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Landuse, Clay Mineral Type and Organic Carbon Content in Two Millisols-Alfisols-Vertisols Catenary Sequences of Tropical India

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Abstract : *Soils under different land use attain a certain value of soil organic carbon (SOC) over a period of time. Research attempts to understand such value of major soil types of India are rare. The present study was therefore undertaken to find out SOC value in two Mollisols-Alfisols-Vertisols catenary sequences of Deccan basalt area in Central (Satpura Range) and Western Ghats regions of India. The results indicate that the Vertisols dominated by smectites, are usually under agriculture and has a SOC of ~8 g kg-1 in the top 30 cm of soils. On the other hand the spatially associated Mollisols and Alfisols under forests and dominated by smectites, maintain relatively high SOC values of 12 to 26 g kg-1 in the top 30 cm of soils. The results show that SOC content is mainly a function of clay mineral type rather than clay content. The identification of smectite interstratified with 0.7 nm minerals in these soils demonstrate its influence in SOC accumulation of tropical soils. Establishment of SOC values in relation to land use, and clay mineral type provides valuable hints about the upper limit of SOC sequestration in Vertisols of arid and semi-arid regions of India and elsewhere for their sustained productivity.*

The influence of topography in the formation of different kinds of soils is very conspicuous in basaltic terrain of Peninsular India. At the crest and on pediment slopes shallow to moderately deep red soils (Entisols/Inceptisols/ Alfisols), and in the lower piedmont plain or valleys deep soils with vertic properties (Vertisols and their intergrades) are quite common in arid and semi-arid part of the Peninsular India (Murthy *et al*., 1982). The arid and semi-arid part cover more than 50% area of the country. These soils are in general calcareous and impoverished in soil organic carbon (SOC) (Srivastava *et al*., 2002). These soils specially, the shrink-swell soils require SOC accumulation to strengthen their health because at present they have limitations that restrict their full potential

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to grow both rainy season and winter crops (Kadu *et al*., 2003).

By and large, the shrink-swell soils under agricultural systems in India contain a SOC value of 0.5% in surface layers. In order to increase the level of SOC in these soils, it is necessary to understand the capacity of these soils to sequester organic carbon. An earlier attempt indicated that the SOC level of these soils under agricultural system of semi-arid environment may be raised from 0.44-0.51% to 0.70-0.80%, considering the SOC of shrink-swell soils (vertic intergrade of Inceptisols) under forest cover of semi-arid (moist) climate (Naitam and Bhattacharyya, 2004). In recent years we have found a repetitive catenary association of Mollisols-Alfisols-Vertisols under various land uses in humid tropical climate (HTC) of the Deccan basalt area in central and western India (Figs. 1 and 2). The formation of these soils under this climate has been possible because of the presence of Ca-rich zeolites (Bhattacharyya *et al*., 1993, 1999a; Pal *et al*., 2003). The Mollisols and Alfisols developed in central and western India under mean annual rainfall (MAR) of 1200 and 3947 mm and mean annual temperature (MAT) of 24.4 and 27.0^{o}C, respectively have vertic characters. These two catenary sequences of soils provided us an opportunity to gain knowledge about their limit of OC accumulation in non-calcareous soils with vertic characteristics under a particular land use system over a period of time. The information on the limit of SOC accumulation under variable soil climatic environments in HTC is very rare, although this is of value as input parameter to develop a model of understanding on the sequestration of organic carbon in shrink-swell soils not only of HTC but also of arid and semi-arid climates. Keeping in view of the importance of such information the present study was undertaken with two catenary sequences of central and western India (Fig. 2) to find out the scope of SOC accumulation in calcareous shrink-swell soils especially of Vertisols of semi-arid subtropical climate. This is likely to be achieved from the information gained through this study on land use, clay mineral type and potentiality of SOC accumulation in Mollisols-Alfisols-Vertisols catenary sequence.

Materials and Methods

Figure 1 gives the location of the study area. Two soil catenas consisting of Mollisols-Alfisols-Vertisols (P1 to P7) under study are described schematically showing landuse, SOC content (0-30 cm), mineral suit and other information (Fig. 2).

The Mollisols (P1, P5) and Alfisols

Fig. 1. Study area showing the profile locations in Madhya Pradesh and Maharashtra, India.

(P2, P6) have been under thick forest vegetation for centuries. The Alfisols (P3) have been brought under cultivation for the last 20-30 years. The Vertisols (P4 and P7) are under agriculture for the last 50 years. In view of the land use histories of these soils under study it is expected that under a particular management regime in soil system a steady-state in terms of SOC content is likely to be established (Swift, 2001).

