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REVIEW

Carbon Sequestration in Indian Soils: Present Status and the Potential

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Abstract India's growing self-sufficiency in food production and food stocks since independence suggest that soils have the capacity to produce. Therefore, a review of Indian soils and their capacity to sequester carbon; and the factors favouring C sequestration under different land uses is in order. Several researchers, especially those in The National Bureau of Soil Survey and Land Use Planning and the International Crops Research Institute for Semi-Arid Tropics monitored the changes in soil organic (SOC) and inorganic (SIC) carbon as influenced by land use in the Indo-Gangetic Alluvial Plains and black soil regions between 1980 and 2005; and the results showed an increase in SOC stocks due to turnover of greater plant biomass into the soil. Results of long-term fertilizer experiments with rice-based double or triple cropping systems indicate soil's capacity to store greater C, and maintain higher C in passive pools; and that active fraction of soil C can be used as an indicator of soil health. The inclusion of active pool/labile SOC is expected to improve the performance of Century eco-system model in predicting SOC changes under different climatic conditions. Greenhouse gas emissions from the tropical Indian soils (both zeolitic and non-zeolitic) do not seem to contribute significantly to the global warming potential. The application NPK plus FYM emerged as a cost effective technology for Indian farmers. In view of the potential of C sequestration by major zeolitic and non-zeolitic soils, the present SOC stock of about 30 Pg can be further increased.

Keywords Indian soils · Potential of C sequestration · Soil resilience · Greenhouse gases

Introduction

The importance of soil organic carbon (SOC) in sustaining productivity is well known. Organic carbon (OC) serves as soil conditioner, nutrient source, substrate for microbial activity, preserver of the environment, and the major determinant for sustaining or increasing agricultural productivity [1]. SOC status is sensitive to impact by human activities viz. deforestation, biomass burning, land use changes and environmental pollution. It has been estimated that the land use change from natural to agriculture resulted in the transfer of 1–2 Pg C year^{-1} from terrestrial ecosystem to the atmosphere of which 15–17 % carbon is contributed by decomposition of SOC [2]. On broader perspective, global climate change since 1880 has led to the reduction of the terrestrial and arctic snow cover [3], the rise in sea level [4, 5], decline in crop yields [6], reduction in ecosystem services [7], increase in the frequency of extreme events especially drought, flooding and change in biodiversity [8], and increase in global hunger and food insecurity [9]. Lal [10] also points out that soils in the Asia/pacific region and Sub-Saharan Africa are impoverished in SOC and nutrient reserves, and severely degraded, which make about 90 % of the 1,020 million people food-insecure [11, 12]. Due to climate change, the increase in temperature and decrease in mean annual rainfall (MAR) is expected to cause further food insecurity

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in these regions. The twin crisis of climate change and food insecurity can however, be overcome by restoring the SOC pool and the attendant improvement in soil quality. Among the several options to mitigate climate change [13], the sequestration of C in agricultural soil is an important one [10].

Much of the demand for food in tropical areas of the world is met by converting natural ecosystems to cultivated or pastoral land, thereby releasing C from soil to the atmosphere [14, 15]. To sustain the soil quality and productivity, the knowledge of SOC in terms of its amount, quality and dynamics is essential. In the recent past, the effect of greenhouse gases (GHGs) on global climate change has become of a great concern; and this has stimulated research on GHGs emissions in relation to SOC quality and quantity [16–19]. India being a developing and populous nation of the world, cannot escape the adverse effects of climate change.

Jenny and Raychaudhuri [20] conducted one of the first comprehensive studies on the distribution of OC in Indian soils in relation to the prevailing climate. However, these authors did not provide estimates of the total soil C reserves. Dadhwal and Nayak [21] using ecosystem areas and representative global average C density, estimated organic C at 23.4–27.1 Pg in Indian soil. Chhabra et al. [22] estimated organic C pool at 6.8 Pg C in the top 1.0 m, using estimated SOC density and remote sensing based area under forest. Gupta and Rao [23] reported SOC stock at 24.3 Pg for the soil ranging from surface to an average subsurface depth of 44–186 cm. This data however, were based on only 48 soil series. Based on a much broader national data base, Velayutham et al. [17] reported on total mass of SOC stock, followed by Bhattacharyya et al. [18] who reported on both organic and inorganic C stocks. Indian sub-continent has a variety of geological formations, diverse climate and varied topography and relief. Temperature varies from arctic cold to equatorial hot. Precipitation varies from <100 mm in the arid to 11,000 mm per year in the per-humid regions. Major part of the land area in India is however, in the region lying between the Tropic of Cancer and Tropic of Capricorn, also known as the Torrid Zone; and the soil therein is termed "tropical soil". Many however think of tropical soil as the soil of the hot and humid tropics only, exemplified by deep red and highly weathered soil [24]. India has 5 distinct bioclimatic systems [25] with varying MAR; and they are arid cold and hot (MAR $<$ 550 mm), semi-arid (MAR 550–1,000 mm), sub-humid (MAR 1,000–1,500 mm), humid to per-humid (MAR 1,200–3,200 mm) and coastal (MAR 900–3,000 mm). The major soils of India are Vertisols, Mollisols, Alfisols, Ultisols, Aridisols, Inceptisols and Entisols covering 8.1, 0.5, 12.8, 2.6, 4.1, 39.4 and 23.9 %, respectively of the total geographical area (TGA) of the country [26].

Although soils of India occur in 5 bioclimatic systems, but only a few soil orders are spread in more than one bio climate. Vertisols belong to arid hot, semi-arid, sub-humid and humid to per-humid climatic environments [27, 28]. Mollisols belong to sub-humid and also humid to per-humid climates [29]. Alfisols belong to semi-arid, sub-humid and also in humid to per-humid climates [30–35], whereas Ultisols belong to only humid to per-humid climates [36, 37]. Both Entisols and Inceptisols belong to all the 5 categories of bio-climatic zones of India, and Aridisols belong mainly to arid climatic environments [38]. This baseline information indicates that except for the Ultisols and Aridisols, the rest 5 soil orders exist in more than one bioclimatic zones of India. The absence of Oxisols and the Ultisols, occupying only 2.56 % of TGA of the country, suggest that soil diversity in the geographic tropics in general and in India in particular, is at least as large as in the temperate zone [24, 39]. Therefore, any generalizations about tropical soil are unlikely to have wider applicability because of the diversity of soil and the factors affecting organic matter (OM) dynamics [40]. As the tropics comprise $\sim$40 % of the land surface of the earth, more than one-third of the soil of the world is of tropical type [24]. Global extent of such soil suggests that any agricultural management practice that is developed in India for enhancing crop productivity and maintaining soil health through C sequestration might also have application in similar soils occurring elsewhere in the tropical and subtropical parts of the world.

A review of Indian soils and their capacity to sequester organic and inorganic carbon in seven soil orders; and the factors favoring C sequestration amidst nuances of pedogenesis and polygenesis due to tectonic, climatic and geomorphic episodes during the Holocene [28, 41] appears an excellent model case study to address and understand the factors for the variability in SOC and SIC stocks of Indian soils vis-a vis various land uses and productivity. The primary objective of this review is to develop state-of-the-art information on the potential and challenges in C sequestration in various soil orders of tropical and subtropical India. Ultimate goal is to use this information to guide various stake holders to protect soil health and food security through C sequestration in the tropical and subtropical parts of the world during the twenty-first century.

Carbon Stocks in Indian Soils

Soil C is of global importance because of its role in the global C cycle and the part it plays in the mitigation of atmosphere levels of GHGs, with special reference to CO_2. To reduce the emission of CO_2, carbon capture and storage (CCS) is an important option. Among the other known sources that enhance CCS, the role of soils in capturing and storing carbon has not been adequately covered.

Soil captures and stores both organic and inorganic carbon (SIC). In developing appropriate management practices for SOC sequestration, basic information on SOC and SIC stocks is needed. The SOC, SIC, and the total carbon (TC) stocks in seven soil orders indicate that the SOC stock (in the first 0–150 cm) of Indian soils is less (29.92 Pg) than that of SIC (33.98 Pg) (Table 1). The SOC and SIC stocks in the 0–30 cm depth in five bio-climatic zones of India (Table 2) however, indicate that SOC stocks are two times more than SIC stocks. Although the presence of $CaCO_3$ in the humid and per-humid region is due to its inheritance from strongly calcareous parent material [17], the SIC stock in dry climates is relatively large [18]. In all soil orders, except the Ultisols, the SIC stock increases with soil depth (Table 1), indicating that most of the soil orders in India are affected by dry climatic conditions that cause more calcareousness in the subsoil [42].

Carbon Stocks and Their Distribution in the Soil Profile in Agro Ecological Sub Regions (AESR)

Using broad soil data, total C stocks in Indian soils was estimated in 60 AESRs [18]. The SOC and SIC stocks in Indian soils based on point data of bench mark (BM) soils and from other soils reported in the literature in 60 AESRs, were used to estimate stocks to different soil depths namely 0–30, 0–50, 0–100 and 0–150 cm. This estimate indicates 29.97 Pg SOC in the 0–150 cm depth of the soil. The first ever estimate of total SIC stock of Indian soils indicates 34.03 Pg in the first 0–150 cm depth. The TC stock (SOC plus SIC) is 64.0 Pg [18]. However, the contents of SOC and SIC (point data) follow a reverse trend with depth (Table 3). The relative contribution of SOC and SIC stock to the total stock in 0–30 cm depth is 71 and 29 %, respectively. However, in the 0–150 cm soil depth, the contribution of SOC and SIC is 47 and 53 %, respectively [18]. The enrichment of SOC in the upper horizon (0–30 cm) is due to the accumulation of organic C in various agricultural land uses, whereas that of SIC in deeper layers (beyond 30 cm) is a result of accumulation of pedogenic $CaCO_3$ (PC) due to regressive pedogenesis in the arid and semi-arid climates of the Holocene [43].

