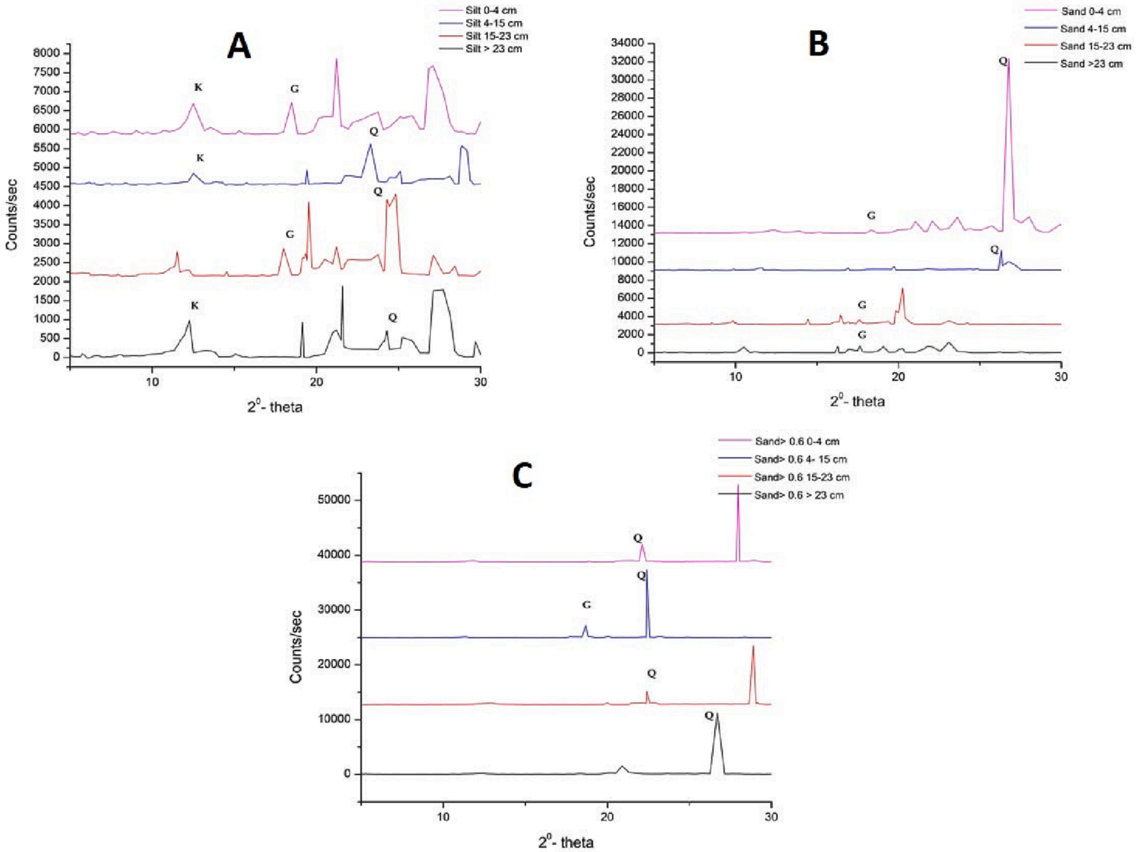

Fig. 4. Random oriented XRD spectra of soil particles from the moist deciduous forest soil in the southern Western Ghats: (A) Silt, (B) sand less than 0.6 mm, (C) sand above 0.6 mm.

(Fig. 10A). The soil of evergreen forest had a clay loss of 6.72 g/ cc/ horizon in the A horizon and gains of 14.68, 21.79, and 28.47 g/cc/ horizon clays in BA, Bt1, and Bt2, respectively. The presence of parent material was appreciable in all the layers and varied from 44.97 g/cc/ horizon in the A horizon to 19.14 g/cc/horizon in the Bt3C horizon. In moist deciduous forest soil, the gain of clay was attributed to clay accumulation as indicated in the schematic Fig. 10B. In plantation, maximum clay gain was in Bt1 (28.34 g/cc/ horizon), below which there was a decrease in the clay content with depth indicating a stratification in the profile (Fig. 10C).

The weight of parent material was higher in evergreen forest than in both moist deciduous forest and plantation soil. In evergreen forest, the maximum volume change was observed in A which can be attributed to erosion losses in the surface horizons. In moist deciduous forest, Bt3C horizon was found to have the maximum volume change, whereas in plantation soil all the lower horizons had more or less similar volume change values.

4. Discussion

4.1. General properties

All the analyzed forest system in the Southern Western Ghats were found to be acidic (pH ranged from 4.6 to 5.8). The soils in the humid tropical regions are subjected to intense leaching of bases and tend to be acidic (Sandeep and Sujatha, 2014; Nanganoa et al., 2019). Rubber plantations add acidic litter to the soil, hence should have been relatively more acidic than those in the natural forest systems (Persson et al., 1987; Vadiraj and Rudrappa, 1990). The rubber plantation in the present study had soil pH ranging from 5.4 (A horizon) to 5.0 (Bt3C horizon) which didn't vary significantly from the upslope natural forest systems. The downslope topographic position of the studied rubber plantation facilitates the accumulation of bases and maintains a pH comparable to that of the natural systems. Studies by Bojko and Kabala (2016) have shown that irrespective of the vegetation type there would be a higher concentration of bases down the slope by way of selective transportation of materials. In the evergreen system soil, the pH values had a gradual decline down the profile, whereas the soil reaction in the moist deciduous and man-made plantation (rubber plantation) showed an uneven trend giving primary indications of ionic movement and their accumulation in the horizons.

