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Quasi-equilibrium of organic carbon in shrink–swell soils of the subhumid tropics in India under forest, horticulture, and agricultural systems

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Abstract. Restoration of soil quality through soil organic carbon (SOC) management has been a major concern for tropical soils. SOC is sensitive to human activities such as deforestation, biomass burning, land-use changes, and environmental pollution. Our aim in this study was to elucidate the effect of land-use systems on quasi-equilibrium values (QEV) of SOC. To determine the QEV of SOC, 4 representative pedons from Nagpur district, Maharashtra, under horticulture (orange), agriculture (cotton, cotton + pigeonpea), and forest (teak) with the time of cultivation ranging from 20 years to centuries were selected. The study indicated that the QEV of SOC in the shrink–swell soils decreased when they were used for agricultural crop production. Since all these soils have similar substrate, the SOC equilibrium values obtained in soils of horticultural and forest ecosystems may also be attainable in the soils under agricultural system. In other words, addition of external sources of farmyard manure or other green manure may raise the QEV of SOC from 0.44–0.51% to 0.70–0.80% in soils of agricultural system.

Additional keywords: quasi-equilibrium, swell–shrink soils, land-use systems.

Introduction

Restoration of soil quantity and quality through soil organic carbon (SOC) management is a major concern for tropical soils. To sustain their quality and productivity, knowledge of SOC in terms of its amount and quality needs to be improved.

The amount of SOC declines (Arrouays and Pelisser 1994) when the land area under agricultural activity is increased to produce more food grains. Through the process of decomposition of available SOC due to increased exposure of soil surface for cultivation, its content further decreases (Lal *et al*. 1995). There is a rapid change in SOC within the first 5–25 years, with losses ranging from 25 to 75% in the uppermost soil horizons with a change from forest to agriculture (Lal *et al*. 1995).

Soil systems attain a quasi-equlibrium stage after accumulation of dry matter as well as loss of SOC over time depending on land-use system. Thus, SOC levels often show tooth-like cycles of accumulation and loss (Batjes 2001). After each change in land-use system, a period of constant management is required to reach a new quasi-equilibrium stage. In this way the SOC is stabilised to another quasi-equilibrium value (QEV) characteristic of that changed situation in terms of new land-use pattern, vegetation cover, and management practice. It has been reported that under natural vegetation, SOC values tend to attain QEVs with varying duration of 500–1000 years in a forest system (Jenny 1950; Dickson and Crocker 1953), 30–50 years in agricultural systems after forest cutting (Arrouays *et al*. 1995; Johnson 1995; Batjes 2001), and 5–15 years in agricultural systems after forest cutting in red soils in Orissa (Saikh *et al*. 1998). Such reports confirm changes in SOC due to changes in land-use systems.

By and large, the shrink–swell soils (Vertisols and their associates) under agricultural system in India show a QEV of 0.5–0.6% SOC in the surface layers (Bhattacharyya *et al*. 2000*b*). These soils have been reported to occupy the deficient zone of the soil organic carbon map of India (Velayutham *et al*. 2000). 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. This knowledge can be acquired if we can study soils with similar substrate (mineralogy). In view of this, the present study aims to provide SOC QEVs of soils under various landuse systems. This information can be used as a guideline for the future organic carbon sequestration in the shrink-swell soils under agriculture in areas having similar climate.

Material and methods

Sites and environments

The study area of Nagpur district, Maharashtra, India is characterised by a hot summer and dry weather conditions, except during the south-west monsoon season, and thus represents a typical subhumid (moist)

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climate (Mandal and Mandal 1998). Mean annual temperature and rainfalll of the area are 25.9°C and 1010 mm, respectively.