The SOC stock of Indian soils stored in the upper 30 and 150 cm depths (Table 1) when compared to the stock for tropical regions and the world [16], shows that the share of Indian soils is not substantial (Table 4) because in India there are very few OM rich soils like Histosols, Spodosols, Andosols and Gelisols, and the area under Mollisols is relatively small. Moreover, the soils of India cover only 11 % of the total area of the world. Even under unfavourable environmental conditions for OC rich soils, the SOC stocks of Indian soils demonstrate enough potential to sequester organic C. Impoverishment in SOC in Indian soils, is largely due to less accumulation organic C in soils of the arid and semi-arid and dry sub-humid climatic regions, which cover nearly 50 % of the TGA of India [42].

SOC Stocks in Relation to AESRs

SOC stocks of different AESRs (Fig. 1) do not help identifying areas for OC sequestration because C stocks in soil depend largely on the areal extent of the soil besides other

Table 1 Carbon stock (in Pg = 10^{15}g) distribution by order in Indian soils

Soil order	Soil depth Range (cm)	Carbon stock (Pg) SOC	SIC	TC
Entisols	0–30	0.62(6)	0.89(21)	1.51(11)[a]
	0–150	2.56(8)	2.86(8)	5.42(8)
Vertisols	0–30	2.59(27)	1.07(26)	3.66(27)
	0–150	8.77(29)	6.14(18)	14.90(23)
Inceptisols	0–30	2.17(23)	0.62(15)	2.79(20)
	0–150	5.81(19)	7.04(21)	12.85(20)
Aridisols	0–30	0.74(8)	1.40(34)	2.14(16)
	0–150	2.02(7)	13.40(39)	15.42(24)
Mollisols	0–30	0.09(1)	0.00	0.09(1)
	0–150	0.49(2)	0.07(0.2)	0.56(1)
Alfisols	0–30	3.14(33)	0.16(4)	3.30(24)
	0–150	9.72(32)	4.48(13)	14.20(22)
Ultisols	0–30	0.20(2)	0.00	0.20(1)
	0–150	0.55(2)	0.00	0.55(1)
Total	0–30	9.55	4.14	13.69
	0–150	29.92	33.98	63.90

Adapted from Bhattacharyya et al. [18]

[a] Parentheses show percentage of total SOC (soil organic carbon), SIC (soil inorganic carbon) and TC (total carbon, summation of SOC and SIC)

Table 2 Soil organic and inorganic carbon stock (Pg, 0–30 cm) in different bioclimatic zones in India

Bioclimatic zone	Area coverage (mha)	% of TGA	SOC		SIC		TC		Stock per unit area (~~Pg m~~$^{-1}$ ~~ha~~)	
			Stock	% of SOC stock	Stock	% of SIC stock	Stock	% of TC stock	SOC	SIC
Cold arid	15.2	4.6	0.6	6	0.7	17	1.3	10	0.39	0.046
Hot arid	36.8	11.2	0.4	4	1.0	25	1.4	10	0.011	0.27
Semi-arid	116.4	35.4	2.8	30	2.0	47	4.8	35	0.025	0.016
Subhumid	105.0	31.9	2.4	26	0.33	8	2.73	20	0.024	0.003
Humid to perhumid	34.9	10.6	2.0	21	0.04	1	2.04	15	0.060	0.001
Coastal	20.4	6.2	1.3	13	0.07	2	1.37	10	0.064	0.033

Adapted from Bhattacharyya et al. [18, 38]

factors such as C content, depth and bulk density of soils. Even with a relatively small SOC content (0.2–0.3 %), the SOC stock of arid and semi-arid soils indicates a high value due to large area under dry regions. The concept of C stock per unit area (Pg ~~m~~$^{-1}$ ~~ha~~) to realize the influence of soil and/or management parameters for C sequestration in soil was therefore, advocated [38, 44]. They set a threshold value of 0.03 ~~Pg SOC m~~$^{-1}$ ~~ha~~, as an effective approach in determining a system (agriculture, horticulture, forestry) that can sequester substantial amount of OC in the soil.

Following SOC per unit area (Table 2) and also point data for individual soils, it is observed that vast areas of lands in arid (AESR 3), semi-arid and drier part of subhumid (AESRs 4.1–4.4, 5.1–5.3, 6.4, 7.1–7.3, 8.1–8.3, 9.1–9.2, 10.1–10.4, Fig. 1) of India are impoverished in SOC, but are high in SIC to 30 cm depth (Fig. 1) [18]. These specified areas are the prioritized ones for OC management in soil. These areas cover 155.8 m ha of which, arid areas cover 4.9, semi-arid 116.4 and dry subhumid 34.5 m ha [38] (Fig. 1).

Factors Affecting Carbon Sequestration in Soil

Soils poor in bases (Dystrochrepts/Dystropepts and Ultisols) with almost similar pH and CEC values are prevalent in the Indian states of Tripura (north-eastern state), Kerala and Karnataka (southern states) under typical humid tropical climate (Table 5). The OC content of these soils however, differs [17]. Soils in Tripura have higher OC than those in Kerala and Karnataka due to cooler winter in Tripura (mean January temperature 15°C) than in Karnataka and Kerala (mean January temperature 25 °C), suggesting that cooler temperature even for a period of a few months (November, December, January and February) can influence the accumulation of OC. Similar inference can be drawn from the soils of Maharashtra (Western Ghats) and Madhya Pradesh in central India (Table 5); the soils in these states have comparable expanding clay minerals with high shrink-swell and similar parent material (alluvium of the Deccan basalt), elevation (~1,000 m above msl) and vegetation (forest), but they differ in their OC content. Soil of Madhya Pradesh contains higher OC (≥2.0 % in the top 30 cm of soil) than those of Maharashtra (≥1.0 % in the first 30 cm of the soil depth) (Table 5). This is again due to comparatively cooler winter in Madhya Pradesh (minimum January temperature 7–8 °C) than in Maharashtra (minimum January temperature 20–22°C) [29]. However, cooler temperature alone may not be able to influence accumulation of OC as observed in the soils of Punjab and Haryana states, which are low in SOC (<1 %) [45], although the minimum temperature of these geographical areas varies between 6 and 8 °C in winter months [46]. The impoverishment in SOC is due to low rainfall, which does not favour an adequate vegetative cover. The MAR in these areas vary from 600 to 800 mm [46].

Major portion of SOC is retained through clay–organic matter complex formation, indicating the importance of inorganic part of the soil as a substrate to build the SOC. Smectites and vermiculites have the largest specific surface area, and are capable of accumulating greater amounts of OC than the non-expanding minerals. It however, is paradoxical that smectitic Vertisols of India of the arid and semi-arid climates are low in OC content (0–30 cm depth) (Fig. 2). The OC in clayey, smectitic Vertisols (Haplusterts) decreases rapidly from humid to arid ecosystem, despite that they possess large surface area and bulk density [47, 48].

The importance of expanding 2:1 clay minerals in the accumulation of SOC is well demonstrated in the ferruginous red soils (Alfisols and Ultisols) of north-eastern, eastern, western and southern parts of the country. These soils are not dominated by clay minerals of advanced weathering stage [30, 36, 37, 49, 50]. Studies indicate that even in the Ultisols of Kerala [37] and Meghalaya in the north-eastern regions of India [36], the presence of smectite

Table 3 Changes in SOC, and $CaCO_3$ with depth in representative soils from different ecosystems

Soil depth (cm)	pH (water)	CEC cmol(+) kg^{-1}	OC (%)	$CaCO_3$ (%)
Kibber Series: Typic Cryorthid—Jammu & Kashmir—Arid (cold) AESR 1.1				
0–25	7.8	9	1.4	13.8
25–50	8.2	6.1	0.66	13.8
50–100	8.1	4.5	0.57	17.3
Shobsar Series: Typic Camborthid—Rajasthan—Arid (hot) AESR 2.1				
0–25	8.5	2.8	0.01	1.4
25–50	8.6	3.8	0.01	8.2
50–100	8.5	2.9	0.3	10.7
Bhola Series: Vertic Ustochrept—Gujarat Semi arid (hot, dry)—AESR 5.1				
0–25	8.4	38.5	0.65	17.5
25–50	8.6	43.6	0.37	20.7
50–100	8.7	38.9	0.25	26.6
Nimone Series: Typic Haplustert—Maharashtra—Semi arid (dry)—AESR 6.1				
0–25	8.1	56.9	0.6	3
25–50	8.3	56.1	0.4	8.8
50–100	8.5	35	0.4	10.2
Channasandra Series: Oxic Rhodustalf—Karnataka—Semi-arid (hot, moist)—AESR 8.2				
0–25	6.7	4.4	0.65	nil
25–50	6.5	10.3	0.4	nil
50–100	6.8	6.3	0.2	nil
Itwa Series: Aeric Ochraqualf—Uttar Pradesh—Subhumid (hot, dry)—AESR 9.2				
0–25	6.6	12	0.32	0.1
25–50	6.7	14.7	0.21	6.4
50–100	7.8	15.1	0.19	16.5
Gogji Pather Series: Typic Haplustalf—Jammu & Kashmir—Subhumid (warm, moist, dry) -AESR 14.2				
0–25	7.9	11.6	0.35	0.2
25–50	7.8	14.3	0.25	0.23
50–100	8.3	14.2	0.2	7.7
Mahimbari Series—Aeric Haplaquept—Assam—Humid-per-humid (hot)—AESR 15.2				
0–25	5.8	10	0.85	nil
25–50	6.4	9.2	0.11	nil
50–100	6.5	4.5	0.11	Nil
Sagar Series: Typic Haplaquept—West Bengal Coastal—AESR 18.5				
0–25	6.6	22	0.69	nil
25–50	7.5	25.7	0.24	nil
50–100	7.8	26.1	0.2	nil