The pH-KCl was lower than that of pH-H_2O in all the systems indicating an abundance of poorly crystalline minerals with variable charges in these systems (Bhattacharyya et al., 1994; Chandran et al., 2004, 2005). The evergreen system soil with higher Δ pH values (−0.7 to −1.3) indicated that the system had relatively larger amounts of poorly crystalline materials, while the manmade rubber plantation soil had the least of these materials (Δ pH range: −0.3 to −1.0). Poorly crystalline minerals characterized by their small particle size impart high specific surface areas, charge properties and a higher capacity to support processes ranging from solute transport to soil stability (Harsh, 2005). Soil age gradient studies establish that poorly crystalline minerals usually accumulate in systems with initial weathering stages and reduce in content as the primary minerals (such as feldspars) exhaust and these transient and metastable short-range order minerals nucleate rapidly in aqueous solutions to less reactive crystalline aluminosilicates (e.g., phyllosilicate clays) (Masiello, 2004; Arredondo et al., 2019; Slessarev et al., 2022). The lower quantities of these materials in moist deciduous forest and rubber plantation indicate weathering and loss of these poorly crystalline minerals (Su and Harsh, 1994).

Soils from all the studied forest types were classified into the order of Ultisols with mineral weathering, subsurface clay illuviation, and

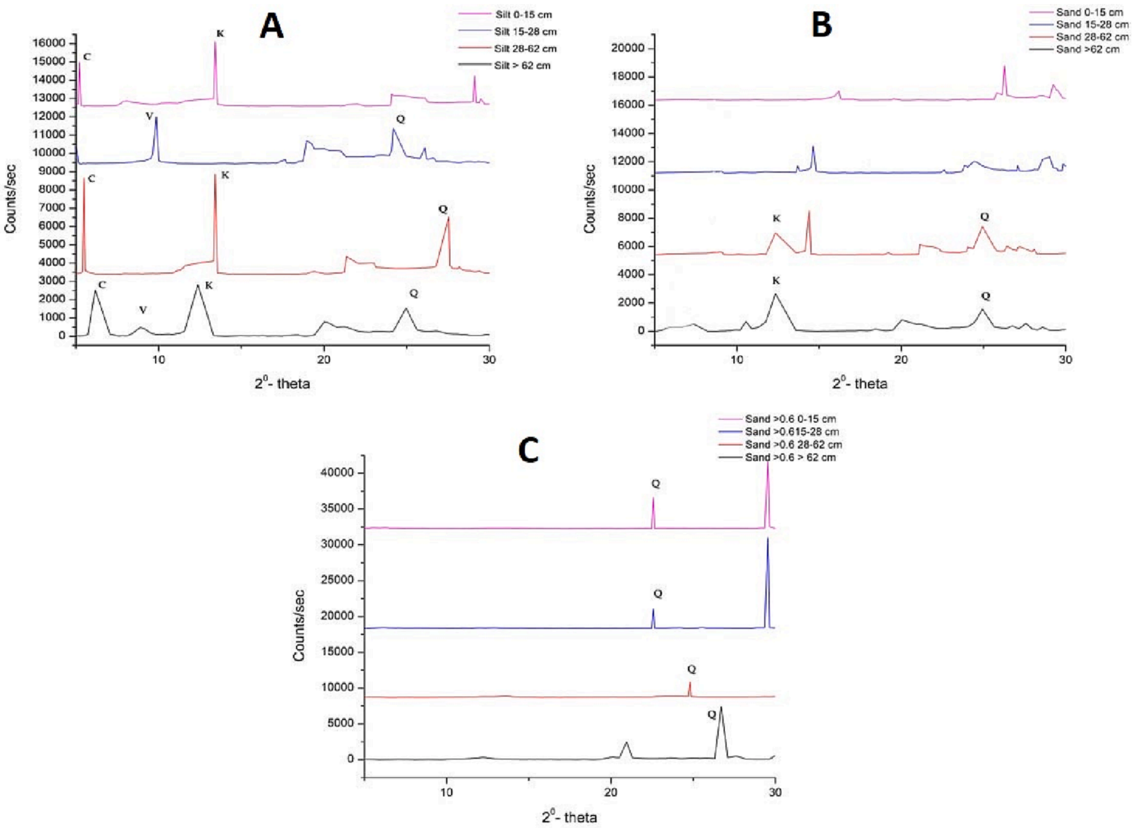

Fig. 5. Random oriented XRD spectra of soil particles from the plantation soil in the southern Western Ghats: (A) Silt, (B) sand less than 0.6 mm, (C) sand above 0.6 mm.