The thickness of the mollic epipedon has been found to be thinner than as laid

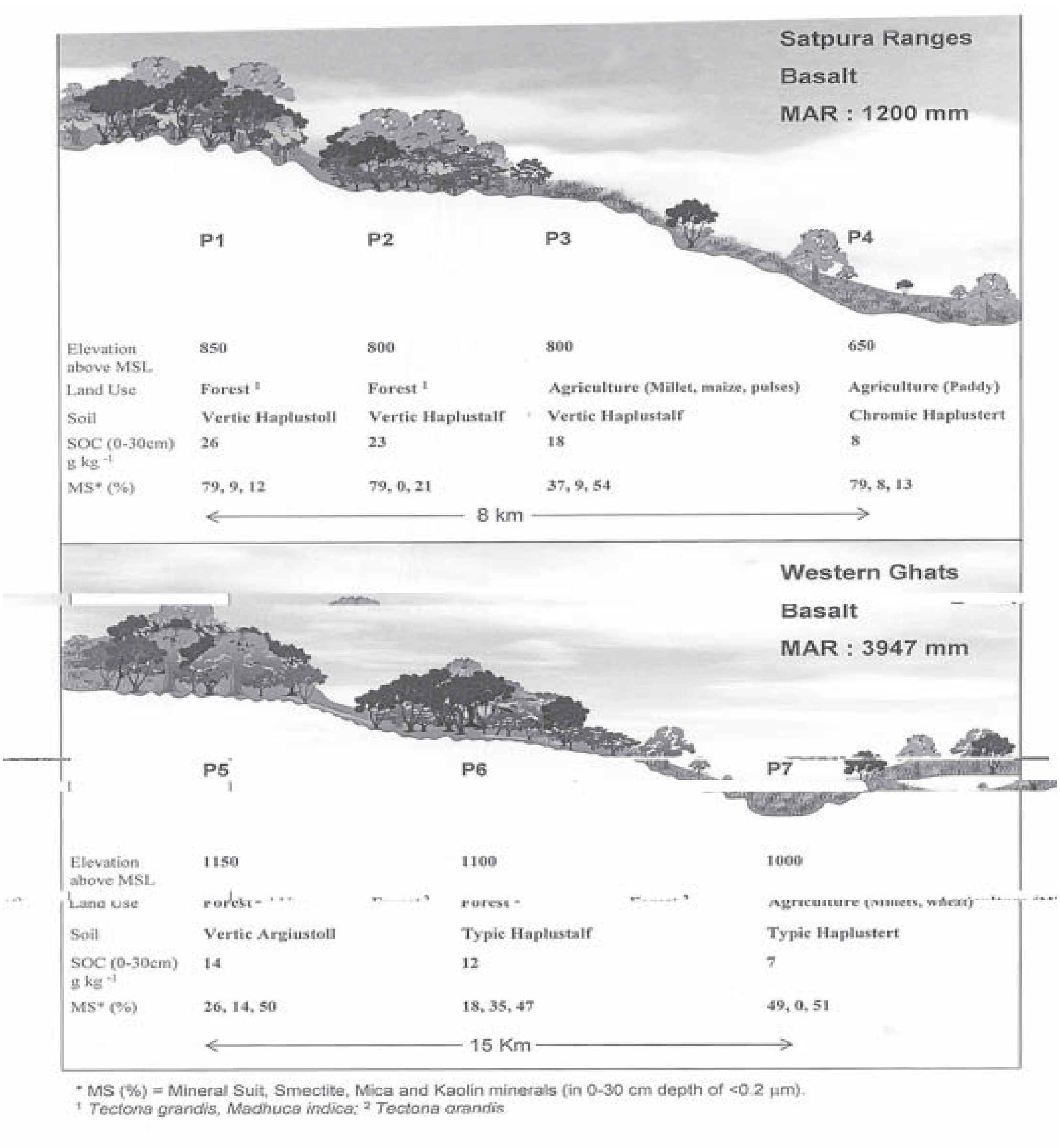

Fig. 2. A schematic diagram of the Mollisols-Alfisols-Vertisols catenary sequence in (a) the Satpura Ranges, Madhya Pradesh and (b) the Western Ghats, Maharashtra, India.

down in Soil Survey Staff (2003); more so for Pedon 1. However judging by SOC content, colour and structure (soft when dry) both the pedons (P1 and P5) have been grouped into Mollisols. The recent modifications of mollic epipedon has been proposed for soils under eroded conditions. The eroded conditions have been explained as a pre-requisite for the cultivated soils (Olson *et al*., 2005). The Mollisols (P1 and P5), although under forest are prone to erosion due to slope factor. This may perhaps justify the thinner mollic epipedon even in soils under forest.

Soil analyses

The profiles were examined to describe the morphological properties of soils (Soil Survey Division Staff, 1995; Soil Survey Staff, 2003). The international pipette method was used to determine particle size distribution. Sand, silt, and clay (coarse and fine) fractions were separated following the procedure described by Jackson (1979). Chemical properties such as cation exchange capacity, extractable bases (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) and base saturation were determined following standard methods (Jackson, 1973). Soil organic carbon (SOC) was determined following the procedure of Walkley and Black (1934). The SOC content over the soil depths of 0-30 cm of each soil was measured. The oriented Ca and K saturated silt and clay fractions were examined by X-ray diffraction (XRD) using a Philips diffractometer and Ni-filtered CuKα radiation at a scanning speed of $1^{o}2\theta$/min. The powdered sand samples were also examined by XRD after box mounting. Minerals were identified following various diagnostic methods (Jackson, 1979; Brown, 1984). The semi-quantitative estimates of clay minerals were carried out for coarse and fine clay fractions following the method of Gjems (1967). The peak shift analysis (Wilson, 1987) has been found to be a useful method to determine the components of Sm/K interstratified minerals (Bhattacharyya *et al*., 1993, 1997; Shirsath *et al*., 2001).

Results

Morphological, physical, chemical and mineralogical properties of soils

Mollisols of Satpura (P1) had a clay loam texture with subangular blocky structure and were black to dark reddish brown in colour whereas these soils on the Western Ghats (P5) had a clay texture, granular to subangular blocky structure and dark brown to dark reddish brown in colour (Tables 1 and 2). The Alfisols of the former (P2, P3) had a silty clay loam to silty clay texture in the solum and a sandy clay loam texture in the C horizons.