Adapted from Velayutham et al. [17] and Bhattacharyya et al. [18]

and/or vermiculite either in the form of interstratification with 0.7 nm mineral or in a discrete mineral form is quite common. The presence of these minerals favours the accumulation of OC in the soil (Table 5). Therefore, besides the dominating effect of humid climate with cooler winter months with profuse vegetation, the soil substrate quality (quality and quantity of expanding clay minerals) is of fundamental importance in the sequestration of OC in the soil [51] (Fig. 3). In addition to the above factors, a study on the formation and persistence of acidic and fairly weathered Mollisols on zeolitic Deccan basalt of humid tropical India [29] in contrast to commonly found alkaline Mollisols in temperate humid climate, shows that Ca–zeolite is another important factor in OC sequestration. The Ca–zeolites (soil modifier) provide bases to prevent complete transformation of smectite to kaolinite by maintaining high base saturation level in these acidic Mollisols. This improved moisture storage, which in turn helps in OC sequestration for the soils to qualify as Mollisols even in tropical humid climatic conditions. In semi-arid dry region

Table 4 Total SOC stock in India, tropical regions and world (Pg)

SOC	0–30 cm	0–150 cm
Soil organic Carbon (India)[a]	9.55	29.92
Tropical regions[a]	201–203	616–640
World[b]	684–724	2376–2456
SOC, India % of Tropical region stock	4.72	4.77
SOC stock % of world stock	1.4	1.2

[a] Adapted from Bhattacharyya et al. [18]

[b] Adapted from Batjes [16], average values were taken

of India, zeolitic (heulandites) Vertisols (Teligi soils at Bellary of Karnataka; Jhalipura soils at Kota of Rajasthan and Jajapur at Mehboobnagar, of Andhra Pradesh) [47] under wetland rice–rice/rice–wheat system have a tendency to show wider C/N ratio, indicating enough potential to sequester atmospheric carbon [52]. This suggests that the presence of zeolites could be beneficial for soil OM conservation under global climate change.

Calcareous soil in India occurs in 228.8 m ha and cover 69.4 % of the TGA; and it is spread over 38 out of 60 AESRs. Such soil are present in arid and semi-arid, and also in humid and per-humid climatic regions [42] (Fig. 4). The $CaCO_3$ stock (<2 mm) in the top 100 cm of soil in major climatic regions is estimated to be 195.5 Pg; and the soil of arid and semi-arid climate constitutes 78 % of the stock [42].

Reaction to HCl does not distinguish $CaCO_3$ in soil as the result of wide variability in its genesis such as fluvial, lacustral, pedogenic and ground water [42]. Although arid and semi-arid climates are most conducive for the formation of pedogenic $CaCO_3$ (PC) in soils [53]; wide occurrence of strongly developed carbonate-rich horizons in dry regions has commonly been attributed to steady aeolian deposition of carbonates, and also to their pedogenic origin [42]. In India, areas under arid and semi-arid climate cover 54 % of the TGA [54]; and the soil of these climates is calcareous. Calcite nodules of such soil that show reaction to HCl may not be of pedogenic origin. Micromorphological thin section study of $CaCO_3$ [42, 55] indicates that among the major soil types, the presence of PC is quite common in soil of the IGP and red soil of the arid and semi-arid regions, except for the Vertisols and vertic intergrades wherein both PC and non-pedogenic $CaCO_3$ (NPC) are present. The formation of PC is a contemporary pedogenetic process, whereas the NPC is a part of the parent alluvium [28, 43].

In an aqueous solution, CO_2 gas plays a role in the dissolution and precipitation of $CaCO_3$ as indicated by the following equations:

$$CO_2(\text{gas}) + H_2O \rightleftharpoons H_2CO_3(\text{or } CO_2 \text{ aqueous}) \quad (1)$$

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \quad (2)$$

$$CaCO_3 + H^+ \rightleftharpoons Ca^{2+} + HCO_3^- \quad (3)$$

The above three equations are summarized by a single equation

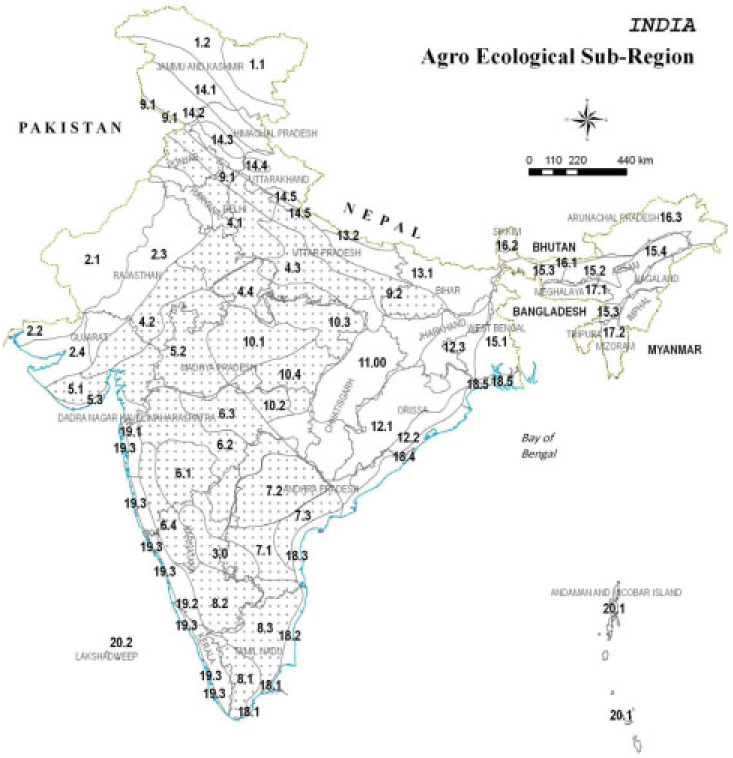
$$CO_2 + H_2O + CaCO_3 \rightleftharpoons Ca^{2+} + 2HCO_3^- \quad (4)$$

The above reactions suggest that with the increase in pCO_2 in soil solution, the solubility of $CaCO_3$ in soil solution also increases [56]. Due to the microbial respiration during the decomposition of organic materials and respiration of plant roots, the pCO_2 of soil air is greater than that in the atmosphere. This causes an increase in calcite solubility. Once the $CaCO_3$ is dissolved, it remains in solution as HCO_3^-. Carbonate precipitation is generally induced either by lowering of pCO_2 or by evaporation. Thus, the loss of water through evapo-transpiration is considered the primary mechanism in the precipitation of PC [42]. In addition, temperature also plays an important role in controlling water flow in the soil [42]. This is particularly true in the soil of the dry (sub-humid to arid) regions of India as evidenced by a progressive increase of PC in Vertisols from the humid to arid regions (Fig. 5). The major factor in the formation of PC is the climatic aridity as is demonstrated in ferruginous Alfisols of southern India. In Alfisols with clay (>29 %) dominated by 2:1 expanding clay minerals and developed in humid tropical climate of pre-Pliocene, the formation of PC is observed due to an impact of the present semi-arid climate. Therefore, unlike in the case of Ultisols of the humid tropics, Alfisols are calcareous. The PCs in such a soil is mainly concentrated as lubinites that are formed only when the soil solution is supersaturated with $CaCO_3$ under semi-arid environments [42], suggesting that during the formation of PC, texture also has a role in carbonate accumulation [57].

In addition to the above factors, the formation of $CaCO_3$ is observed in high rainfall regions due to the addition of HCO_3^- ions via underground water used for irrigating winter crops [32, 58–60].

Sequestration of SIC (PC)

Major soil types of India are polygenetic as they have experienced a change of climate from humid to arid and semi-arid during the Holocene period [28, 30, 41, 42, 61]. The formation of PC increases soil pH and also the relative abundance of Na^+ ions on soil exchange and in soil solution; the Na^+ ions in turn cause dispersion of the fine clay particles. The dispersed fine clays are liable to translocation in



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AESRs	SOC (Pg)	SIC (Pg)	TC (Pg)	AESRs	SOC (Pg)	SIC (Pg)	TC (Pg)	AESRs	SOC (Pg)	SIC (Pg)	TC (Pg)
1.1	0.032	0.039	0.071	7.3	0.113	0.159	0.272	14.5	0.029	0	0.029
1.2	0.554	0.660	1.214	8.1	0.092	0.100	0.192	15.1	0.098	0.041	0.139
2.1	0.057	0.390	0.447	8.2	0.153	0.058	0.211	15.2	0.109	0	0.109
2.2	0.018	0.021	0.039	8.3	0.106	0.140	0.249	15.3	0.099	0	0.099
2.3	0.102	0.120	0.222	9.1	0.049	0.004	0.053	15.4	0.097	0	0..097
2.4	0.089	0.360	0.446	9.2	0.101	0.002	0.103	16.1	0.019	0	0.019
3	0.121	0.050	0.171	10.1	0.250	0	0.250	16.2	0.148	0	0.148
4.1	0.117	0.149	0.266	10.2	0.088	0.019	0.107	16.3	0.620	0	0.620
4.2	0.191	0.070	0.261	10.3	0.170	0.034	0.204	17.1	0.450	0	0.450
4.3	0.229	0	0.229	10.4	0.108	0	0.108	17.2	0.321	0	0.321
4.4	0.129	0	0.129	11.0	0.141	0	0.141	18.1	0.023	0	0.023
5.1	0.078	0.130	0.208	12.1	0.630	0	0.630	18.2	0.051	0	0.051
5.2	0.470	0.161	0.631	12.2	0.056	0	0.056	18.3	0.070	0	0.070
5.3	0.061	0.057	0.118	12.3	0.079	0	0.073	18.4	0.063	0	0.063
6.1	0.130	0.111	0.241	13.1	0.081	0.153	0.234	18.5	0.031	0	0.031
6.2	0.230	0.470	00.700	13.2	0.091	0	0.091	19.1	0.082	0.063	0.145
6.3	0.149	0.030	0.179	14.1	0.319	0	0.319	19.2	0.390	0	0.390
6.4	0.139	0.216	0.355	14.2	0.369	0.109	0.478	19.3	0.371	0	0.371
7.1	0.131	0.059	0.190	14.3	0.010	0	0.10	20.1	0.059	0	0.059
7.2	0.31	0.148	0.458	14.4	0.020	0	0.20	20.2	0.062	0.014	0.076