leaching of base cations from the profile. The occurrence of Ultisols in peninsular India is common and present results add to the repository of enabling environments and vegetation categories facilitating the development of soils of this order (Bhattacharyya et al., 1994). Generally, a humid tropical climate with a stable landscape and acidic parent material facilitates the development of soils with an oxic horizon, low CEC, ECEC, and weatherable minerals ($<$10%) enabling them to be classified in the soil order of Oxisols in the Soil Taxonomy (Soil Survey Staff, 2014). Though the region in the Southern Western Ghats of India satisfies all the requirements that are conducive to the development of Oxisols, the results indicate that these soils have not yet reached the stage of this particular soil order (Bhattacharyya et al., 1994; Velayutham and Bhattacharyya, 2000; Chandran et al., 2005). The profiles in the natural forest and rubber plantation fail to fulfil the requirements of an oxic horizon as this soil has a CEC $>$ 16 cmol (+)/kg soil, hence their placement in the order of Oxisols is unjustified. With a proper combination of precipitation (2900 mm), and high mean annual temperature (25 °C), the humid tropical climate of the region provided a weathering condition that should have usually nullified the effects of the acidic parent rock material by forming oxidic or/ and kaolinitic mineral assemblages consistent with the soil formation concepts of residua (Chesworth, 1973) or haplosoil (Chesworth and Dejou, 1980). These models hypothesize that the parent rock effects will be shadowed and nullified with time and that their effects will be pronounced only in relatively younger and immature soils. Further, these models consider time as the only independent state factor of soil formation in nature. The presence of K-l-HIV in the clay fractions of the studied systems (described later) indicates that despite the prolonged weathering since the Tertiary period, the mineralogical products of weathering are yet to reach even the kaolinitic stage (Tardy et al., 1973). Therefore, the present results indicate that soils can remain in the soil order of Ultisols without crossing over to Oxisols even under conducive weathering environments for periods spanning a few thousand to millions of years (Yaalon, 1975; Smeck et al., 1983). Further, the results contradict Chesworth's models of soil formation in tropical humid conditions and suggest that the hypothesis may fail to explain the sustenance of Ultisols in the region. The results add to the repository of data on the persistence of Ultisols in the Southern Western Ghats for millions of years and suggest that in open systems (eg, soil), a steady-state model would give more meaningful insights than a rigorous thermodynamic equilibrium concept (Smeck et al., 1983). In view of the limitations in the existing pedogenic models, it is difficult to reconcile whether these Ultisols would ever weather sufficiently over time to reach the Oxisols stage as envisaged by Smeck et al. (1983).

4.2. Mineralogy of soils

The soils developed under the humid tropical intense weathering conditions usually contain dominant proportions of kaolinite minerals and gibbsite along with insignificant amounts of weatherable minerals. But the present results indicate the presence of appreciable amounts (i.e., $>$10%) of weatherable minerals such as mica, vermiculite, M–HIV, K-I and K-l-HIV in clay-sized fractions of the soils. Gibbsite and quartz were the dominant minerals in the sand and silt fractions of the natural forest system, while the plantation soil showed mica as well as mixed-layer minerals (Chandran et al., 2005). The occurrence of mica and mixed layer minerals in the sand and silt fractions, and vermiculite and M−HIV in the clay-sized fractions suggest that mica has been transformed into vermiculite and further to M–HIV in these systems. Studies have shown that under an acid weathering environment with an abundance of Al^{3+}, interlayering of hydroxy-Al in the expanding 2: 1 layer alumino - silicates are one of the major reactions towards the interstratification reactions (Pal et al., 1989; Bhattacharyya et al., 1994), and a diverse group of such interstratified minerals exist commonly in the acid ferruginous