Table 1. *Morphological, physical and chemical properties of soils of the Satpura Ranges*

Horizon	Depth (cm)	Morphological Properties[A]			Particle size distribution (g kg^{-1})				pH (1:2) water	OC g kg^{-1}	Extractable bases				CEC	BS (%)
		Munshell Colour (moist)	Texture	Structure	Sand (2000-50 µm)	Silt (50-2 µm)	Clay (<2 µm)	Fine clay (<0.2 µm)			Ca	Mg	Na	K		
											← cmol (+) kg^{-1} →					
						Pedon 1: Vertic Haplustalf										
A1	0-6	5YR 2.5/1	cl	1f gr	310	390	300	220(73)B	5.9	35.0	29.6	14.4	1.0	2.3	52.2	91
A2	6-20	5YR 2.5/1	cl	1f gr	230	380	390	190(46)	5.8	30.0	32.8	16.4	1.0	2.0	59.8	87
Bw1	20-37	5YR 2.5/2	cl	1f sbk	300	410	290	220(76)	5.8	20.0	33.2	18.8	1.1	1.8	59.8	92
Bw2	37-74	5YR 2.5/2	cl	2m sbk	380	310	310	220(71)	5.9	12.1	36.8	19.2	1.1	1.4	67.4	87
Bw3	74-106	5YR 4/3	cl	2m sbk	420	270	310	200(64)	5.6	8.1	45.4	18.4	1.2	0.8	71.7	92
Bw4	106-150	5YR 4/3	scl	2m sbk	520	200	280	160(57)	5.5	5.0	45.2	17.6	1.1	1.0	73.9	88
						Pedon 2: Mollic Haplustalf										
A	0-10	7.5YR 3/2	sic	1f gr	81	412	507	333 (65)	5.1	33.0	18.4	9.0	0.3	1.4	40.8	71
Bt1	10-26	7.5YR 2.5/2	c	1f sbk	107	396	497	333 (67)	5.2	21.0	16.4	9.2	0.3	0.6	35.2	75
C1	26-50	7.5YR 2.5/3	c	m	321	149	531	468 (88)	5.3	15.0	16.0	9.6	0.4	0.7	35.2	76
C2	50-85	7.5YR 3/3	c	m	389	152	459	369 (80)	5.6	12.0	15.8	12.7	0.2	0.5	35.4	82
						Pedon 3: Vertic Haplustalf										
Ap	0-10	5YR 3/2	sicl	1m sbk	140	480	380	230(60)	6.2	19.1	16.0	5.2	0.4	1.0	25.5	89
Bt1	10-30	5YR 3/2	sic	1m sbk	90	440	470	280(59)	5.9	18.0	16.0	6.9	0.4	0.8	29.1	83
Bt2	30-59	5YR 3/2	c	2m sbk	180	310	510	330(65)	5.9	10.2	16.8	3.9	0.3	0.8	28.8	76
C1	59-94	5YR 3/2	scl	m	550	150	300	240(80)	6.5	7.1	16.8	8.6	0.4	1.0	28.8	93
C2	94-151	5YR 3/2	scl	m	580	130	290	190(65)	6.7	5.0	25.5	8.6	0.4	1.2	36.4	98

Table 1. *Morphological, physical and chemical properties of soils of the Satpura Ranges (contd.)*

Hori-zon	Depth (cm)	Morphological Properties[A]			Particle size distribution (g kg^{-1})				pH (1:2) water	OC g kg^{-1}	Extractable bases				CEC	BS (%)
		Munshell Colour (moist)	Tex-ture	Stru-cture	Sand (2000-50 µm)	Silt (50-2 µm)	Clay (<2 µm)	Fine clay (<0.2 µm)			Ca	Mg	Na	K		
											← cmol (+) kg^{-1} →					
Pedon 4: Chromic Haplustert																
Ap	0-17	10YR 5/4	sic	1m sbk	20	520	460	260(56)	7.1	8.1	23.3	8.9	0.4	0.6	33.8	98
Bw	17-54	10YR 5/4	sic	2m sbk	20	410	570	380(67)	7.4	8.0	26.3	13.4	0.4	0.6	42.4	91
Bss1	54-81	10YR 4.5/3	sic	2m sbk	20	420	560	390(70)	7.3	7.9	21.2	11.6	1.1	1.0	44.6	78
Bss2	81-133	10YR 4/3	sic	2c abk	20	430	550	270(49)	7.4	7.1	27.2	6.4	1.1	1.1	44.6	80
Bss3	133-161	10YR 4/3	c	2c abk	10	340	650	200(31)	7.7	5.9	26.4	11.2	1.1	1.1	45.6	87

A 5YR 2.5/1 = Black; 5YR 2.5/2 = Dark reddish brown; 5YR 3/2 = Reddish grey; 5YR 4/3 = Reddish brown; 7.5YR 2.5/2 = Dark brown to very dark grey; 7.5YR 2.5/3 = Dark brown; 7.5YR 3/2 = Dark brown; 7.5YR 3/3 = Dark brown; 10YR 4/3 = Brown; 10YR 4.5/3 = Brown to dark yellowish brown; 10YR 5/4 = Yellowish brown; c = clay; cl = clay loam; scl = sandy clay loam; sic = silty clay; sicl = silty clay loam; 1 f gr = weak fine granular; 1 f sbk = weak fine subangular blocky; 2m sbk = moderate medium subangular blocky; 2c abk = moderate coarse angular blocky; m = massive; B parentheses indicate % of fine clay in total clay.
(Also see Soil Survey Division Staff, 1995).