From a reconnaissance survey, 4 pedons were selected for the present study. These pedons represent the soils belonging to Linga, Panjri, Rui, and Makardhokra series. The 4 soil series represent the dominant land use pattern of the district. The sites for collecting soil samples were selected from the available information in the soil map of the district (Anon. 1990). Each soil polygon mapped at the level of soil

Table 1. Soils and different systems of study area in Nagpur district, Maharashtra, India

Pedon no.	Soil Series	Village/tahsil	Soil Classification (family)[A]	System	Crops	Duration (years)
1	Linga	Wandli/Katol	Very fine, smectitic, hyperthermic, Udic Haplusterts	Horticulture	Orange	30
2	Panjri	Panjri/Nagpur	Very fine, smectitic, hyperthermic, Typic Haplusterts	Agriculture	Cotton (monocrop)	20
3	Rui	Rui/Nagpur	Very fine, smectitic, hyperthermic, Leptic Haplusterts	Agriculture	Cotton + pigeonpea intercropping	50
4	Makardhokra	Boripani/Umred	Fine, smectitic, hyperthermic, Vertic Haplustepts	Forest	Teak (*Tectona spp.*)	Centuries

[A] Soil Survey Staff (1999), Soil Taxonomy.

Table 2. Morphological properties of soils

Horizon	Depth (cm)	Munsell Colour (moist)	Texture	Coarse fragments (vol/vol basis) %	Structure[A]	Roots Size	Roots Quantity	Effervescence in dil. HCl	Other features
Pedon 1: Horticultural system (orange)									
Ap	0–15	10YR3/2	Clay	5–8	m2 sbk	Fine, medium, coarse	Few	Slight	Pressure faces
Bw	15–41	10YR3/2	Clay	5–8	m2 sbk	Fine, medium, coarse	Few	Slight	Slickensides
Bss1	41–70	10YR3/2	Clay	3–5	c2 abk to m2 abk	Fine, medium, coarse	Few	Slight	Slickensides
Bss2	70–95	10YR3.5/2	Clay	3–5	c3 abk	Very fine, fine	Few	Slight	Slickensides
Bss3	95–135	10YR4/2	Clay	1–2	c3 abk	Very fine	Few	Slight	Slickensides
Bss4	135–155+	10YR4/3	Clay	1–2	m2 abk	Nil	Nil	Strong	Pressure faces
Pedon 2: Agricultural system (cotton)									
Ap	0–13	10YR3/2	Clay	3–5	m2 sbk	Coarse, fine	Few	Slight	–
Bw1	13–38	10YR3/2	Clay	3–5	m3 sbk	Very fine, fine	Few	Slight	Pressure faces
Bss1	38–60	10YR4/2	Clay	5–8	m3 abk(w)	Very fine, fine	Few	Slight	Slickensides (weak)
Bss2	60–89	10YR3/2	Clay	3–5	c3 abk	Very fine, fine	Few	Slight	Slickensides
Bss3	89–131	10YR4/3 10YR3.5/2	Clay	1–3	c3 abk	Very fine, fine	Few	Slight	Slickensides
Bss4	131–150	10YR4/3.5	Clay	5–8	m3 abk	Very fine	Few	Slight	Slickensides
Pedon 3: Agricultural system (cotton + pigeonpea)									
Ap	0–17	10YR3.5/2	Clay	3–5	m2s bk	Fine, very fine	Few	Slight	–
Bwk	17–47	10YR3.5/2	Clay	3–5	m2 sbk	Coarse	Few	Slight	Pressure faces
Bssk	47–80	10YR3.5/2	Clay	3–5	m3 abk	Fine	Few	Slight	Slickensides
Ck	80–94			Weathered basalt				Strong	
Pedon 4: Forest system (teak)									
A1	0–16	10YR3/2	Clay	2–3	c2/1 pr m2 sbk	Fine, medium	Many	Slight	–
BW1	16–44	10YR3/2	Clay	2–3	m2 sbk	Fine, medium, coarse	Many	Slight	Pressure faces
BW2	44–57	10YR3/2	Clay	3–5	m2 sbk	Fine, medium, coarse	Many	Slight	Pressure faces
CK1	57–94	10 YR4/6 (R)	Clay	45–50	Massive	Fine, medium	Common	Violent	–

[A] m, Medium; c, coarse; 1, weak; 2, medium; 3, strong; abk, angular blocky; sbk, subangular blocky; pr, prismatic.

series association was studied carefully to locate the exact pedon sites. The soil series information showing latitudes and longitudes available in earlier soil survey report (Anon. 1990) allowed us to reach the exact Benchmark spot using a global positioning system (GPS).