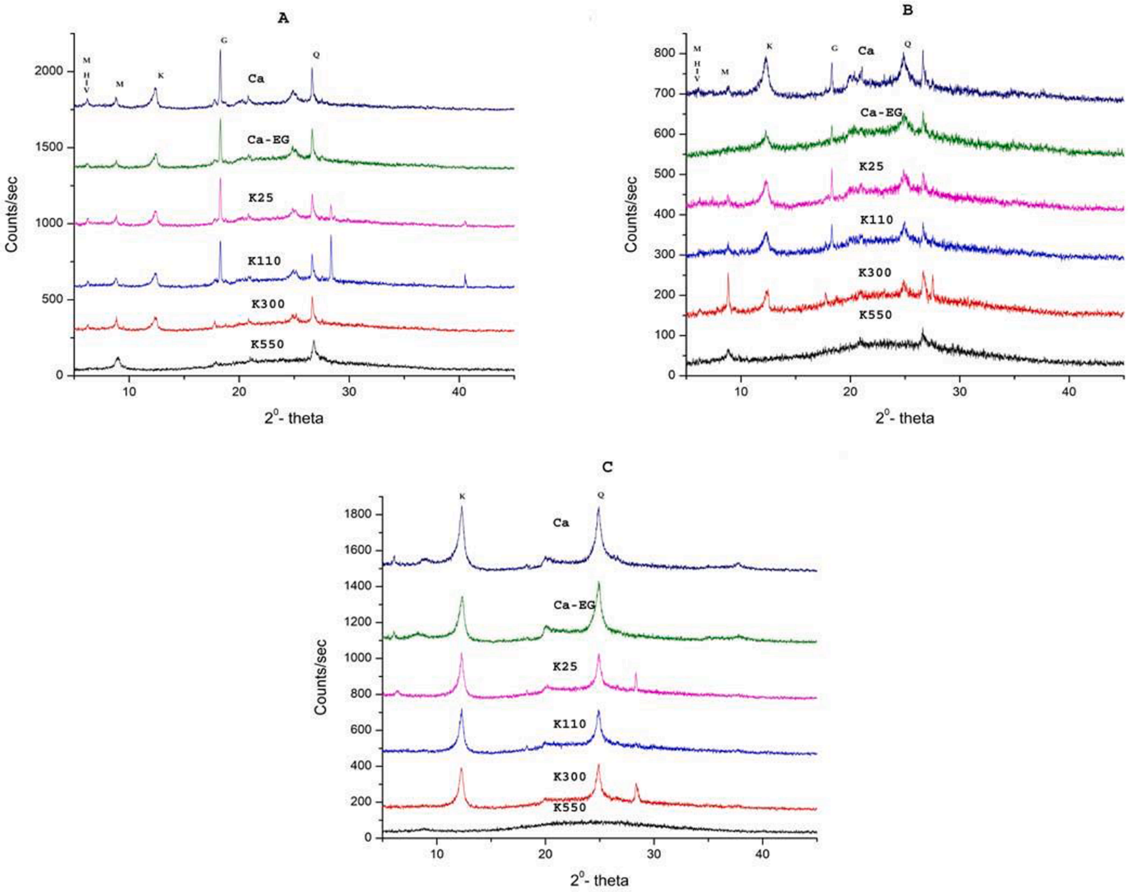

Fig. 6. Representative X-ray diffractogram of total clay Ca, Ca-saturated; Ca–EG, calcium-saturated and ethylene glycol-solvated; K25, K110, K300, K550, K-saturated and heated to 25 °C, 110 °C 300 °C, 550 °C, respectively. (A) Evergreen forest soil, (B) Moist deciduous forest soil, (C) Rubber plantation soil.

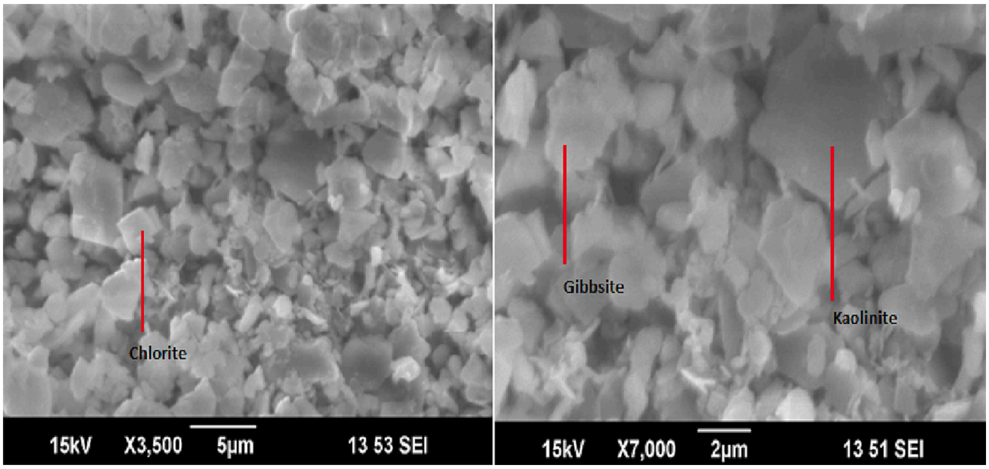

Fig. 7. SEM images of clay particles from the evergreen forest soil in the southern Western Ghats.

soils (Pal et al., 1989; Bhattacharyya et al., 2000). Hence, the expanding lattice minerals act as a template for HIV formation and the formation of gibbsite is usually considered improbable in the presence of these 2: 1 minerals - referred to as 'anti -gibbsite effect' (Jackson, 1963, 1964). In view of this theory, the co-existence of HIV and gibbsite under acidic soil environments is usually ruled out. Contrary to such expectations, gibbsite and HIV forms were found to occur simultaneously in the Ultisols under the present study. The sharpness of the peak at 0.48 nm in all the size fractions of soils from evergreen, moist deciduous and rubber plantation suggest that gibbsite in these soils is well crystallized. The SEM images show that these minerals have a hexagonal prism form and that they may be pseudomorphs of feldspars (Figs. 7 and 8). Well-developed hexagonal or rod-shaped gibbsite crystals are developed in alkaline environments (Tait et al., 1983; Balasubramaniam and Sabale, 1984). Generally, HIVs and well crystallized gibbsite develop under distinctly varying soil environments, and as such their co-existence has been rarely reported (Ndayiragije and Delvaux, 2003). The results show that tropical weathering under an acidic soil reaction in both the natural

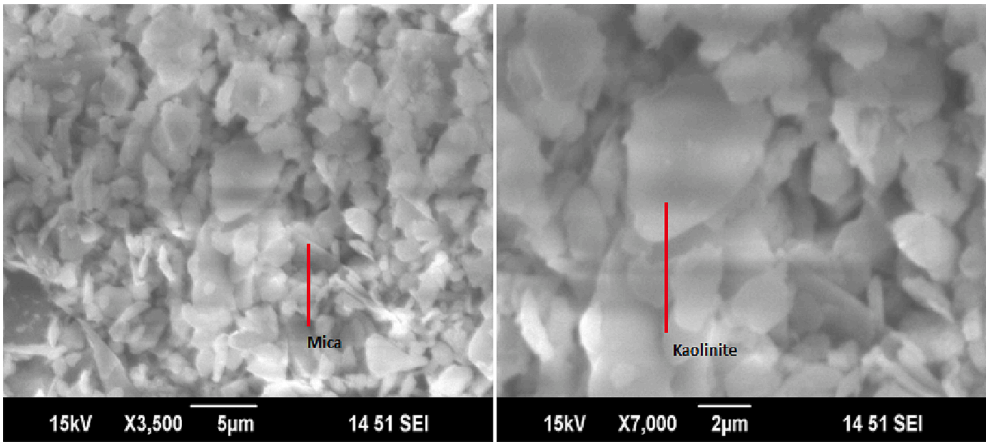

Fig. 8. SEM images of clay particles from the moist deciduous forest soil in the southern Western Ghats.