Table 2. *Morphological, physical and chemical properties of soils of the Western Ghats*

Horizon	Depth (cm)	Morphological Properties[A]			Particle size distribution ($g\ kg^{-1}$)				pH (1:2) water	OC $g\ kg^{-1}$	Extractable bases				CEC	BS (%)
		Munshell Colour (moist)	Texture	Structure	Sand (2000-50 μm)	Silt (50-2 μm)	Clay (<2 μm)	Fine clay (<0.2 μm)			Ca	Mg	Na	K		
											← cmol (+) kg^{-1} →					
Pedon 5: Vertic Argiustalf																
A1	0-15	7.5YR 3/2	c	1f gr	160	330	510	290 (57)B	5.7	20.0	9.2	2.5	0.4	0.5	18.6	68
Bw	15-40	7.5YR 3/2	c	1f gr	120	350	530	310 (58)	5.7	12.1	10.3	2.7	0.4	0.4	18.5	74
Bt1	40-74	5YR 3/3	c	2m sbk	100	290	610	360 (59)	5.7	7.1	10.3	2.8	0.4	0.2	18.7	73
Bt2	74-108	2.5YR 3/4	c	3c sbk	110	280	610	350 (57)	6.1	4.0	12.0	3.9	0.4	0.2	18.6	89
Bt3	108-146	2.5YR 3/4	c	2m sbk	130	340	590	310 (51)	6.1	3.2	12.0	4.6	0.5	0.2	18.7	92
BC1	146-175	2.5YR 3/4	c	2m sbk	130	360	530	250 (47)	6.1	1.1	11.9	5.7	0.4	0.2	20.0	91
BC2	175-190	2.5YR 3/4	c	2m sbk	130	360	510	200 (39)	6.1	1.0	11.7	5.9	0.5	0.3	19.5	94
Pedon 6: Typic Haplustalf																
A	0-9	5YR 3/4	c	1f sbk	150	290	560	330 (59)	5.7	13.1	6.7	3.0	0.6	0.4	8.4	127
Bw1	9-31	5YR 3/4	c	1m sbk	110	330	560	360 (64)	5.3	12.0	7.1	1.5	0.5	0.3	9.8	96
Bt1	31-60	2.5YR 3/4	c	2m sbk	130	370	500	370 (74)	5.3	10.2	6.8	1.6	0.4	0.3	10.6	86
Bt2	60-107	2.5YR 3/4	c	2m sbk	60	270	670	450 (67)	5.6	9.1	9.1	3.3	0.3	0.3	8.6	151
Bt3	107-155	2.5YR 3/4		2m sbk	30	280	690	320 (46)	5.6	6.3	10.4	2.8	0.3	0.3	7.3	189

Table 2. *Morphological, physical and chemical properties of soils of the Western Ghats (contd.)*

Horizon	Depth (cm)	Morphological Properties[A]			Particle size distribution (g kg^{-1})				pH (1:2) water	OC g kg^{-1}	Extractable bases				CEC	BS (%)
		Munshell Colour (moist)	Texture	Structure	Sand (2000-50 µm)	Silt (50-2 µm)	Clay (<2 µm)	Fine clay (<0.2 µm)			Ca	Mg	Na	K		
											←— cmol ($^+$) kg^{-1}	—→				
								Pedon 7: Typic Haplustert								
Ap	0-15	10YR 3/3	c	1m sbk	30	360	610	330 (54)	6.6	9.0	17.3	6.1	0.5	0.4	30.7	79
Bw	15-35	10YR 3/3	c	2m sbk	30	370	600	480 (86)	6.4	7.1	17.4	6.3	0.5	0.4	28.8	85
Bss1	35-82	10YR 3/3	c	3m sbk	40	350	610	440 (72)	6.8	6.2	17.8	11.1	0.7	0.5	28.9	104
Bss2	82-125	10YR 3/2	c	3c abk	40	300	660	460 (70)	6.7	4.9	18.4	11.9	0.8	0.4	30.3	104
Bss3	125-150	10YR 3/2	c	3c abk	40	350	610	510 (84)	6.5	4.8	18.9	11.0	0.8	0.4	39.1	79

A 2.5YR 3/4 = Dark reddish brown; 5YR 3/3 = Dark reddish brown; 5YR 3/4 = Dark reddish brown; 7.5YR 3/2 = Dark brown; 10YR 3/2 = Very dark grayish brown; 10YR 3/3 = Dark brown; c = clay; 1 f gr = weak fine granular; 2m sbk = moderate medium subangular blocky; 3c sbk = strong medium subangular blocky; 3c abk = strong coarse angular blocky; B parentheses indicate % of fine clay in total clay.

(Also see Soil Survey Division Staff, 1995).

These soils were dark grayish brown in colour and had weak columnar structures which broke into subangular blocks whereas the Alfisols of the Western Ghats (P6) had clay texture, subangular blocky structures and dark brown colour. The Vertisols of the Satpura (P4) were clayey and dark brown to dark reddish brown in colour with coarse prismatic structure whereas those of the Western Ghats (P7) had clay texture, angular blocky structures and dark brown colour (Tables 1 and 2).

In general, the sand and silt contents of the soils under study were low compared to clay content (Tables 1 and 2). Total clay and fine clay contents ranged from 280 to 690 g/kg, and from 160 to 510 g/kg, respectively. A higher proportion of the fine clay fraction (Tables 1 and 2) indicates more available reactive surface in these soils.

The Mollisols and Alfisols were more acidic and contain more SOC than the Vertisols (Tables 1 and 2). The Mollisols of Satpura (P1) had much higher CEC than those of the Western Ghats due to the presence of smectites (Tables 1 and 2). Extractable bases indicated a higher proportion of Ca and Mg ions in the exchange sites despite acidic to nearly acidic reaction of the soils (except P4). High base saturation (Tables 1 and 2) was earlier explained by the presence of zeolites (Si-poor heulandites) concentrated in the coarser soil size fractions (Bhattacharyya *et al*., 1993; 1999a). The higher value of OC in the Mollisols as compared to the Alfisols thus appears to be related to their extensive vegetative cover as well as clay mineral type as discussed later.