The site for pedon 1 (Linga soil series, Udic Haplustert; Soil Survey Staff 1999) has been under horticulture (orange) for last 30 years (Table 1). These soils are developed in basaltic alluvium on very gently sloping plains. The natural vegetations are *Acacia* and jujube (*Zizyhpus jujuba*). The site for pedon 2 (Panjri soil series, Typic Haplustert) has been under cotton for >20 years (Table 1). These soils are also developed in basaltic alluvium on level to very gently sloping plains. The natural vegetation consists of *Acacia*, mango, mahua (*Madhuca indica*), and *dub* grass (*Cynodon dactylon*). The site for pedon 3 (Rui soil series, Leptic Haplustert) has been under cotton + pigeonpea for last 50 years (Table 1). These soils are developed in basaltic alluvium on very gently sloping plains. The natural vegetations are dominated by *Acacia* and jujube. The site for pedon 4 (Makardhokra soil series, Vertic Haplustept) is under forest for centuries (Table 1). These soils are developed in weathered basalt on very gently sloping to undulating land. The dominant forest species include teak (*Tectona* sp.). Other forest species include khair (*Acacia catechu*), palas (*Butea* sp), mahua, and different wild varieties of shrubs and bushes.

These 4 pedons, representing dominant soils of the district, occupy nearly 25% of the total geographical area of the district (986 397 ha). They represent Benchmark sites of shrink–swell soils in terms of areal extent as well as major land uses (Sehgal *et al.* 1988). Since the forest soils have experienced less disturbance than agricultural soils they were used as control.

Materials

Keeping in view the available information about the soil sites, the profiles were dug and examined in terms of the morphological properties of the soils following standard methods (Soil Survey Division Staff 1995) (Table 2). Horizon-wise soil samples were collected for laboratory analyses. Core samples were also collected in the field to determine bulk density values. The soils were classified following Soil Taxonomy (Soil Survey Staff 1999).

Methods

Physical properties of the soils, such as particle-size distribution, were determined by the International Pipette method after removal of organic matter, $CaCO_3$, and free iron oxide using citrate–bicarbonate–dithionite treatment (Mehra and Jackson 1960). The coefficient of linear extensibility (COLE) was estimated following the methods of Schafer and Singer (1976), and is defined as the ratio of the difference between the moist length (Lm, length of soil clod at 33 kPa) and dry length of a clod to its dry length [Ld, length of soil clod when dry (room temperature)] (Soil Survey Staff 1999). The bulk density was determined by a field-moist method using core samples (diam. 50 mm) of known volume (100 cm^3) (McIntyre 1974; Klute 1986). The physical (particle size separates) and chemical [pH, extractable cations, cation exchange capacity (CEC)] properties of the soils were determined by standard methods (Richards 1954).

For the determination of SOC, the modified Walkley and Black rapid titration procedure was used (Walkley and Black 1934; Jackson 1973). Organic matter was fractionated using the procedure of