Fig. 1 Soil carbon stock (in Pg = 10^{15} g) map in different agro-ecological sub regions showing prioritized areas (*shaded area*) for carbon sequestration (0–0.3 m soil depth). *AESRs* agro-ecological sub-regions, *SOC* soil organic carbon, *SIC* soil inorganic carbon, *TC* total carbon. Adapted from Bhattacharyya et al. [38]

the soil profile [28, 33]. Therefore, the formation of PC and the illuviation of clay are two concurrent and contemporary pedogenetic events that increase sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) in sub-soils (Fig. 6). These pedogenetic events represent a pedogenic threshold during the dry climates of the Holocene [28, 33, 41].The formation of PC is a basic natural degradation process [42] induced by tectonics-climate linked events [32, 41], which immobilizes C in unavailable form. Also the presence of PC as SIC is considered of little

Table 5 SOC concentration in BM soils of India

Horizon	Depth (cm)	pH (water)	CEC Cmol(+) kg^{-1}	OC (%)	SOC %[a]
Typic Dystrochreprt: Tripura					
A1	0–10	5.0	5.3	1.6	
B1	10–37	4.7	5.6	1.0	
B2	37–73	4.9	5.8	1.2	0.012
B3	73–120	4.8	7.4	0.8	
B4	120–155	4.8	7.4	0.6	
Ustic Kandihumult: Kerala					
Ap	0–15	5.1	6.5	1.2	
Bt1	15–39	5.2	6.2	1.0	
Bt2	39–119	5.3	6.6	0.9	0.059
Bt3	119–162	5.2	5.9	0.6	
Bt4	162–205	5.4	5.3	0.5	
Kanhaplic Haplustult: Karnataka					
Ap	0–14	6.4	6.3	1.2	
AB1	14–34	6.3	5.7	1.1	
AB2	34–50	6.3	5.3	0.6	0.004
Bt1	50–83	5.9	4.9	0.3	
Bt2	83–107	5.2	5.1	0.2	
Typic Vertic Argiudoll: Maharashtra					
A1	0–15	5.7	18.6	2.0	
Bw	15–40	5.7	18.5	1.2	
Bt1	40–74	6.1	18.7	0.7	–
Bt2	74–108	6.1	18.6	0.4	
Bt3	108–146	18.7	0.3		
Bc1	146–175	6.1	20.0	0.1	
Bc2	175–180	6.1	18.5	0.1	
Vertic Haplustroll: Madhya Pradesh					
A1	0–6	5.9	52.2	3.5	
A2	6–16	5.8	59.8	3.0	
B1	16–37	5.8	59.8	2.0	–
B2	37–74	5.9	67.4	1.2	
B3	74–106	5.6	71.7	0.8	
B4	106–120	5.5	73.9	0.5	
Typic Haplustalf: Madhya Pradesh					
Ap	0–10	6.2	25.5	1.9	
Bt1	10–30	5.9	29.1	1.8	
Bt2	30–59	5.9	28.8	1.0	–
C1	59–94	6.5	28.8	0.4	
C2	94–131	6.7	36.4	0.4	
Aquic Natrustalf: Punjab					
A1	0–6	10.3	8.2	0.2	
BA	6–24	9.8	11.8	0.2	
Bt1	24–48	9.6	13.6	0.1	
Bt2	48–73	9.4	14.2	0.14	–
Bt3	73–97	9.4	13.8	0.1	
Bc	97–124	9.4	9.8	0.1	
Ck	124–145	9.3	9.0	0.1	

Adapted from Velayutham et al. [17]

[a] Weighted mean in 0–100 cm depth

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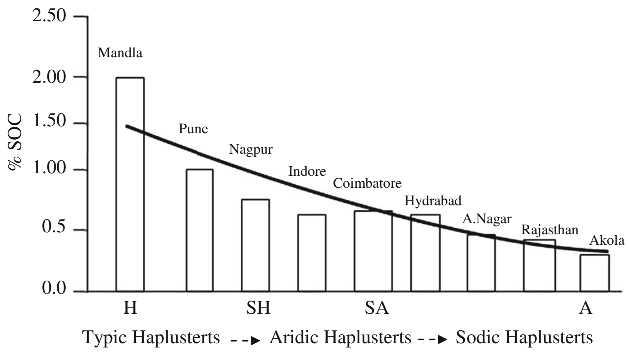

Fig. 2 Adverse effect of climate on SOC (soil organic carbon) accumulation in surface (0–30 cm) of Vertisols. *H* humid, *SH* sub-humid, *SA* semi-arid, *A* arid). Adapted from Goswami et al. [48]

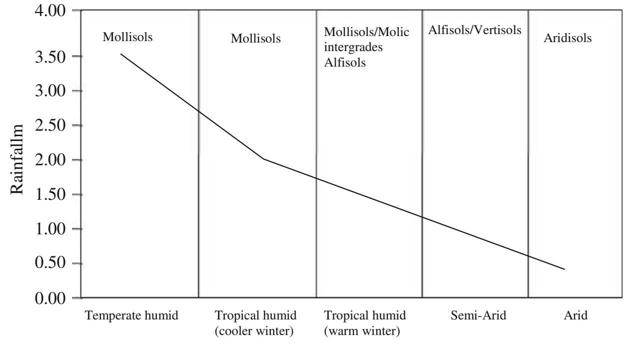

Fig. 3 Factors influencing SOC (soil organic carbon) accumulation. Adapted from Goswami et al. [48]. SOC as influenced by rainfall, temperature and soil substrate quality. Soils contain 2:1 minerals either in the form of interstratifications or in a discrete mineral form

significance as the displacement of exchangeable Na by Ca^{2+} ions from $CaCO_3$ is not feasible in soil with pH >8.0 [42]. Therefore, the natural soil degradation process reduces the hydraulic properties of such soils (Fig. 6). The rate of formation of PC in the BM IGP soils, Vertisols and red ferruginous soils of semi-arid climate has been estimated to be 129, 37.5 and 30 kg $CaCO_3$ ha^{-1} $year^{-1}$ or 15.5, 4.5 and 3.6 kg SIC ha^{-1} $year^{-1}$, respectively [42]. The soil of the dry climates still shows the ability to sequester SIC; and for Vertisols (Sodic Calciusterts) [28, 41], it is estimated to be 275 kg $CaCO_3$ ha^{-1} $year^{-1}$ or 33 kg SIC ha^{-1} $year^{-1}$ [55]. Higher sequestration of SIC in dry climates, suggests that rapid calcification is one of the dominant pedogenetic processes that capture atmospheric CO_2 for the formation of PC in the soil, which retards the emission of CO_2 from it.

Systems for Increased SOC Sequestration

Agricultural Land Use

To feed increasing human population, 10^9 ha of global natural ecosystems need to be brought under agriculture by 2050 [62]. An increase in C sink strength in the remaining natural ecosystems and in the agro-ecosystems is required by implementing appropriate management practices [63]. Cropping systems of the intermediate nature involving crop rotation, agro-forestry and mulching is a better strategy for farmers in the tropics [64].

It is often implied that intensified agricultural systems during and following green revolution in India, led to the loss of soil C amidst widespread degradation of natural resources including plant nutrients [65–68]. The vision 2020 document of the Government of India [69] envisages rice and wheat production levels at 207 and 173 million t considering bio-physical factors that constrain crop production. The decline in SOC and its adverse impact on productivity need adequate research by monitoring soil C dynamics at regular intervals. The National Bureau of Soil Survey and land Use planning (NBSS and LUP) of the Indian Council of Agricultural Research (ICAR) monitored management practices to sustain the agricultural productivity of the country [70]. Through the ICRISAT and NBSS and LUP research initiative sponsored by the National Agricultural Technology Project (NATP), and by NBSS and LUP through a Global Environmental Facility Soil Organic Carbon (GEFSOC) project [70], the changes in soil C were assessed in 1980 and 2005 in two food production zones of India.

The food production zones studied were the Indo-Gangetic Alluvial Plains (IGP) and black (shrink-swell) and associated red (BSR) soil areas. Various BM spots selected in 1980 in the IGP and BSR [70] followed recommendations for agricultural management practices (for reviews see Tables 5 [70] and 6 [71]) from the National Agricultural Systems (NARS). In 2005, soil samples from these BM spots were collected after a gap of 25 years to assess the changes in soil OC dynamics. The time taken for a new equilibrium to occur is highly variable. The period for the soil in a temperate location to reach a new equilibrium following a land use change is about 100 years [72, 73]. However, in tropical soil a new equilibrium might reach relatively faster. Soils in boreal regions may take centuries to approach a new equilibrium. Thus as a compromise, IPCC good practice guidelines for greenhouse gas inventories use a figure of 20 years for soil C to approach a new equilibrium [74, 75]. Studies on Indian soils indicate that SOC tends to attain quasi-equilibrium values (QEV) in duration varying from 500 to1,000 years in a forest system [76, 77], 30–35 years in agricultural system after forest cutting [78], 5–15 years in agricultural system after forest cutting in red soils [79], and 20–50 years under different agricultural systems with cotton for 20 years, cotton and pigeon pea system in 50 years and horticultural system (citrus) in 30 years [80]. Observations made by NBSS&LUP in1980 and 2005 [81, 82] determined changes