The fine clay content ranges from 31 to 84% of the total clay and in general it is more than 50% (Tables 1 and 2). Being the most reactive part of the soil colloids, the XRD of the fine clay fractions is discussed here. The fine clay fractions contain smectite, kaolin and insignificant to moderate amounts of mica. Mollisol (P1), Alfisol (P2) and Vertisol (P4) of Satpura range and Vertisol (P7) of the Western Ghats are dominated by smectite, whereas the other Alfisols (P3 and P6) contain much less amount of smectite but are enriched with kaolin mineral (Fig. 3) of 0.7 nm peak. However, a slight shift and tailing of the 0.70 nm peak on glycolation, gradual reinforcement of the 1.00 nm peak with a corresponding decrease in the 0.7 nm peak intensity on K-saturation and subsequent heating (110^{o}-550^{o}C) (Fig. 3), suggested that these kaolins are to some extent interstratified with chloritized smectite (Sm/K) (Bhattacharyya *et al*., 1993, 1999a) and thus are not discrete kaolinite (Bhattacharyya *et al*., 1993, 1997). The interstratification of expanding lattice

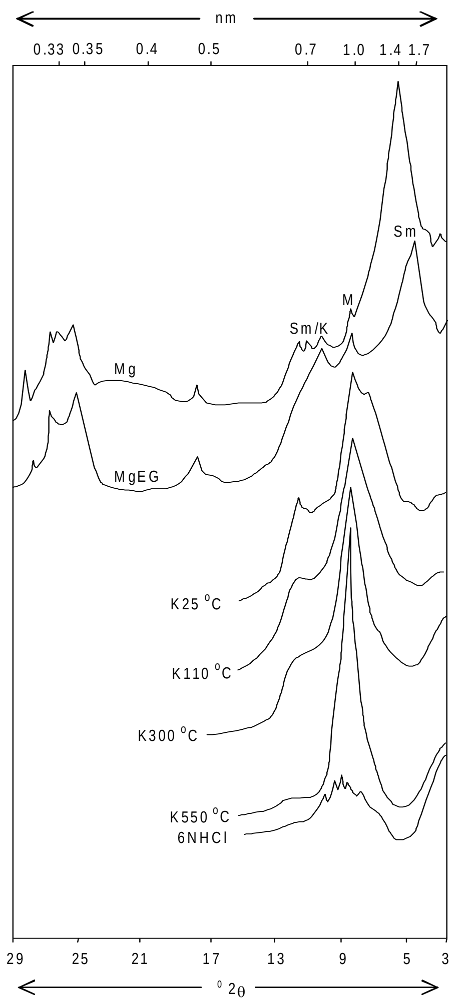

Fig. 3. XRD diagrams of the representative fine clay fractions of Mollisols developed in the Western Ghats (P5) (Bw1-16-37 cm). Mg, Mg-saturated; MgEG, Mg-saturated plus glycerol vapour; K25/110/300/550°C, K-saturated and heated to 25°C, 110°C, 300°C and 550°C; 6 *N* HCl, samples boiled in 6 *N* HCl for 30 minutes. Sm=smectite; M=mica; Sm/K=smectite-kaolin.

minerals in 0.7 nm mineral would thus favour the SOC accumulation because of their much larger surface area as compared to kaolinite. The proportion of smectite in these fractions after peak shift analysis (Wilson, 1987) indicates that the Alfisols (P3 and P6) and Mollisol (P5) also contain small to moderate amount of smectite (Table 3).

The relative proportion of smectite in these Sm/K interstratified minerals is shown in table 3. It shows that although the 0.7 nm reflection appears to be a peak of kaolinite (Hajek, 1985; Yerima et al., 1985, 1987), it actually indicates the presence of some smectite in it (Bhattacharyya *et al.*, 1997). This smectite, along with the discrete smectite minerals, is primarily responsible for the storage of high amounts of SOC in the Mollisols and Alfisols.

Discussion

The land use history of the study area indicates the enrichment of OC in soils under forest vegetation. This is reflected in Mollisol (P1) and Alfisol (P2) of Satpura and Mollisol (P5) of the Western Ghats. However, the extent of SOC accumulation as a function of clay mineral type (smectite) is evident when SOC content of Mollisols and Alfisols under forest of the Satpura and also between Mollisols of Satpura and those of the

Western Ghats are compared (Fig. 2 and Table 3). It is also evident when SOC content and smectite content of Alfisols of Satpura (P3) and that of the Western Ghats (P6) are compared. Even under forests, the Alfisols of the Western Ghats (P6) had lesser amount of SOC due to lower amount of smectite than the Alfisols of the Satpura (P3) under agriculture. This emphasizes a fact that the clay mineral type instead of clay content is a more important factor in accumulation and sequestration of SOC (Feller and Beare, 1997; Parfitt *et al.*, 2002; Wattel-Koekkoek *et al.*, 2003). The correlation coefficient (for the selected horizons within the first 30 cm depth of soils) of the SOC and smectite content for Mollisols and Alfisols support this observation (Fig. 4). The Vertisols of the two catenas although highly enriched with smectites (Table 3) are not, however, enriched with SOC like Mollisols. This is a paradoxical situation. The reality is that the Vertisols not only under this study but also occurring elsewhere do not support

Table 3. *Semi-quantitative estimates of minerals in fine clay fractions (<0.2 µm) of soils (%)*

Depth (cm)	Smectite (Sm)[A]	Mica	Sm/K (Sm:K) (K)[B]
	Satpura Range		
	Pedon 1 : Vertic Haplustoll		
0-6	68 (74)	8	24 (23 : 77) (18)
6-20	73 (79)	10	17 (33 : 67) (11)
20-37	76 (82)	9	15 (33 : 67) (9)
37-74	76 (85)	4	20 (43 : 57) (11)
74-106	72 (82)	5	23 (43 : 57) (13)
106-150	81 (93)	0	19 (65 : 35) (7)
	Pedon 2 : Vertic Haplustalf		
0-10	72 (76)	—	28 (16:84) (23)
10-26	75 (81)	—	25 (24:76) (19)
26-50	71 (78)	—	29 (24:76) (22)
50-85	73 (79)	—	27 (24:76) (20)
	Pedon 3 : Vertic Haplustalf		
0-10	26 (44)	9	65 (28 : 72) (47)
10-30	17 (33)	9	56 (28 : 72) (58)
30-59	34 (50)	9	57 (28 : 72) (41)
59-94	49 (78)	6	45 (65 : 35) (16)
94-151	60 (84)	5	35 (70 : 30) (11)