Table 3. Selected physical properties of soils

Horizon	Depth (cm)	Particle size (%)					COLE	Bulk density (Mg/dm^3)
		Sand (200–50 μm)	Silt (50–2 μm)	Coarse clay (2–0.2 μm)	Fine clay (<0.2 μm)	Total clay (<2 μm)		
				Pedon 1: Horticultural system (orange)				
Ap	0–15	0.9	33.4	19.7	46.0	65.7	0.24	1.4
Bwk1	15–41	0.5	30.5	18.0	51.0	69.0	0.23	1.4
Bssk1	41–70	0.3	29.0	15.0	55.7	70.7	0.24	1.3
Bssk2	70–95	0.2	28.7	15.1	56.0	71.1	0.23	1.3
Bssk3	95–135	0.3	27.0	14.5	58.2	72.7	0.25	1.4
Bssk4	135–155+	0.2	28.8	20.0	51.0	71.0	0.20	1.3
				Pedon 2: Agricultural system (cotton)				
Ap	0–13	0.6	44.0	13.4	42.0	55.4	0.21	1.5
Bwk1	13–38	0.4	42.1	8.0	49.5	57.5	0.21	1.5
Bssk1	38–60	0.3	31.7	15.0	53.0	68.0	0.22	1.4
Bssk2	60–89	0.3	32.5	12.9	54.3	67.2	0.22	1.5
Bssk3	89–131	0.3	43.7	6.8	49.2	58.0	0.23	1.4
Bssk4	131–150+	0.2	31.2	14.6	54.0	68.5	0.23	1.4
				Pedon 3: Agricultural system (cotton + pigeonpea)				
Ap	0–17	0.9	34.7	17.5	46.9	64.4	0.23	1.5
Bwk1	17–47	1.1	31.4	16.6	50.9	67.5	0.22	1.6
Bssk	47–80	0.8	30.9	17.5	50.8	68.3	0.22	1.6
Ck	80–94	3.2	25.8	16.7	54.3	71.0	0.23	n.d.
				Pedon 4: Forest system (teak)				
A1	0–16	1.0	29.0	27.4	42.6	70.0	0.25	1.3
Bwk1	16–44	1.0	25.0	31.0	43.0	74.0	0.27	1.3
Bwk2	44–57	1.2	24.0	23.2	51.6	74.8	0.23	1.4
2Ck1	57–94	35.1	16.7	11.8	36.4	48.2	0.13	1.3

n.d., Not determined.

Stevenson (1982). Acid (0.1 M HCl) washed soil samples were shaken with 0.5 M NaOH to separate the humic acid fraction of organic matter using concentrated HCl. The process was repeated to improve yield before purification. QEVs were calculated from the SOC values for depths of 0–30, 0–50, and 0–100 cm, using weighted mean values of SOC for each horizon thickness. The weighted mean values for individual horizons were then calculated for the 30 (0–30 cm), 50 (0–50 cm), and 100 (0–100 cm) cm soil depths to estimate the QEV for those soil depths.

The E_4/E_6 ratio measurement is taken to provide a measure of degree of condensation of aromatic rings present in these materials, i.e. the relative proportions of aliphatic and aromatic groups. The high percentage transmittance values (or optical density values) at longer wavelength are believed to be associated with an increased mobility of the delocalised electron clouds over aromatic carbon nuclei. This is why humic acids are expected to register higher E_6 and lower E_4 values than the corresponding fulvic acids. It has been stated that the E_4/E_6 ratio of soil humic substances is primarily governed by the particle size, molecular weight, and degree of aromacity. Higher molecular weight and higher degree of aromatisation indicate the formation of more humic acid over a period of time through the process of decomposition. Since the higher molecular weight and more aromatised humic acid takes more time to form through decomposition of organic matter in soil, identification of humic acid in soil organic matter indicates a greater lapse of time, showing greater maturity of humus. Optical density and E_4/E_6 ratio of the humic acid in alkaline solution (1 M KOH) were studied using a Hitachi (124/1908) spectrophotometer at 465 nm and 665 nm wavelengths (Schnitzer 1977).

Results and discussion

The particle size separates (sand, silt and clay) are given in Table 3. These soils were clayey, as also shown by the very fine textural class (Table 2) (Soil Survey Staff 1999). The COLE values indicated that these soils have high shrink–swell properties (Shirsath *et al.* 2000). Bulk density values ranged from 1.3 to 1.6, with pedon 3 under cotton+pigeonpea system registering a relatively high value (Table 3).