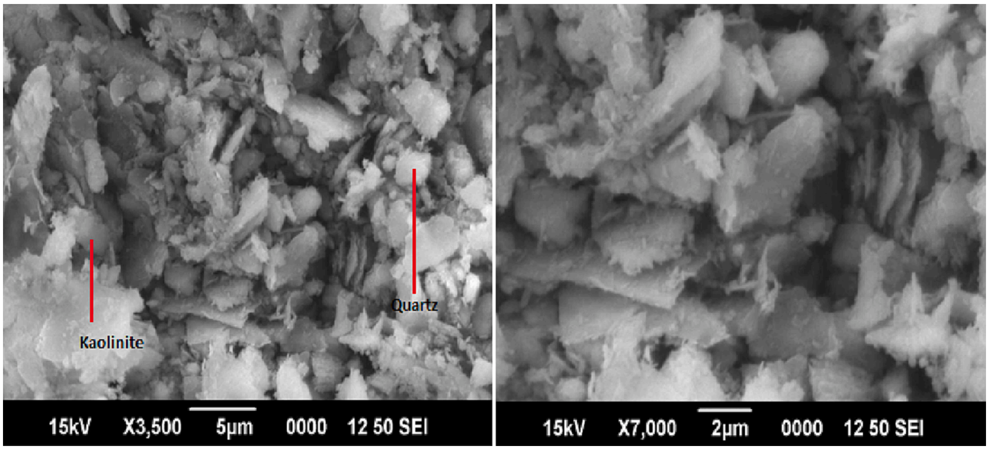

Fig. 9. SEM images of clay particles from the plantation soil in the southern Western Ghats.

Table 4
Mineral composition of evergreen forest soil in the southern Western Ghats.

Depth (cm)	Fraction	C	ML	V	M	K	G	F	Q
0–9	Clay	+	–	–	+	+++	+	–	–
9–20	Clay	+	–	–	+	+++	++	–	–
20–28	Clay	+	–	–	+	+++	++	–	+
28–57	Clay	+	–	–	+	+++	+	–	+
57–150	Clay	+	–	–	+	+++	++	–	+
0–9	Silt	+	–	–	–	–	–	–	++++
9–20	Silt	–	–	–	–	++	++	+	+++
20–28	Silt	–	–	–	–	++	+	+	+++
28–57	Silt	–	–	–	–	++	++	+	+++
57–150	Silt	–	–	–	–	++	++	–	++++
0–9	F. Sand	–	–	–	–	–	–	–	++++
9–20	F. Sand	–	–	–	–	–	++	–	++++
20–28	F. Sand	–	–	–	–	–	++	–	+++
28–57	F. Sand	–	–	–	–	–	–	–	++++
57–150	F. Sand	–	–	–	–	++	++	–	++++
0–9	C. Sand	–	–	–	–	–	++	–	+
9–20	C. Sand	–	–	–	–	–	++	–	+
20–28	C. Sand	–	–	–	–	–	++	–	+
28–57	C. Sand	–	–	–	–	–	–	–	++
57–150	C. Sand	–	–	–	–	–	++	–	++

forests has produced significant quantities of K-l-HIV. Under such a condition, kaolinite should be considered still in a transient stage (i.e., not fully transformed to kaolinite) in these natural forest systems, hence kaolinite transformation to gibbsite in these soils is highly improbable. These observations suggest that the gibbsite would have formed in an alkaline soil reaction whereas the K-l-HIV in an acidic environment. Chandran et al. (2005) showed that during the initial stages of weathering, primary minerals such as feldspars and biotites dissolve to produce Al^{3+} in soil solution, which crystallises to form gibbsite on mineral surfaces. As the weathering advances, the soil pH becomes acidic and the Al^{3+} ions released as $Al(OH)^{2+}$ would be precipitated in the interlayers of vermiculites thereby neutralizing the unbalanced negative charges and transforming them into HIVs (Lowe, 1986; Hsu, 1989; Mulyanto et al., 1999; Bhattacharyya et al., 2000). Hence, the presence of gibbsite and interstratified minerals (K-l-HIV, M-HIV) in the natural forest soil confirms that gibbsite would have formed in these Ultisols in an earlier alkaline soil condition and HIVs at a later acidic condition. The co-existence of gibbsite along with HIVs in these systems presents strong experimental evidence to counteract the 'anti – gibbsite effect' in soil and confirms the earlier studies (Bhattacharyya et al., 2000; Chandran et al., 2005).