Table 3. *Semi-quantitative estimates of minerals in fine clay fractions (<0.2 μm) of soils (%) (contd.)*

Depth (cm)	Smectite (Sm)[A]	Mica	Sm/K (Sm:K) (K)[B]
Pedon 4 : Typic Haplustert			
0-17	78 (80)	8	14 (15 : 85) (12)
17-54	73 (79)	8	19 (31 : 69) (13)
54-81	83 (91)	5	12 (64 : 36) (4)
81-133	66 (83)	8	26 (64 : 36) (8)
133-161	85 (91)	3	10 (64 : 36) (6)
Western Ghats			
Pedon 5 : Vertic Argiustalf			
0-15	12 (29)	14	74 (23:77) (57)
15-40	12 (23)	14	74 (15:85) (63)
40-74	16 (26)	15	58 (15:85) (59)
74-108	12 (33)	19	69 (31:69) (48)
108-146	0 (21)	8	92 (23:77) (71)
146-175	0 (7)	8	92 (8:92) (85)
175-190	0 (7)	7	92 (8:92) (85)
Pedon 6 : Typic Haplustalf			
0-9	6 (22)	26	68 (23:77) (52)
9-31	3 (17)	37	60 (25:77) (46)
31-60	9 (23)	30	61 (25:77) (47)
60-107	9 (18)	32	59 (15:85) (50)
107-155	9 (15)	20	71 (8:92) (65)
Pedon 7 : Typic Haplustert			
0-15	22 (48)	—	78 (33:67) (52)
15-35	32 (50)	—	68 (27:73) (56)
35-82	31 (50)	—	69 (28:72) (50)
82-125	44 (58)	—	56 (25:75) (42)
125-150	51 (62)	—	49 (23:73) (36)

[A] Effective smectite (after peak shift analysis) = % Smectite + % smectite from Sm/K
[As an example say for 0-6 cm layer of Mollisol effective smectite] = 68% + 23% of 24
= 68% + 6%
= 74% (for 0-6 cm layer of Mollisol).

[B] Effective kaolin (K) content
(after peak shift analysis) = 77% of 24 = 18% (for 0-6 cm layer of Mollisol).

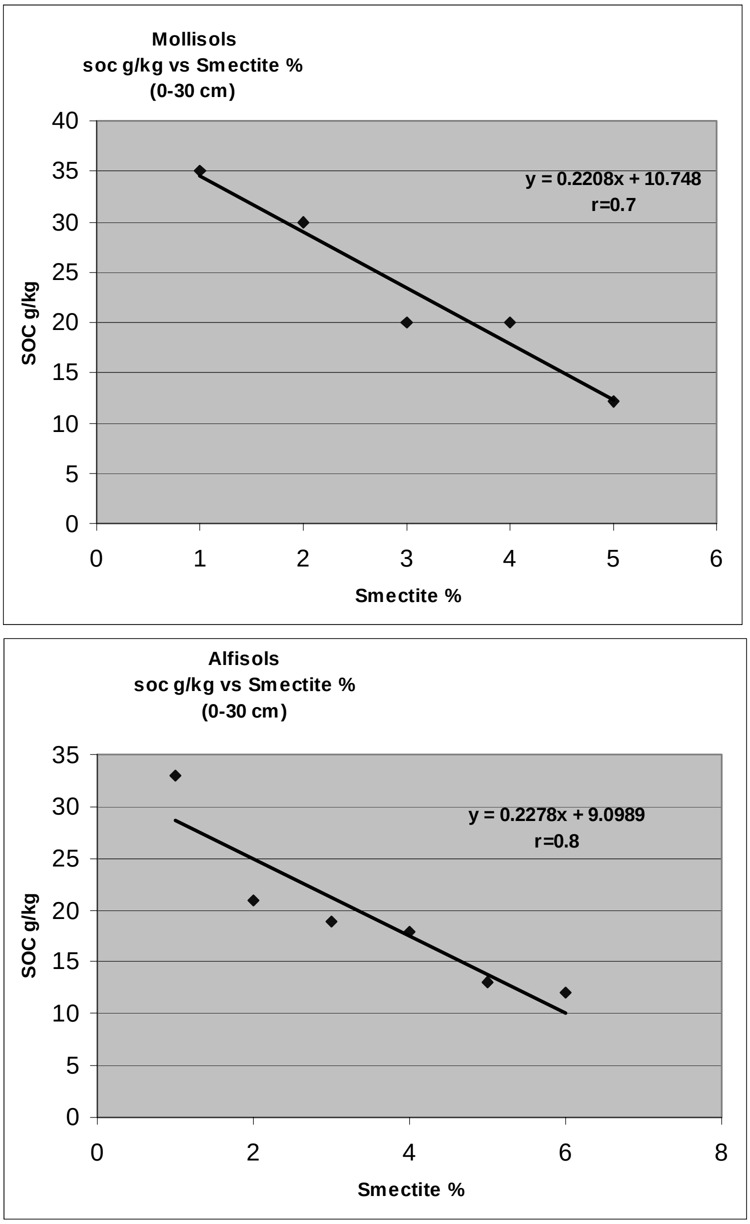

Fig. 4. Relation between SOC and smectite content for (1) Mollisols and (2) Alfisols.

forest plant species with fast growing deep root system (Soil Survey Staff, 1975; Buol *et al*., 1978; Bhattacharyya *et al*., 1999b) because Vertisols (with a depth >100 cm) are capable of tilting trees. This suggests that the Vertisols are capable of sequestering OC but can not because of nonestablishment of forest vegetation in them. Conversely, the Vertisols of the world have high potential of agricultural productivity and thus they are primarily used for agriculture. For any particular soil system under a particular land use, a steady-state is reached in terms of SOC content (Swift, 2001, Batjes, 2001). In the present study under forest and agriculture, Mollisols-Alfisols-Vertisols are tending to attain a stabilized value under the prevailing climate and landuse (Fig. 2). It is understood that the soil environments of Mollisols provide the best conditions for the sequestration of OC. However, in any agriculture dominated country under semi-arid subtropical to humid tropical climates, agriculture is the dominant landuse in Vertisols and soils with vertic intergrades. The SOC values for Vertisols under agricultural system always remain less than those of the Mollisols and Alfisols.