Calcium carbonate ($CaCO_3$) content increased with depth in all of the soils. The soils were mildly to moderately alkaline except those in forest system. The low electrical conductivity values indicated that these soils were not saline. CEC of the soils was high. It was found that 66–82% of the total cations were Ca^{2+} ions, indicating good reserves of nutrient in these soils (Table 4).

Soil organic carbon

The SOC decreased with depth particularly below 50 cm in the case of the agricultural system (cotton and cotton +

Table 4. Selected chemical properties of soils

SCS, Soil Control Section which is defined by a depth of 25 cm to (i) a lithic contact or paralithic contact if it is within a depth of 1 m; (ii) a depth of 1 m if the regolith is >1 m thick (Soil Survey Staff 1999)

Depth (cm)	pH (1:2.5 water)	Electrical conductivity (dS/m)	$CaCO_3$ (%)	Extractable bases				CEC		
				Ca	Mg	Na	K	Soil	Clay[A]	Clay (SCS)
Pedon 1: Horticultural system (orange)										
0–15	8.2	0.2	6.0	37.6	10.4	1.7	1.3	51.3	87	125
15–41	8.0	0.2	7.0	39.4	9.8	1.7	0.8	70.0	101	
41–70	8.0	0.2	7.0	37.2	9.4	1.9	0.8	70.6	100	
70–95	8.0	0.2	6.1	36.2	11.2	2.0	0.8	62.7	88	
95–135	8.1	0.2	5.2	38.0	14.6	2.2	0.9	55.6	76	
135–155+	8.0	0.3	8.5	34.8	13.2	2.0	0.9	63.0	89	
Pedon 2: Agricultural system (cotton)										
0–13	8.0	0.1	5.0	43.6	8.8	1.4	1.1	57.7	104	127
13–38	8.0	0.1	5.0	42.0	8.4	1.4	0.8	56.4	98	
38–60	8.1	0.1	6.2	42.2	9.0	1.5	0.8	56.6	83	
60–89	8.1	0.1	8.5	41.2	11.8	1.4	0.8	56.4	83	
89–131	8.0	0.2	6.1	42.4	10.0	1.3	0.8	56.0	94	
131–150+	8.3	0.2	6.3	34.0	19.4	1.4	0.8	51.7	75	
Pedon 3: Agricultural system (cotton + pigeonpea)										
0–17	8.0	0.2	5.1	42.0	7.4	1.6	1.3	44.2	68	103
17–47	7.9	0.2	4.3	43.4	6.0	1.5	0.9	54.7	81	
47–80	8.0	0.2	6.5	40.8	3.6	1.5	0.9	52.4	76	
80–94	7.9	0.2	8.3	40.8	4.6	1.5	0.9	54.6	77	
Pedon 4: Forest system (teak)										
0–16	7.5	0.1	4.1	44.4	8.8	1.3	0.7	55.5	79	146
16–44	7.6	0.1	4.5	49.6	7.6	1.4	0.6	64.5	68	
44–57	7.8	0.1	7.7	47.2	8.6	1.4	0.7	61.0	81	
57–94	7.9	0.2	11.2	55.6	11.2	1.4	0.3	76.7	159	

[A] Clay CEC is estimated by dividing soil CEC by clay percentage.

pigeonpea). The SOC under horticulture ranged from 0.2 to 0.8% at soil depth 0–155 cm, whereas the soils in the forest system contained higher amounts of SOC, ranging from 0.7 to 0.9% to a depth of 57 cm. Below this depth the SOC content reduced sharply to 0.1% due to the presence of weathered rock materials. In the horticultural system, the SOC content was maintained at 0.5% to a depth of 100 cm with the surface soil containing SOC as high as 0.8%. In the cotton and cotton + pigeonpea systems, on the other hand, SOC was 0.5% in the top 50 cm depth (Table 5).