Generally, the uniform pattern of distribution of resistant minerals such as quartz and gibbsite indicate the homogeneity of the parent material with depth as these materials remain more or less unaltered during soil formation. Quartz and gibbsite, dominant in humid tropical soils have very high activation energies for their Si—O/Al—O bonds facilitating slow dissolutions and nearly negligible precipitation in soil systems (Marini, 2007), hence used in the present study as well to get indications about the parent material homogeneity with depth. The increase in the quartz content in the sand-sized fraction down the profile in the evergreen and moist deciduous forest soil indicates an incomplete fractionation or decomposition of the primary minerals with depth

Table 5

Mineral composition of moist deciduous forest soil in the southern Western Ghats.

Depth (cm)	Fraction	C	ML	V	M	K	G	F	Q
0–4	Clay	+	–	+	+	+++	–	–	++
4–15	Clay	+	–	–	+	++++	–	–	–
15–23	Clay	–	–	–	–	+++	–	+++	+++
23–150	Clay	–	–	–	–	+++	–	+++	++
0–4	Silt	–	–	–	–	+++	+	–	+++
4–15	Silt	–	–	–	–	+	–	–	+++
15–23	Silt	–	–	–	+	+	+	–	+++
23–150	Silt	–	–	–	+	++	–	–	+++
0–4	F. Sand	–	–	–	–	–	+	–	++++
4–15	F. Sand	–	–	–	–	–	–	–	++++
15–23	F. Sand	–	–	–	–	–	+	–	+
23–150	F. Sand	–	–	–	–	–	+	–	+++
0–4	C. Sand	–	–	–	–	–	–	–	++
4–15	C. Sand	–	–	–	–	–	+	–	++
15–23	C. Sand	–	–	–	–	–	–	–	++
23–150	C. Sand	–	–	–	–	–	–	–	++

Table 6

Mineral composition of plantation soil in the southern Western Ghats.

Depth (cm)	Fraction	C	ML	V	M	K	G	F	Q
0–15	Clay	–	–	–	+	++	–	–	–
15–28	Clay	–	–	–	–	++++	+	–	–
28–62	Clay	–	–	–	+	+++	–	–	–
62–150	Clay	–	–	–	+	+++	+	–	–
0–15	Silt	++	–	–	–	+++	–	–	++++
15–28	Silt	–	–	++	–	+++	+++	–	+++
28–62	Silt	++	–	–	–	++++	+++	–	–
62–150	Silt	++	–	+	–	+++	–	–	+++
0–15	F. Sand	–	–	–	–	–	–	–	+
15–28	F. Sand	–	–	–	–	–	–	–	–
28–62	F. Sand	–	–	–	–	+	–	–	+
62–150	F. Sand	–	–	–	–	+	–	–	+
0–15	C. Sand	–	–	–	–	–	–	–	++
15–28	C. Sand	–	–	–	–	–	–	–	++
28–62	C. Sand	–	–	–	–	–	–	–	+++
62–150	C. Sand	–	–	–	–	–	–	–	+++

(Gutiérrez-Castorena and Effland, 2010; Martín-García et al., 2015). Gibbsite, another resistant mineral in these soils didn't show any definite trend in the soil profiles of either the natural forests or rubber plantation. The presence of sizeable amounts of well-developed hexagonal gibbsite crystals amidst easily weatherable layer silicates in certain horizons (eg. BA, Bt1 of evergreen forest) of these systems should be construed as a result of the cogenesis of gibbsite and layer silicates in horizons with localized favourable pedochemical conditions (as described above) (Bhattacharyya et al., 2013), rather than through the normal alumino - silicate desilication step. Hence unlike quartz, gibbsite may not be an ideal indicative mineral for homogeneity assessment of the parent material with depth in these soils.

The presence of mica (<5%) in both the fine sand and silt fractions and vermiculites/ HIVs in the clay fractions of the systems suggest that mica would have weathered to mixed-layer minerals (mica – vermiculites and mica – HIV) along with vermiculite in these systems (Tardy et al., 1973). The diversity in the contents of these 2:1 and mixed-layer minerals in natural (evergreen and moist deciduous) than manmade systems (rubber plantation) under similar parent material, climatic, and slope conditions indicates the vegetation and management effects on weatherable minerals in ferruginous soils of southern Western Ghats. (Pal et al., 1989, 2014). Earlier studies have shown that such losses of reactive minerals would provide an initial boost to plant productivity by enhancing the availability of plant nutrients, but decline as the supply of weatherable minerals is depleted (Stark, 1978). However, such weathering patterns in natural systems cause gradual changes in vegetation, resulting in higher fertility-demanding plant communities reaching a climatically controlled maximum of vegetative biomass. As the depth of weathering increases, the soil can no longer supply the climax vegetation's nutrient demands, and the succession trend shifts away from the biomass maximum (Walker et al., 1983).

4.3. Quantitative evaluation by the chemical analysis

The f values in any horizon of the moist deciduous forest and plantation were lower than evergreen forest indicating that the present non-clay fractions in these systems were improvised with respect to clay formation than the latter systems. In all the systems, the losses of SiO_2 in the non-clay fraction and enrichment of the constituent in the clay-sized fraction in all the horizons indicate an active ongoing weathering process. As the surface layers are more vulnerable to exposure and subsequent transformations, it is expected that the k values would be higher in these layers. However, the increases in k values with depth in both moist deciduous and plantation systems suggest that the SiO_2 released would have leached down and accumulated at various locations in the profiles of these systems. This observation was substantiated by the texture analysis results of these two forest soils which didn't show an increase in clay percentage in lower horizons. Schwandes et al. (2001) observed that the amount of available Si in the Ultisols was affected by the clay fraction.