It is known that agricultural systems have an in-built exhaustive mechanism by which soil organic carbon gets depleted (Fenton *et al*., 1999). Recent studies on Vertisols from the semi-arid tropics in India indicate that adoption of agricultural system under monocropping (cotton) has reduced the quasi-equilibrium (QE) values of SOC to 0.4% (Naitam and Bhattacharyya, 2004), indicating that the QE value is reduced in the semi-arid tract with the rise in temperature. By contrast, the present study indicates that SOC content could be much higher in subhumid ecosystems. It is often advocated that OC could be sequestered in soils through green manuring and application of farmyard manure (Prasad and Goswami 1992). Continuous application of farmyard manure for 45 years in black soils with cotton-sorghum cropping system increased SOC from 0.6 per cent to 1.1 per cent (Swarup *et al*., 2000). This suggests that due to the presence of smectite, the Vertisols of the semi-arid tropics could be enriched from their present state of impoverished SOC by improving their physical properties such as low hydraulic conductivity (Kadu *et al*., 2003) and soil compaction (Brevik *et al*., 2002) through appropriate rehabilitation programme (Pal *et al*., 2000, 2003) and cropping systems (Goswami *et al*., 2000; Naitam and Bhattacharyya, 2004) and also by external application of organic inputs (Bhattacharyya *et al*., 2000). This study thus provides a SOC value as upper limit. The SOC of the smectitic and calcareous Vertisols of arid and semi-arid regions could be raised from their impoverished status (~0.5%) to a much higher level (~1%) through agricultural management interventions that are likely to reduce the calcareousness and subsoil sodicity of soils (Pal *et al*., 2000; Swarup *et al*., 2000; Srivastava *et al*., 2002). This possibility may improve the health of shrink-swell soils and also raise the SOC stock of soils in semi-arid part of India to 10.5 Pg in first 30 cm depth soils which could be more than 3 times of the existing SOC stock (Bhattacharyya *et al*., 2000).

Conclusions

Information on the limits of SOC content of the typical soil association of smectitic and non-calcareous Mollisols-Alfisols-Vertisols of tropical India under various land uses indicates that the clay mineral type of soils could be one of the important factors influencing the building up of the SOC. The study also suggests that the impoverished status of SOC of shrink-swell soils of arid and semi-arid climates could be raised to a level of at least ~1% (10 g kg^{-1}) by making them more resilient through appropriate agricultural management interventions.

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References

Batjes, N.H. 2001. Options for increasing carbon sequestration in West African soils : an exploratory study with special focus on Senegal. *Land Degrad. Dev*., **12:** 131-142.

Bhattacharyya, T., Pal, D.K. and Deshpande, S.B. 1993. Genesis and transformation of minerals in the formation of red (Alfisols) and black (Inceptisols and Vertisols) soils on Deccan basalt. *J. Soil Sci*., **44**: 159-171.

Bhattacharyya, T., Pal, D.K. and Deshpande, S.B. 1997. On kaolinitic and mixed mineralogy classes of shrink-swell soils. *Aust. J. of Soil Res*., **35**: 1245-1252.

Bhattacharyya, T., Pal, D.K. and Srivastava, P. 1999a. Role of zeolites in persistence of high altitude ferruginous Alfisols of the Western Ghats, India. *Geoderma*, **90**: 263-276.

Bhattacharyya, T., Pal, D.K. and Velayutham, M. 1999b. A mathematical equation to calculate linear distance of cyclic horizons in Vertisols. *Soil Sur. Hor*., **40**: 109-134.

Bhattacharyya, T., Pal, D.K., Velayutham, M., Chandran, P. and Mandal, C. 2000. Total Carbon stock in Indian soils: Issues, priorities and management. In : Land Resource Management for Food and Environmental Security. *Soil Conservation Society of India*, New Delhi, pp.1-46.

Brevik, E.C., Fenton, T.E. and Moran, L.P. 2002. Effect on soil compaction on organic carbon amounts and distribution, South-Central Iowa, *Environmental Pollution*, **116**, S137-S141.

Brown, G. 1984. Associated minerals. In (G.W. Brindley and G.W. Brown, Eds), *Crystal Structures of Clay Minerals and Their X-ray Identification*. Mineralogical Society, London, pp.361-410.

Buol, S.W., Hole, F.D. and McCracken, R.J. 1978. *Soil Genesis and Classification*. Oxford and IBH Publ. Co., New Delhi, India.

Feller, C. and Beare, M.H. 1997. Physical control of soil organic matter dynamics in the tropics. *Geoderma*, **79**: 69-116.

Fenton, T.E., Brown, J.R. and Mausbach, M.J. 1999. Effects of long-term cropping on organic matter content of soils : implications for soil quality. In (R. Lal, Ed.), *Soil Quality and Soil Erosion*, CRC Press, New York, pp.95-124.

Gjems, O. 1967. Studies on clay minerals and clay mineral formation in soil profiles in Scandinavia. *Medd. Nor. Skogsforsk*, **21**: 303-415.