Humic acid

Relatively more humic acid in surface (0.03–0.09% of soil) than subsurface (0.003–0.004% of soil) layers was due to more decomposition of plant tissue to soil humic substances in the surface layer where the biochemical conversion of open chain compounds into aromatic products resulted in the formation of humus. The relative proportions of decomposed, partly decomposed, and undecomposed organic material determine the amount of humic acid present in various soil layers (Bhattacharyya 1984). Maximum Walkley–Black humic acid carbon (HAC) was found in the horticultural system (orange). This was followed by the soil under cotton and cotton + pigeonpea and the forest system, respectively (Table 5). For the cotton + pigeonpea and forest systems these values were low when compared with the values obtained under other systems.

E_4/E_6 ratio

Judging by the relatively low E_4/E_6 values (0.60–0.72), it appears that humic acid in the surface soils are more aromatised than those in the subsurface soils (Table 5). More aromatisation indicated higher degree of maturity of humus (Kononova 1966; Schnitzer 1977; Sanyal 2001). The higher HAC values also support this observation (Bhattacharyya 1984). When E_4/E_6 values were compared between soils under different systems, the surface soils under horticulture registered the lowest E_4/E_6 values of 0.6, followed by those under cotton + pigeonpea system. This suggests that the degree of maturity of humus in the horticultural and cotton + pigeonpea systems was higher than in the forest and cotton systems. The introduction of a leguminous crop in the form of pigeonpea thus helped to improve aromatisation, as observed by the low E_4/E_6 value. Forest systems generally provide an environment where degree of aromatisation was expected to be high. However, the forest system in the basaltic landscape with shrink–swell soils in this study area showed a poor rate of decomposition of organic matter based on high E_4/E_6 values and low HAC (Table 5). The major reason was the thin crop canopy in the forest area due to poor

Table 5. Characteristics of humic acids extracted from soils

Depth (cm)	SOC (%)	% Transmittance 465 nm (E_4)	665 nm (E_6)	E_4/E_6 ratio	HAC[A] (%)
		Pedon 1: Horticultural system (orange)			
0–15	0.80	47.0	78.0	0.60	55.4
15–41	0.70	46.0	75.0	0.61	41.2
41–70	0.60	49.0	78.5	0.62	46.5
70–95	0.50	45.5	76.0	0.60	33.9
95–135	0.42	57.0	72.0	0.79	42.5
135–155+	0.20	63.0	72.5	0.87	37.1
		Pedon 2: Agricultural system (cotton)			
0–13	0.50	47.0	66.0	0.71	49.7
13–38	0.40	57.0	67.0	0.76	54.5
38–60	0.40	72.0	82.0	0.93	39.7
60–89	0.20	76.0	84.0	0.90	24.9
89–131	0.20	61.0	70.0	0.87	15.0
131–150+	0.10	64.0	74.0	0.86	15.2
		Pedon 3: Agricultural system (cotton + pigeonpea)			
0–17	0.60	49.0	75.0	0.65	29.3
17–47	0.50	39.0	69.0	0.56	30.7
47–80	0.40	42.0	75.0	0.56	34.1
80–94	0.30	54.0	69.0	0.78	20.0
		Pedon 4: Forest system (teak)			
0–16	0.90	61.0	85.0	0.72	36.1
16–44	0.70	74.0	88.0	0.84	34.2
44–57	0.70	83.0	90.0	0.92	32.0
57–94	0.10	71.0	84.0	0.84	18.5

[A] HAC, humic acid carbon, percentage of humic acid.