The pool of soil minerals is maintained by the exchange of mineral nutrients between the soil and plants (Stephen, 2008). The soil of evergreen forest entails sufficient quantities of reactants (non-clay) and products (clays, salts, and oxides) to activate the forward and backward reactions, once the requisite energy barrier is crossed. Soil mineral transition or transformation processes occur at an infinitesimally slow

Table 7
Quantitative pedogenesis in the evergreen forest soil of the southern Western Ghats.

Horizon	**Depth** (cm)	**Present Clay** (g/100 g soil)	**f** (g)	**k**	**F** (g)	**O** (g)	**Amount of clay originally present** (g/horizon)	**Loss or gain of clay** (g/horizon)	**Present volume per horizon (cc)**	**Bulk density (g/cc)**	**Weight of present soil** g/cc/horizon	**Weight of parent material** cc/horizon	**Original volume**	**Change in volume**	**Relative clay loss or gain (g/cc/horizon)**
A	0–9	16	28.69	0.68	49.91	256.98	10.78	−6.72	14.46	0.92	13.30	44.97	48.88	−34.42	−0.14
BA	9–20	26	48.65	1.57	44.54	66.03	3.45	14.68	18.02	0.92	16.58	14.40	15.65	2.37	0.94
Bt1	20–28	30	70.67	2.47	68.33	47.01	2.76	21.79	18.22	1.02	18.58	11.0.49	11.27	6.95	1.93
Bt2	28–57	34	54.49	1.87	42.36	53.03	3.32	28.47	18.22	1.09	19.86	13.85	12.71	5.51	2.24
Bt3C	57–150	34	–	–	–	–	–	–	18.24	0.95	17.33	19.14	20.14	−1.90	1.38

Table 8
Quantitative pedogenesis in the moist deciduous forest soil of the southern Western Ghats.

Horizon	**Depth** (cm)	**Present Clay** (g/100 g soil)	**f** (g)	**k**	**F** (g)	**O** (g)	**Amount of clay originally present** (g/horizon)	**Loss or gain of clay** (g/horizon)	**Present volume per horizon (cc)**	**Bulk density (g/cc)**	**Weight of present soil** g/cc/horizon	**Weight of parent material** cc/horizon	**Original volume**	**Change in volume**	**Relative clay loss or gain (g/cc/horizon)**
A	0–4	22	13.23	1.19	9.98	63.33	3.58	21.83	14.41	1.21	17.43	14.62	12.08	2.32	1.81
Bt1	4–15	26	0.16	1.00	0.12	77.99	4.63	21.61	18.12	1.01	18.30	18.91	18.72	−0.60	1.15
Bt2	15–23	26	40.90	1.36	37.65	71.34	5.06	21.14	18.05	1.21	21.84	20.64	17.06	1.00	1.24
Bt3C	23–150	26	–	–	–	0	−1.17	31.73	18.21	1.02	18.57	–	−4.70	22.90	−6.75

Table 9
Quantitative pedogenesis in the plantation soil of the southern Western Ghats.

Horizon	Depth (cm)	Present Clay (g/100 g soil)	f (g)	k	F (g)	O (g)	Amount of clay originally present (g/horizon)	Loss or gain of clay (g/horizon)	Present volume per horizon (cc)	Bulk density (g/cc)	Weight of present soil g/cc/horizon	Weight of parent material cc/horizon	Original volume	Change in volume	Relative clay loss or gain (g/cc/horizon)
A	0–15	16	−57.56	0.79	−38.98	86.04	3.51	20.71	17.24	0.98	16.89	18.04	18.41	−1.17	1.13
Bt1	15–28	26	0.08	1.00	0.06	84.02	4.41	28.34	17.27	1.26	21.77	22.70	18.02	−0.74	1.57
Bt2	28–62	24	45.83	1.15	55.75	116.56	6.29	15.41	17.34	1.29	22.36	32.35	25.08	−7.74	0.61
Bt3C	62–150	18	52.13	1.23	72.50	115.64	–	6.36	17.24	1.27	21.90	31.43	24.75	−7.51	0.26

rate in natural conditions and take millions of years to complete (Sandeep et al., 2019). These systems could also have negative Gibbs energy i.e., ΔG. On the other hand, plantation soils could be considered highly weathered soils with little non-clay fractions to favour most of these reactions. Consequently, the evergreen system can be considered the most active system and the plantation the least active with respect to the present soil condition. The features of soils in natural tropical forests reflect long-term soil-vegetation feedbacks, which are impacted by the high productivity, canopy, consistent litter input, and persistent deep root systems. Tropical forests, in contrast to agricultural land, promote efficient soil-nutrient recycling and regulate soil temperature and moisture (Lucas, 2001; Davidson et al., 2007; Barnes et al., 2014; Grass et al., 2020). In short, land-use changes could be detrimental in affecting dynamic soil parameters (soil pH, effective cation-exchange capacity, base saturation, bulk density, and soil organic carbon). Strategies to recalibrate the changes would decide the success of any afforestation programme or productivity issues in the humid tropics (Krishnaswamy and Richter, 2002; Veldkamp et al., 2020).