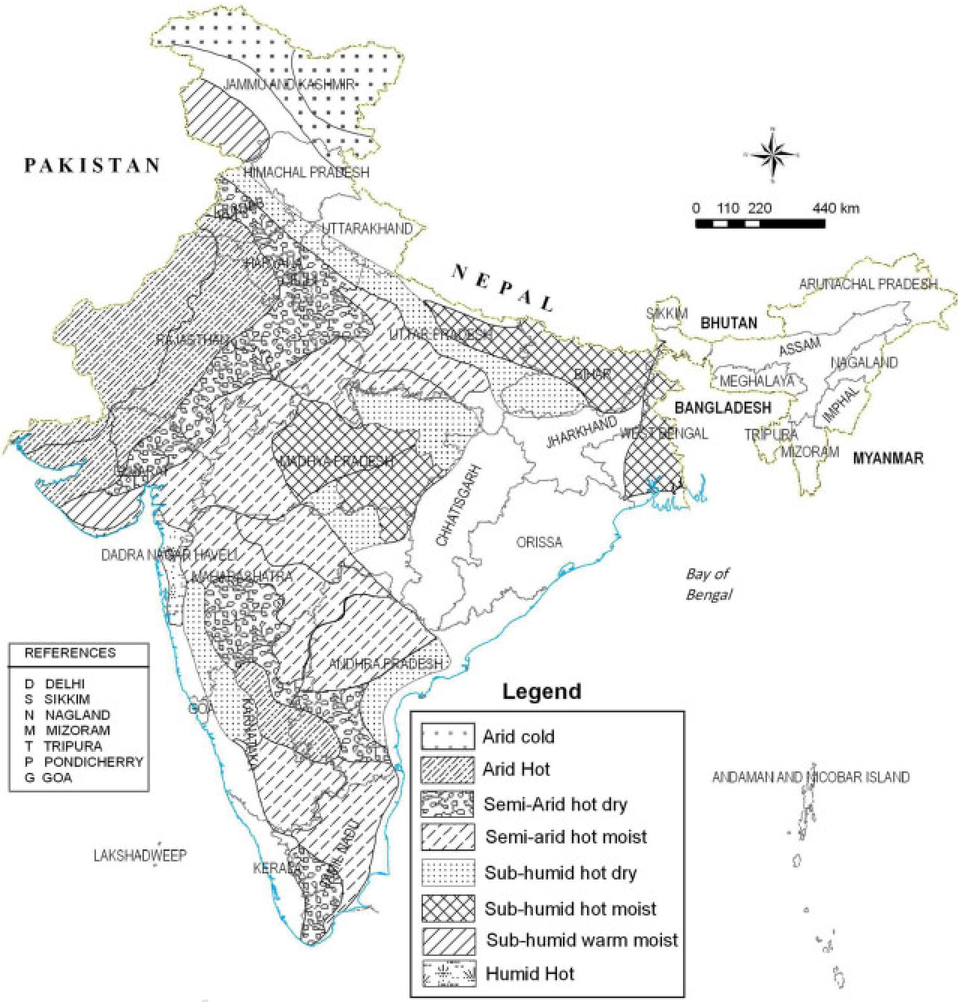

Fig. 4 Distribution of calcareous soils in different climatic regions of India. Adapted from Pal et al. [42]

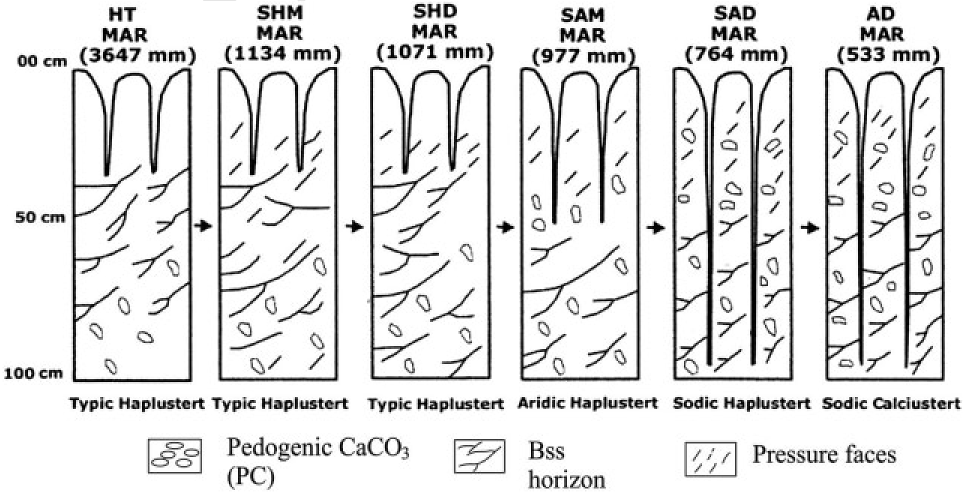

Fig. 5 Progressive increase of PC (pedogenic $CaCO_3$) in Vertisols from humid to arid climates. Adapted from Pal et al. [28]

in carbon stock over the last 25 years. In view of the time period suggested to reach the QE stage for agricultural system, the assumption that QE is reached after 25 years in soils of India, is justified in estimating SOC stocks of the selected BM spots at two times. In the semi-arid bio-climate system of the IGP, the stock increased from 30 to 395 % since 1980. The SIC stock increased only in Phaguwala soils. In Fatehpur and Dhadde soils, SIC was not detected in 1980, but was in 2005 in both field and laboratory examination. The increase in SIC was 100 %

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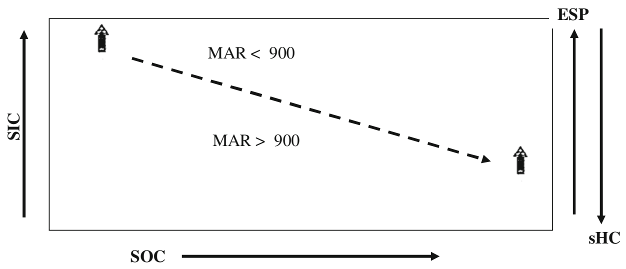

Fig. 6 Schematic diagram showing relation between SIC, SOC, ESP, sHC and climatic parameters. Adapted from Bhattacharyya et al. [19]

(Table 6). In Ghabdan, Sakit, and Zarifa Viran soils (originally sodic soils, Natrustalfs), the increase in SOC was accompanied by a decrease in SIC stock. This was as a result of reclamation of these soils with the addition of gypsum, and by the effects of rice–wheat cropping for over 10 years [83].

Under the sub-humid bio climates, SOC stock increased in general, except in Haldi soils (Table 6). The SIC stock increased to a greater extent in the Jagjitpur site. In Bhanra and Haldi soil, $CaCO_3$ was not detected in the first 150 cm in 1980, but was apparently formed during the last 25 years, indicating 100 % increase in SIC stock (Table 6). In the humid bioclimatic system, the SOC stocks increased by 25–61 %, and SIC stock to about 100–400 %. In Hanrgram soil, $CaCO_3$ was not detected in 1980. In general, in all BM spots of the IGP (except the Haldi soil), the increase in SOC stock was higher in the relatively dry tract (semi-arid and dry sub-humid) of the IGP. The observed increase in SIC stock in the wetter part could possibly be due to the accumulation of carbonates and bicarbonates from tube well water used for irrigation in the dry season [59].

The changes in C stocks in selected BM spots in the BSR were gradual increase in $CaCO_3$ with depth, except in the Semla soil (Table 7). In Kheri soil, the first 50 cm depth was non-calcareous in 1980, but was calcareous in 2005, suggesting that intensified agricultural systems led to an increase in SIC along with SOC accumulation.

From a total area of 328.2 m ha in the country, cultivated area comprises 141 m ha. The IGP has an area of 43.7 m ha [45]; and the black soil covers 66 m ha [26]. Both IGP and BSR are the two important food-growing regions. The productivity in the IGP has been higher as compared to BSR. During the post-green-revolution era, the cropping intensity in the dominant states of the IGP (Punjab, Haryana, Uttar Pradesh, Bihar, and West Bengal) increased from 137 % (1976–1977) to 158 % (1999–2000). During the same period, the BSR in the states of Andhra, Pradesh, Madhya Pradesh, Karnataka, Gujarat and Maharashtra remained less intensively cultivated [84, 85] with an increase in cropping intensity from 111 to 123 %. Despite the difference in cropping intensity, SOC stock of both the soils increased from 1980 to 2005. However, the increase was greater in the IGP than in BSR. This is due to the turnover of more biomass to the soil (both as above-ground and below ground biomass) as indicated by increased SOC in the fertilized (NPK) areas of a long experiment of the IGP [86]. The application of GEFSOC Modelling System on the data from the long-term experiments of selected BM spots of the IGP [81, 82] also projected an increase in SOC stock. The SOC stocks in the BSR indicated an increase, more in double- cropped areas viz. Kaukuntala, Kheri and

Table 6 Changes in carbon stock (Tg = 10^{12} g) over years in the selected benchmark spots of the IGP (0–150 cm)

Bioclimatic systems	Soil series	SOC stock (Tg/10^5 ha)			SIC stock (Tg/10^5 ha)		
		1980	2005	SOC change over 1980 (%)	1980	2005	SIC change over 1980 (%)
Semi arid	Phaguwala	3.66	5.48	68	13.10	26.14	9
	Ghabdan	2.63	7.04	167	18.95	7.71	−59
	Zarifa Viran	4.13	5.38	30	22.36	16.98	−24
	Fatehpur	1.11	5.50	395	0	58.13	100
	Sakit	4.05	8.55	111	51.03	5.37	−89
	Dhadde	4.47	5.84	31	0	10.15	100
Sub-humid	Bhanra	1.81	5.34	197	0	0.58	100
	Jagjitpur	2.52	8.76	248	2.52	8.86	251
	Haldi	8.55	6.28	−26	0	2.84	100
Humid	Hanrgram	6.93	11.02	59	0	3.68	100
	Madhpur	3.99	4.97	25	4.03	15.98	296
	Sasanga	5.25	8.42	61	0.88	4.45	405

Adapted from Bhattacharyya et al. [70]

Table 7 Changes in carbon stock (Tg = 10^{12} g) over years in the selected benchmark spots of the BSR (0–150 cm)

Bioclimatic systems	Soil series	SOC stock (Tg/10^5ha)			SIC stock (Tg/10^5ha)		
		1980	2005	SOC change over 1980 (%)	1980	2005	SIC change over 1980 (%)
Arid	Sokhda	11.19	9.20	−18	23.63	62.92	158
Semi-arid	Asra	6.29	13.59	116	2.00	2.00	0
	Teligi	7.41	15.20	105	21.01	29.60	41
	Semla	15.78	13.28	−16	73.82	46.11	−37
	Vijaypura	7.70	7.70	0	0	0	0
	Kaukantla	4.41	10.25	118	0	12.52	100
	Patancheru	8.39	16.72	101	0	11.78	100
Sub-humid	Kheri	5.62	10.51	87	8.32	9.71	17
	Linga	9.66	12.92	34	15.41	21.66	40

Adapted from Bhattacharyya et al. [70]

Teligi soils and also in areas where green manuring was practised (Asra soils). This prediction suggests that the prevailing agricultural land uses, recommended by National Agricultural Research Systems (NARS) [70], helped in sequestering more OC in Indian soils during the post-green revolution period [58, 70, 87, 88].