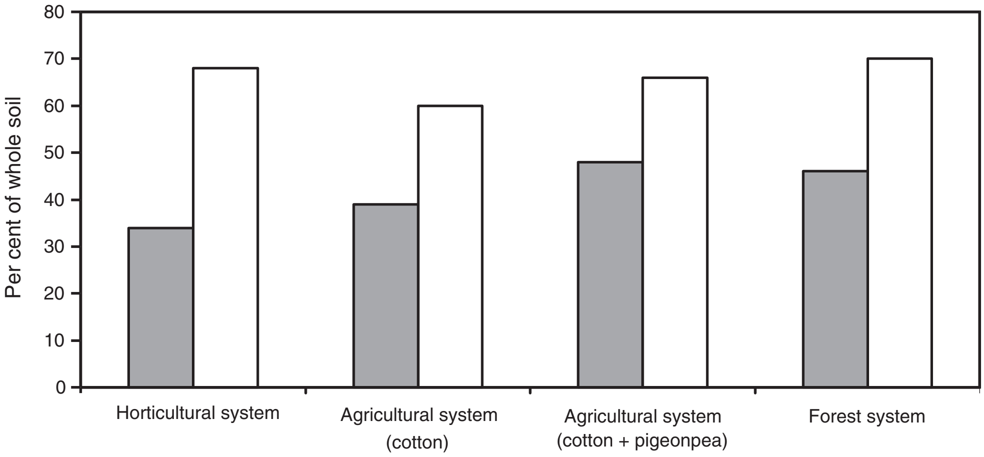

Fig. 1. Substrate quality of swell-shrink soils in terms of clay (☐) and smectite (▨) content under different systems.

management and also shallow soil depth (~50–57 cm). Similar observations were made by Stevenson (1982) while reporting characteristics of humic acid extracted from forest soils.

Quality of soil substrate

Organic carbon in soil is retained in a complex form (Grim 1968; Greenland 1971; Bhattacharyya and Ghosh 1995). The decomposed soil organic matter is stored in the form of humic acid with inorganic clay through polyvalent cations as bridge-linked compounds (Varadachari *et al*. 1991; Bhattacharyya and Ghosh 1994, 1995; Ahmed *et al*. 2002). This suggests that carbon sequestration depends primarily on the quantity and quality of the inorganic colloid as the main substrate and reactive surface of soils (Tate and Theng 1980; Feller and Beare 1997; Parfitt *et al*. 2002). The present investigation showed that the quantity (total clay and fine clay) (Table 3) and the quality of soil substrate (total clay, smectites) (Fig. 1) were similar across the 4 soils. Mineralogical analysis of clay samples indicated the dominance of smectite in all 4 soils. We conclude therefore that the observed variation of SOC in these soils was primarily due to differences in land-use systems.

Quasi-equilibrium value of SOC

While establishing the trend in QEV of SOC, it was observed that under the horticultural system within the first 50 cm depth, a QEV of 0.7% had been attained over the past 30 years of orange cultivation. Among the 3 systems, the highest QEV was attained in forest (Fig. 2). This value ranged from 0.76 to 0.80% within the first 50 cm depth of soils. Low QEV in the cotton system, however, indicated greater nutrient uptake characteristics of this crop, as observed in the present study. When pigeonpea was

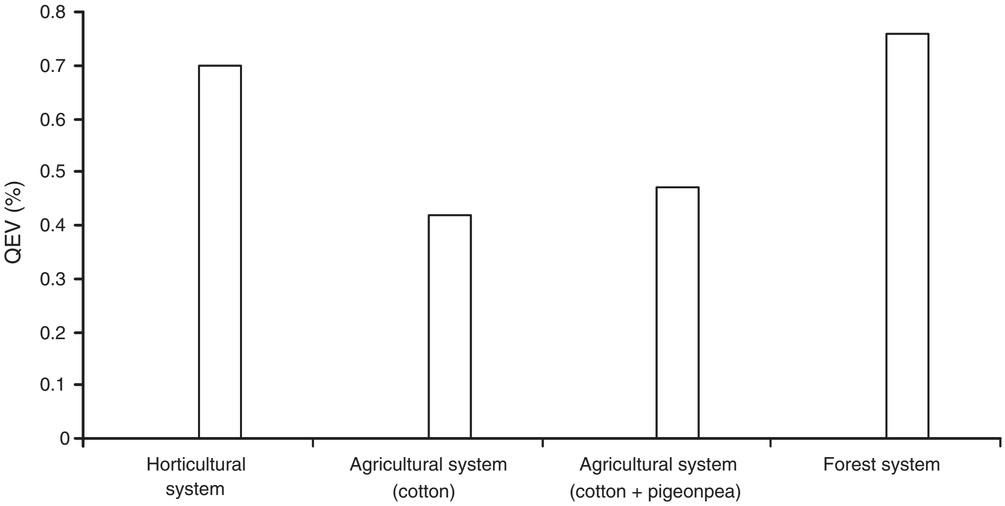

Fig. 2. QEV of organic carbon in swell–shrink soils under different systems.