A comparison of the quantities of clay formed with depth in any horizon with the present clay confirms the clay migration and their accumulation in specific horizons as a major feature in these pedons. Maximum clay content was observed in the lower horizons of evergreen (Bt2) and moist deciduous (Bt3C) forests while in plantation it was at the Bt1 horizon. The gradual decrease of clay formation in the Bt2 and Bt3C horizons of plantation indicates the stratification in the pedon. According to Zhong et al. (2018) clay content was positively correlated with vegetation diversity (Simpson diversity index and Shannon-Wiener diversity index). Because of the proliferation of roots with different diameters, lengths, and tortuosity, more plant diversity may be expected to contribute to higher rhizospheric variation and, as a result, mechanical clod breakdown. Furthermore, the increase in the canopy and residual cover owing to complex plant characteristics reduces the rain wash of finer soil components affecting increasing clay contents in deeper horizons. Present findings revealed that vegetation features had a considerable impact on clay content under similar climatic conditions (Sinoga et al., 2012; Tracy et al., 2013; Gould et al., 2016; Ren et al., 2017). In the transformation of parent material to soil, clay formation is mainly responsible for the changes in the mineralogical composition, but clay migration reflected by losses or gains of clay may be mainly responsible for the changes in the chemical composition of particular horizons in a profile. Estimations by Brimhall and Dietrich (1987) using mass balance relationships of chemical components, volume, density, porosity, and strain in soil profiles also confirm the above observations in horizon development.

5. Conclusion

The soils under the forest systems (both natural and man-made) in the southern Western Ghats were found to have developed weathered and mature profiles with characteristic features of Ultisols. The greater abundance of 2:1 and mixed-layer minerals in evergreen and moist deciduous forest soils than the rubber plantation (manmade systems under similar parent material and climatic conditions indicates the effects of vegetation and management on weatherable minerals in soils of the southern Western Ghats. The presence of these 2:1 minerals along with dominance of gibbsite discounts the antigibbsite hypothesis and suggests that in all probability gibbsite in these soils would be leftovers from earlier weathering cycles in a neutral to alkaline soil environment. Under similar parent material and climate, the persistence of Ultisols in all the contrasting systems even after intense weathering for thousands of years indicates that a progressive degradation of these Ultisols to Oxisols as conceptualized in the soil genesis models may not be reconcilable by vegetation types, altitude or slope and that their effects may be limited to the mineralogical make up and the associated properties in these soils. Using only three pedons for the study is a limitation, but provides insights into the effects of contrasting forest types on soil

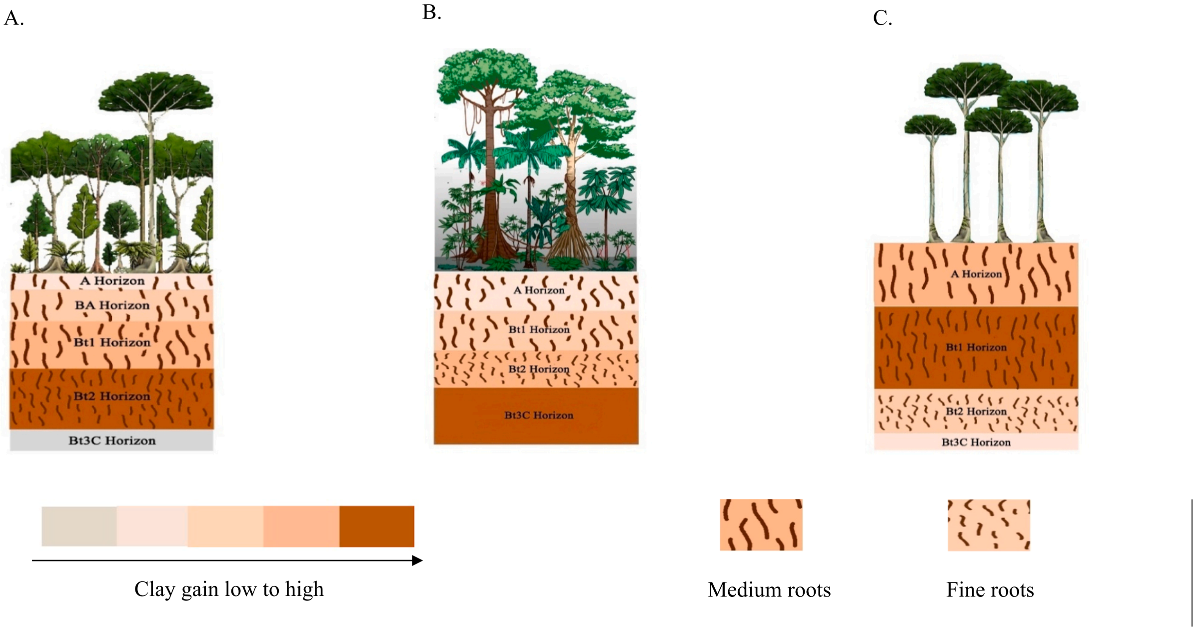

Fig. 10. A – C. Loss or gain in clay in different horizons of the contrasting ecosystems in southern Western Ghats A. Evergreen forest; B. Moist Deciduous forest; C. Plantation.

formation in the southern Western Ghats.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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