Forest and Horticultural Systems

By and large, black soils (Vertisols and vertic intergrades) under agricultural system in India show QEV of 0.5–0.6 % SOC in the surface layer [18]. Naitam and Bhattacharyya [80] made an attempt to provide QE value of SOC of Vertisols under various land use systems (horticulture, cotton, cotton plus pigeon pea and forest (Table 1). Naitam and Bhattacharyya [80] in moist sub-humid central Peninsular India ~~and~~ observed that the SOC sequestration within the first 100 cm was higher in soils under forest, followed by horticultural and agricultural system. The QEV of SOC in the first 50 cm depth of soil under horticultural system was 0.71 % over the past 30 years of orange cultivation. Among the three systems, the soil under forest showed the highest value (0.76 %); and the soil under cotton showed the lowest (0.43 %) in the first 50 cm depth, which was increased to 0.50 % with the introduction of pigeon pea in the system. Thus the variation in QEV in the clayey and smectitic soils is primarily due to the difference in land use systems. This was further confirmed by Chandran et al. [89] who studied ferruginous red soil (Rhodustalfs) with mixed mineralogy class in southern India under various land uses under forest, agriculture and horticulture (Table 1) [89]. The QEV of SOC under different systems indicated that agricultural system at 30 cm depth had the lowest value of OC (0.68 %) after 40 years of agricultural land use [89], and the forest system had the highest QEV (1.78 %). However, the maximum threshold limit of 2.04 % SOC at 30 cm depth was reported to be similar for soil in forest ecosystem in a sub-humid climate under high vegetation, and a minimum threshold of 0.63 % was reported for the shrink-swell soil under agricultural land use [80]. The QEV of SOC in the horticultural system on ferruginous soil [88] was 0.81 %, suggesting that this system with greater crop canopy cover, leaf litter and favourable micro-environment increased SOC content.

Observations made on shrink-swell [80] and ferruginous Alfisols [89] indicate that irrespective of soil types, the sequestration of C is related to land use systems and the highest QEV is obtained in forest system followed by horticulture, and the lowest value is obtained in the agricultural system. Therefore, for C sequestration, horticultural system is a better option if forestry is not feasible. The soil under agricultural system in the sub-humid tropical climate has the potential to attain higher QEV of 1.0 % even under tropical humid climate [29] provided OM is added [80, 90].

Management Practices in Relation to Active Pool of SOC

Long-term experiments (LTEs) conducted over nearly three decades on major soil types in various agro-ecoregions of India, show a general decline in SOC due to continuous application of nitrogen fertilizers alone [91]. However, farm yard manure (FYM), green manure and crop residue application alone or along with NPK fertilizers can maintain SOC due to enhanced yield and greater root mass added to the soil. Improved soil and crop management practices in agricultural production systems help maintain enhanced crop yields and reduce soil degradation.

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LTE in the IGP Inceptisols Under Sub-humid Tropical Environments

Rice-based systems are predominant in the IGP of India. These systems are perhaps the most intensive cereal based crop production systems globally. The yields in these intensified systems have declined or are stagnant [65, 91–94]. Ladha et al. [95] reported that a decline in soil C, N, and K was one of the causes of the decline in crop yield in LTEs in Asia. Manna et al. [86] reported from a 30-year experiment with continuous cropping by rice–wheat-jute system in IGP soils (Typic Eutrochrept) in moist sub-humid bioclimatic zone of eastern India (AESR 15.1, Fig. 1) that a significant decline in yield was observed along with a decline in total organic carbon (TOC) under imbalanced fertilizer application. Yield also declined in plots with NPK, indicating that TOC is not necessarily related to yield decline [95, 96]. Bronson et al. [97] and Yadav et al. [93] reported decline in yield of rice and wheat in the LTE even in the event of SOC increase. Regmi et al. [98] reported similar results when only FYM was added for 20 years to the rice–wheat system. Thus, Manna et al. [86] hypothesized that the depletion of OM pools is most likely to be a major reason for yield decline. Active pools of C declined remarkably in N and NP treatment. The slow pools of particulate OM C and N decreased significantly with concomitant decrease in C and N mineralization rate in the aggregates in N and NP treated plots, leading to lower nutrient supply under NPK alone or in combination with FYM maintained active and slow pools of C and N in the surface layer (0–15 cm depth). Manna et al. [86] concluded that an integrated nutrient supply strategy that can maintain adequate labile and active pool of C is necessary to sustain long- term productivity and soil quality, and therefore the highest soil quality (SQI) index was observed in 100 % NPK plus FYM treatment [99]. Based on the results of a LTE in a Typic Eutrochrept on soil organic pools and productivity relationship of a rice–wheat–jute agro-ecosystem, Majumder et al. [96] reported a significant positive linear relationship between the changes in SOC and the total cumulative crop residue C inputs to the soil in 34 years. Even after 34 years of C addition at a reasonably high rate through FYM (10.0 Mg ha^{-1} year^{-1}) and crop residue in the form of stubbles and roots (2.7–6.7 Mg ha^{-1} year $^{-1}$), soils showed a great potential for C sequestration under moist sub-humid bio-climatic zone of India [100] (AESR 15.1, Fig. 1). Majumder et al. [96] further pointed out that in order to maintain SOC level (zero change), the critical amount of C input to the soil needs to be around 4.6 Mg C ha^{-1} year^{-1}.

Cultivation of two or three irrigated rice crops in a year has been the foundation of Asia's rice supply. This cultivation occupies about 14 m ha and contributes about 25 % of global rice production [101]. Rice crops are grown in submerged soils with use of fertilizers along with the application of OM as compost, FYM, green manure or crop residues. Submergence for a long time during double or triple rice crops may retard oxidation of soil OM decomposition and may also lead to the accumulation of OM in a recalcitrant form [102]. The recalcitrant SOC is relatively stable and retards loss of SOC as CH$_4$, an important greenhouse gas [103]. Mandal et al. [104] reported results from 36-year old LTE with rice–rice in an Inceptisol of the moist sub-humid climate (AESR 12.1, Fig. 1), which had treatments: control (plots receiving no fertilizer or compost), N, NP, NPK, NPK plus compost (5 t ha^{-1} year^{-1}) and a fallow. Results showed that rice cultivation with balanced fertilization with compost caused a net increase in TC content of soil that was associated with a large amount of crop residues and root biomass C accrued and also the compost C added. The increase in total C also led to increased crop yields. A conversion efficiency of around 4 % was observed for crop residue C to SOC. A significant positive linear relationship between the change in SOC and the total cumulative C input to the soil over years, indicated that even after two and a half decades of continuous C additions at a reasonably high rate through compost (5 0.0 Mg ha^{-1} year^{-1}) and crop residues (3.0–4.6 Mg ha^{-1} year^{-1}), the soil remains unsaturated in its capacity to sequester C. However, Six et al. [105] proposed that soil's capacity to store C at the initial rate of storage cannot continue indefinitely and would reach a new steady state of SOC over time.

To maintain SOC level in the LTE with rice–rice cropping system, the critical limit of C input is 3.41 Mg C ha^{-1} year^{-1} [104], which is similar to the one reported by Kong et al. [106] (3.1 Mg C ha^{-1} year^{-1}) under Mediterranean climate, and by Standley et al. [107] (4.0 Mg C ha^{-1} year^{-1}) in Vertisols of summer rainfall zone of Australia. Mandal et al. [104] observed that 51.2 and 48.8 % of the total C could be allocated to the active and passive pools, respectively. It would seem that the rice–rice system stimulates the formation of passive pools of SOC, which retards SOC decomposition and loss even under hot and humid subtropical environments of the Indian sub-continent [104].

LTEs on Ferruginous Soils (Alfisols) of SAT Environments

Ferruginous soils (Alfisols) in general, are low in SOC (<1 %); they are mostly used for rainfed cropping. The estimated SOC stocks in the BM spots (Vijaypura-Typic Rhodustalfs, Kaukantla-Vertic Haplustalfs and Patancheru-Typic Rhodustalfs) in 1980 and 2005 showed an overall increase in C stock (Table 7).