Goswami, N.N., Pal, D.K., Narayanasamy, G. and Bhattacharyya, T. 2000. Soil organic matter - Management Issues. Invited Paper. In : *International Conference on Managing Natural Resources for Sustainable Agricultural Production in the 21st Century*, New Delhi, pp.87-96.

Hajek, B.F. 1985. Mineralogy of Aridisols and Vertisols. In:Proccedings 5th International Soil Classification. *Soil Survey Administration*, Khartoum, Sudan, pp.221-230.

Jackson, M.L. 1973. *Soil Chemical Analysis*, Prentice Hall, India.

Jackson, M.L. 1979. *Soil Chemical Analysis*, Advanced Course. 2nd edn. University of Wisconsin, Madison, WI, USA, 11th Printing, Published by the author. 895 p.

Kadu, P.R., Vaidya, P.H., Balpande, S.S., Satyavathi, P.L.A. and Pal, D.K. 2003. Use of hydraulic conductivity to evaluate the suitability of Vertisols for deep-rooted crops in semi-arid parts of central India. *Soil Use Managt*., **19**: 209-216.

Murthy, R.S., Bhattacharjee, J.C., Landey, R.J. and Pofali, R.M. 1982. Distribution, characteristics and classification of Vertisols. *Trans. 12th Int. Congr. Soil Sci*., **2**: 3-22.

Naitam, R. and Bhattacharyya, T., 2004. Quasi-equilibrium of organic carbon in shrink-swell soils of the subhumid tropics in India under forest, horticulture, and agricultural systems. *Aust. J. Soil Res*., **42**: 181-188.

Olson, K.R., Fenton, T.E., Smeck, N.E., Hammer, M.D., Ransom, C.W., Zanner, C.W., McLeese, R. and Sucik, M.T., 2005. Proposal modifications of mollic epipedon thickness criteria for eroded conditions and potential impacts on existing soil classification. *Soil Surv. Horizons*, **46**: 39-47.

Pal, D.K., Bhattacharyya, T., Ray, S.K. and Bhuse, S.R., 2003. Developing a model on the formation resilience of naturally degraded black soils of the Peninsular India as a decision support system for better land use planning, *NRDMS, DST Project Report*, NBSSLUP (ICAR), Nagpur, 144 p.

Pal, D.K., Dasog, G.S., Vadivelu, S., Ahuja, R.L. and Bhattacharyya, T. 2000. Secondary calcium carbonate in soils of arid and semi-arid regions of India. In (R. Lal, J.M. Kimble, H. Eswaran, and B.A. Stewart, Eds), *Global Climate Change and Pedogenic Carbonate*, Lewis Publishers, CRC Press, Boca Raton, Florida, pp. 149-185.

Parfitt, R.L., Purshotam, A. and Salt, G.J. 2002. Carbon turnover in two soils with contrasting mineralogy under long term maize and pasture. *Aust. J. Soil Res*., **40**: 127-136.

Prasad, R. and Goswami, N.N., 1992. Soil fertility restoration and management for sustainable agriculture in South Asia. *Adv. Soil Sci*., **17**: 37-77.

Shirsath, S.K., Bhattacharyya, T. and Pal, D.K. 2000. Minimum threshold value of smectite for vertic properties. *Aust. J. Soil Res*., **38**: 189-201.

Soil Survey Division Staff, 1995. *Soil Survey Manual*, United States Department of Agriculture, Handbook No. 18, New Revised Edition Scientific Publishers, Jodhpur, India, p. 437.

Soil Survey Staff, 1975. *Soil Taxonomy : A Basic System of Soil Classification for making and Interpreting Soil Surveys*. USDA-SCS Agricultural handbook 436. U.S. Govt. Printing Office, Washington, DC.

Soil Survey Staff, 2003. *Keys to Soil Taxonomy*, 9th Edition, United States Department of Agriculture, Natural Resources Conservation Service, Washington, D.C. p.332.

Srivastava, P., Bhattacharyya, T. and Pal, D.K. 2002. Significance of the formation of calcium carbonate minerals in the pedogenesis and management of cracking clay soils (Vertisols) of India. *Clays Clay Miner*., **50**: 111-126.

Swarup, A., Manna, M.C. and Singh, G.B. 2000. Impact of land use and management practices on organic carbon dynamics in soils of India. In (R. Lal, J.M. Kimble and B.A. Stewart, Eds), *Global Climate Change and Tropical Ecosystems*, CRC Press, Boca Raton, Florida, pp. 261-281.

Swift, S.R. 2001. Sequestration of carbon by soil, *Soil Sci*., **166**: 858-871.

Walkey, A. and Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter and proposed modification of the chromic acid and titration method. *Soil Sci*., **37**: 29-38.

Wattel-Koekkoek, E.J.W., Buurman, P., van der Plicht, J., Wattel, E. and van Breemen, N. 2003. Mean residence time of soil organic matter associated with kaolinite and smectite. *Eur. J. Soil Sci*., **54**: 269-278.

Wilson, M.J. 1987. X-ray powder diffraction methods. In (M.J. Wilson, Ed.), *A Handbook of Determinative Methods in Clay Mineralogy*, Chapman and Hall, New York, pp.26-98.

Yerima, B.P.K., Colhom, F.G., Senkayi, A.L. and Dixon, J.B. 1985. Occurrence of interstratified kaolinite-smectite in El Salvador Vertisols. *Soil Sci. Soc. Am. J*., **49**: 462-466.

Yerima, B.P.K., Wilding, L.P., Calhoun, F.G. and Hallmark, C.T. 1987. Volcanic ash-influenced Vertisols and associated Mollisols of El Salvador : physical, chemical and morphological properties. *Soil Sci. Soc. Am. J*., **51**: 699-708.