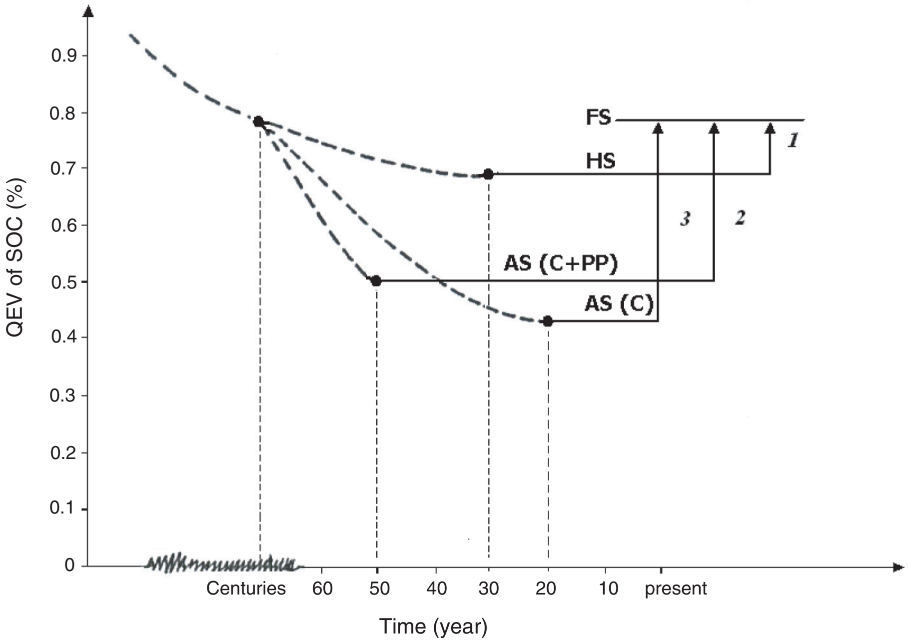

Fig. 3. QEV in swell–shrink soils *v.* time under different systems and their scope for improvement in terms of increasing QEV in the first 30 cm soil depth. FS, Forest system; HS, horticultural system; AS (C + PP), agricultural system (cotton + pigeonpea); AS (C), agricultural system (cotton); 1, scope for soils in HS (0.1%) to reach FS; 2, scope for soils in AS (C + PP) (0.2%) to reach FS; 3, scope for soils in AS (C) (0.3%) to reach FS.

introduced with cotton, the soils became richer in terms of SOC, since pigeonpea is a leguminous crop and contributed more organic matter and nitrogen (Carter *et al.* 1998; Lal 2000).

Conclusions

The present study provides evidence that the shrink–swell soils in the subhumid tropics in India under forest and horticultural systems have attained a QEV of 0.80 and 0.70% over a period of 30 years, and centuries, respectively. Continuous cultivation of cotton (as a single crop) for 20 years and cotton + pigeonpea for 50 years has drastically reduced the QEV. This indicates that when shrink–swell soils are put to agricultural use the QEV of SOC may decrease. Since all these soils have similar clay minerals and mineralogy we conclude that the variation in QEV in these soils is primarily due to difference in land-use systems. The similarity in substrate quality indicates that the soils under agricultural system have the potential to attain QEVs similar to that observed in horticultural and forest systems (Fig. 3). This could be achieved through the addition of external sources of farmyard manure or other green manures (Bhattacharyya *et al.* 2000*a*, 2000*b*), which could potentially increase the present QEV from 0.44–0.51% in soils of agricultural system to 0.70–0.80% observed in the soils of horticultural and forest systems in the subhumid tropical climate of India.

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