Table 8 Selected chemical properties in surface (0–30 cm) soil samples of selected benchmark spots in semi-arid tropical regions of India

Series name	pH water	SOC (%)	SIC (%)	TC (%)	Total N (%)	SOC:N	SIC:N	TC:N	Clay CEC
Jhalipura	8.1	0.53	1.10	1.63	0.0443	12:1	25:1	37:1	77
Jajapur 1	8.5	0.88	0.26	1.14	0.082	11:1	3:1	14:1	62
Teligi	8.0	1.03	1.30	2.33	0.062	17:1	21:1	37:1	90
Teligi 1	7.8	0.88	0.96	1.76	0.0551	14:1	17:1	32:1	99
Jhalipura	8.3	0.44	0.45	0.89	0.051	8:1	9:1	17:1	79
Paral	8.2	0.60	1.19	1.79	0.0354	17:1	33:1	51:1	97
Konheri	8.1	0.30	1.08	1.38	0.0241	12:1	45:1	57:1	90
Kovilpatti	8.0	0.40	0.85	1.25	0.0279	14:1	30:1	45:1	92

Adapted from Sahrawat et al. [52]

SOC soil organic C, *SIC* soil inorganic C, *TC* total C, *CEC* cation exchange capacity

From the results of LTE conducted for 7 years on Alfisols under sorghum (*Sorghum vulgare*, L)-castor (*Ricinus communis*, L) bean rotation, Sharma et al. [108] reported that conventional tillage, application of Gliricidia loppings along with 90 kg ha^{-1} N provided the best soil quality index (SQI). It increased vegetative growth and root biomass, which in turn enhanced soil OM. The enhanced soil microbial biomass carbon (MBC) contributed 31 % towards SQI and MBC served as a sensitive indicator of SQI.

LTE Results in Shrink–Swell Soils (Vertisols) of SAT Environments

The results of a long-term experiment on Vertisols at the ICRISAT center in Patancheru, India demonstrated that improved management (IM) of a catchment under double cropping or intercropping system not only increased overall crop productivity but also improved soil quality [71, 109] as compared to traditional management (TM) system. The IM followed soil and water conservation practices where excess rain water was allowed to safely drain along with the implementation of improved, legume based crop rotation and nutrient management. In the TM system, sorghum and chickpea were grown in the post-rainy season with organic fertilizers (10 t FYM ha^{-1} added every other year), and in the rainy season, the field was maintained as a cultivated fallow. The results from this LTE (Table 8) indicate the average grain yield of the IM over 30 years was nearly fivefold over the TM system with yield about 1.1 t ha^{-1}.The IM increased rainwater efficiency (65 vs 40 %), reduced runoff from 220 to 91 mm and soil loss from 6.64 t to 1.6 t ha^{-1} along with increased crop productivity [71]. This advantage in productivity and soil quality is due to the enhanced saturated hydraulic conductivity (sHC) of Vertisols under IM system. The sHC of IM has increased by almost 2.5 times due to the reduction in ESP through the dissolution of $CaCO_3$. The $CaCO_3$ content of IM decreased from 6.2 % under TM system to 5.7 %. In the last 24 years, the rate of dissolution of $CaCO_3$ is 21 mg year^{-1} in the top 100 cm of the profile [71]. The IM system caused increase in the solubility of $CaCO_3$ and a slight increase in the exchangeable Ca/Mg ratio, leading to better chemical and physical environments for C sequestration and enhanced microbial biomass C (MBC) and nitrogen (MBN) [71, 109, 110]. These results suggest that legume-based system (IM) could sequester C (5 mg year^{-1}) in the top 100 cm layer in the soil profile [60] even without addition of FYM. This finds support from a study conducted by the ICRISAT and its partners in ICAR on Vertisols of SAT that indicated legume based IM system can sequester more carbon than the cereals and horticultural system, whereas grassland sequestered more C than the annual crops [52, 70, 111]. When FYM was added at 10 Mg FYM ha^{-1} along with NPK (100 % of recommended doses), Vertisols further sequestered 330 kg SOC ha^{-1} year^{-1} [112].

Sequestration of SOC in Submerged Rice Soil System

In temperate soils, low rate of OM decomposition leads almost invariably to the accumulation of organic material in soils that are poorly drained. In the tropics, this may not always hold [40]. At a temperature above 30 °C, the rate of decomposition of OM by anaerobic organisms is sufficiently rapid so that poor drainage did not necessarily lead to accumulation of OM [113]. Jenny and Raychaudhuri [20] noted that Indian soils under paddy or lowland rice cultivation generally had greater SOC and N than those under upland cropping systems. The observation of Jenny and Raychaudhuri [20] on relatively high OM status of wet land rice soils finds support with those recently reported by Sahrawat ~~[113]~~, based on a detailed review of global literature on the accumulation of OM in submerged soils and sediments. This review points out that OM preferentially

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accumulates in the soil under submerged condition for a prolonged period. Sequestration of OC has also been reported with relatively short-term experiments [114]. It is significant in LTEs with rice–wheat–jute [86, 96], rice–berseem [115], rice–wheat [81, 116] and rice–rice [103] even under hot and humid subtropical environment. However, the inclusion of an upland crop in the crop sequence with low land rice system caused a decrease in OC and total N due to low C sequestration in the soil [117].

The mechanisms involved in preferential accumulation of OM in wet land soil are mainly associated with anaerobiosis-related chemical and biological changes in submerged soil. Decomposition of soil or added OM is relatively fast, complete and efficient in the soil under aerobic condition, where oxygen acts as electron acceptor. But the decomposition of OM in the absence of oxygen in submerged or anerobic soil is comparatively slow, incomplete and inefficient [114]. The lignin and polyphenol contents in compost and rice crop residue favour the formation of biochemical complexes with protein of plant origin under submergence [117], which make them resistant to microbial decomposition resulting in a comparatively higher proportion of total C in the passive pools [114, 118, 119] because of chemical reactions of the microbially transformed OM with soil minerals imparting resistance to its further decomposition [103]. OM fraction in the anaerobic environments, form complexes with Fe^{2+} ions [120] when Fe^{3+} accepts electron [113] and become stable and resistant to microbial attack. However, ploughing, manuring and puddling in paddy rice cultivation under submergence are confined in the 0–20 cm layer of soil profile. Therefore, improvement in the depth distribution of recalcitrant C pool of the SOC stock may not be a practical proposition to achieve C sequestration in the rice–rice ecosystem [104]. Jenkinson and Rayner [121] and Jenkinson [122] have shown that soil C at depth is older than that on the surface, which may indicate that such OM has greater resistance to decomposition or that the environment at depth is less favourable for microbial decomposition processes. In this context, Sahrawat et al. [52] stressed that there is a need to further test this hypothesis for soils in SAT regions of India and therefore, they conducted a study to provide additional evidence of soil OM status as affected by lowland rice and other arable system. They examined the influence of lowland versus arable systems on the dynamics of SOC, SIC and total N ratios as these are of critical importance in the maintenance of fertility and pedo-environment [42]. The sites of this study were selected from BM locations representing Vertisols under a range of different land use systems. The sites were under the specified production systems for 20 years or more and therefore, represent QEV of SOC and N. In addition to various cropping systems, management levels also varied across the sites. Soils are calcareous and have alkaline pH and clay CEC that ranges from 62 to 99 cmol(+) kg $^{-1}$(Table 8). Soils of lowland rice systems (rice–rice) had higher SOC and total N compared to those under rice-arable crop sequence or other cropping systems with or without legumes (Table 8). The SOC: N ratio of soils varied from 8 to 17. The widest SOC:N ratio was observed in Teligi (rice–rice) and Paral (cotton plus pigeon pea/sorghum) systems. Soils under wetland rice (rice–rice) had a tendency to show wider C:N ratio as compared to those under other upland-based cropping patterns, indicating a change in the quality of OM in sites with wetland rice in comparison to those under arable cropping systems with relatively narrow C:N ratios(Table 8). Olk et al. [123] also reported that the C:N ratio of soils increased with the intensity of irrigated rice and the ratio was wider in soils under rice–rice or rice–rice–rice than soils under dry land rice or rice–soybean system. The SIC:N ratio is relatively narrow in soils under lowland rice–rice system and the TC:N ratio suggests that the narrower values in rice soils indicates a better and conducive pedo-environment. Balance between OM inputs and decomposition is the primary determinant of OM accumulation or depletion in soils [114]. Under prolonged rice (submerged) environment, there is a net addition of OM in soil, whereas the balance is generally negative under arable cropping systems. Soils under lowland rice system preferentially accumulate OM and are important for sequestering atmospheric C Therefore, carbon sequestration under soil submergence is also an important strategy to reduce the atmospheric load of CO_2 and mitigate climate change [114, 124].

Methane and Carbon dioxide Emissions from Soils in Relation to C Sequestration

Paddy cultivation in India covers an area of 42.24 mha and is often blamed for loading methane (CH_4) in the atmosphere. Earlier attempts made to estimate CH_4 were mainly based on extrapolation (United States Environment Protection Agency, US EPA) and default values (Inter Governmental Panel on Climate Change, IPCC) provided estimates, which were several times higher for CH_4 and nitrous oxide (N_2O). Based on data generated from specific experiments carried out at various rice-growing regions of India under different moisture regimes and by accounting for emission of N_2O from fertilizer, crop residue, animal manure and leaching of nitrate and its subsequent volatilization as ammonia, Bhatia et al. [124] estimated CH_4 and N_2O emissions for the base year 1994–1995 to be 2.9 Tg (61 Tg CO_2 equivalent) and 0.08 Tg (39 Tg CO_2 equivalent),respectively, and pointed out that CH_4 and N_2O from Indian agricultural soils are responsible for only about 0.23

and 0.1 %, respectively of the global warming caused by the world's CO_2 emissions. Thus overall greenhouse gas emission from Indian agriculture, especially from the soil is a small fraction of the total world greenhouse gas emission. In view of continuing uncertainties in the estimation of CH_4 and N_2O from Indian agriculture because of diverse soil, climate, land-use types and limited field measurements, further attempt was made using improved primary dataset to simulate emissions of N_2O, CH_4, and CO_2 from rice- and wheat-growing areas of India using the Info Crop simulation model, to prepare a spatial inventory of GHGs emission and their global warming potential (GWP), and assess the impact of irrigation, fertilizer, and organic manure application on the GHGs emission from rice- and wheat-growing areas of India [125]. It was reported that Indian rice fields covering 42.21 mha emitted 2.07, 0.02, and 72.9 Tg of CH_4-C, N_2O-N and CO_2-C, respectively, with a GWP of 88.5 Tg CO_2-C equivalent. Estimated values of CH_4 and N_2O are less than those reported earlier [125]. Annual GHGs emission from 28.08 mha of wheat-growing areas was 0.017 and 43.2 Tg of N_2O-N and CO_2-C, respectively, with a GWP of 44.6 Tg CO_2-C equivalent. Intermittent irrigation in rice reduced methane emissions by 40 %. However, the application of farmyard manure in rice increased the GWP by 41 %.

The present NARS's recommendations to enhance agricultural and horticultural output since post- green revolution period helped in increased OC sequestration in all soil types without leading to increased emissions of GHGs to any alarming proportion. Bhatia et al. [126] estimated emissions that constitute a small fraction of the GWP, suggesting that the C sequestration in major soil types of India has a positive OC balance. However, the insignificant loading of GHGs into the atmosphere and the favorable OC balance seem to be linked to some important pedochemical reactions under soil environments and also management practices, which hitherto were not given due importance in model exercises. These are (i) the formation of PC by sequestering atmospheric CO_2 in soils of dry climates [42, 55], (ii) increased OC sequestration in rice fields under submergence [52, 114], (iii) maintenance of higher amount of soil C in passive pools in rice fields and protection of OC by preventing its oxidative losses to gaseous C loading into the atmosphere [104, 124], (iv) application of moderate amount of N fertilizers (95 kg ha^{-1} as national average, a very low input as compared to many western, European and other Asian countries, NAAS [127]) and FYM (in general <10 t ha^{-1}, [111]), and (v) protection of NH_4^+ produced through the addition of inorganic fertilizers and FYM, on zeolite exchange sites of shrink-swell soils [47] from microbial conversion of NH_4^+ to NO_3^- [128]. However, large fraction of rice cultivation in India is not highly mechanized. In the event of future rapid industrial development, the agricultural activities will be more intense in the coming decades and the agricultural sector will become a more important source of GHGs, through the burning of fossil fuels for running the farm machineries [129]. Thus a new research initiative is warranted to make future projections on the emissions of GHGs by simulation and modeling considering the endeavors to maintain a positive balance of OC sequestration in soils through appropriate natural resources management practices.

Scope of Carbon Simulation Models for Predicting SOC Changes

The Century ecosystem model was evaluated by Bhattacharyya et al. [81] for its ability to simulate SOC changes in the IGP soils. Two LTEs, with all necessary parameters to run the Century, were used for this purpose. They were jute (*Corchorus capsularies* L.), rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) trial on a Typic Eutrudepts at Barrackpur, West Bengal (AESR 15.1, Fig. 1), and a rice–wheat trial on a Typic Ustipsamments at Ludhiana, Punjab (AESR 9.1, Fig. 1). The trial site at Barrackpur represents humid climate with >1600 MAR, and the Ludhiana site represents a dry semi-arid with <800 mm [96]. Both trials involved several treatments involving organic and inorganic fertilizer inputs. At Ludhiana, modeled data simulated observed the data reasonably well for all treatments. However, at the Barrackpur site with triple cropping, Century performed less precisely. Mandal et al. [104] indicated that 29 % of the compost C added to soil was stabilized into SOC mostly in recalcitrant pools in the surface layer of the soil due to reactions with polyphenols and lignin under long soil submergence during rice cultivation, and this may be one of the primary causes for Century C model not to perform as well in humid site of the IGP. This finds support from the results of Century C model exercise on a 19 year old LTE with rice–wheat under humid climates [116] at Mohanpur, West Bengal (AESR 15.1, Fig. 1), conducted on a clay loam, Vertic Endoaqualf [130]. This LTE in humid climatic conditions indicated that the modelled data simulated the measured data reasonably well for all treatments. Milne et al. [131], however, suggested that Century may be less suited to estimate carbon dynamics of soils under rice flooded every year. In contrast, the LTE at Mohanpur [130], flooded rice of rice–wheat rotation yielded a good Century output from the humid bioclimatic system.

Bhattacharyya et al. [~~128~~] evaluated Century model with results from a 9-year old LTE conducted on Vertisols with sorghum and wheat at Akola of the dry semi-arid part of Maharashtra in central India (AESR 6.3, Fig. 1). The model tended to overestimate treatment effects at the end of the experimental period because at present Century does not model deep and wide cracks of Vertisols, affecting plant available water. Additionally, the chemical reaction of microbially transformed OM with smectite clay may impart resistance to decomposition [104]; and this probably might affect the performance of Century C model in Vertisols.

The above exercise on evaluating Century C model indicate that it is more successful when applied to double cropping systems like rice–wheat, which does not require prolonged submergence like in rice–wheat–jute or rice–rice systems. Research results of LTEs so far conducted on Indian soils [86, 96, 104, 115, 116] clearly demonstrate that the labile pool of SOC is a useful indicator for proper assessment of soil health, acquired through balanced fertilization with FYM. The SOC content determined by the Walkley and Black method includes both labile/active fraction and non-labile pools. At present, existing LTEs do not provide data on the status of active/labile pool of SOC on a time scale. It is envisaged that the inclusion of such data may make the Century C model more useful in predicting the SOC changes, possibly in all soil types under diverse climatic environments.

Potential of OC Sequestration in Indian Soils

The soils of tropical India do not have clay minerals of advanced weathering stages. Instead, non-vertic soils have mixed minerals in their clay fractions, and Vertisols and vertic intergrades are dominated by smectite clay. These minerals act as good substrate to sequester OC under good vegetation with favourable parent material (zeolitic) and environmental conditions. These are exemplified by the formation of OC rich Mollisols in both semi-arid and humid tropical climate [29]. Soils (Entisols, Inceptisols, Alfisols, Vertisols) under various agricultural land uses under both short and long–long term experiments also showed their potentiality to sequester OC under both arable and submerged conditions [38, 44, 52, 70, 71, 86, 88, 90, 96, 104, 108, 114, 116] and they still show potential to sequester OC even in humid climates [96, 100, 104]. Results on Vertisols indicated that legume-based IM could sequester OC at the rate of 5 mg year^{-1} in the first 100 cm soil depth even without FYM and gypsum addition [60]. When FYM added (10 Mg FYM ha^{-1}) along with 100 % of recommended doses of NPK, Vertisols showed potential to sequester an additional amount of 330 kg OC ha^{-1} year^{-1} [112].

In addition to the above soils, sodic soils, which cover nearly 3.7 m ha area of the country, ICAR-NAAS [132], and are impoverished with OC, exhibit good potential to sequester OC when ameliorative management practices are implemented. Through the implementation of specific management practices for Typic Natrustalfs of IGP [133] and Sodic Haplusterts of southern India [60, 71], a substantial increase in OC stock was observed for both soil types [85, 86, 108]. The IGP sodic soils were made resilient through gypsum application, followed by rice cropping [83], whereas the IM [71]) made sodic black soils [43, 61] resilient. The observed potential for sequestering OC is, however, dependent on the high rate of dissolution of PC (SIC) in such soils under land uses. After 30 months of reclamation of IGP sodic soils, an increase in exchangeable Ca^{+2}, Mg^{+2}, a decrease in ESP, pH, SAR, ECe and also in native CaCO$_3$ was observed to a considerable depth [83]. Due to 30 months of cultural practices, the rate of dissolution of CaCO$_3$ was 254 mg 100 g^{-1} soil in the top 100 cm of the profile [42]. In Vertisols, after 30 years of IM, the weighted mean (WM) of saturated hydraulic conductivity in the first 100 cm of the profile increased by almost 2.5 times due to the reduction of ESP through the dissolution of CaCO$_3$. The rate of dissolution of CaCO$_3$ is 21 mg year^{-1} in the first 100 cm of the profile. Dissolved Ca^{+2} ions increase Ca/Mg ratio on the exchange complex of Vertisols [60].

The above discussed changes in soil properties highlight a unique role of CaCO$_3$ that remains chemically inert [42] during its sequestration [134], but acts as soil modifier during the amelioration of sodic soils [43, 60]. The improvement in soil properties are also reflected in the classification of both the soil types. The IGP sodic soils (Typic Natrustalfs) now classify for Typic Haplustalfs [60] whereas the Vertisols with subsoil sodicity (Sodic Haplusterts) for Typic Haplusterts [43, 60]. Therefore, the implementation of the technologies to make these sodic soils resilient and potential for OC sequestration may be promoted by providing incentives, technological know-how, required resources and policy support to the farmers. All these initiatives may also be taken up through transferable C credits under CDM of the Kyoto Protocol as C sequestration is one of the important mitigation strategies to cope with the impacts of climate change by reducing the atmospheric concentration of CO$_2$ emissions [15]. In view of the inherent potential of Indian soils (both zeolitic and non-zeolitic) for OC sequestration, the present SOC stock could be further increased beyond 30 Pg (in the first 150 cm depth) at the expense of SIC, when the NARS's recommendations for improved seeds, NPK fertilizers, micronutrients, FYM, and the inclusion of legumes in cropping sequence is implemented in farmers' fields.

Economics of SOC Sequestration and Scope of C-Trading in Indian Agriculture

Pathak et al. [112] made an analysis based on the data from 26 LTEs for calculating potential and cost of C sequestration using most recent data and identical statistical procedure. Application of FYM as an option for C sequestration was considered because the NPK plus FYM treatment demonstrated higher SOC than that under NPK treatment in all the LTEs. Nutrient inputs were compared while calculating the annual rate of C sequestration. As the LTEs had different crops and cropping systems, for comparison of treatments, the yields of different crops were converted to wheat equivalent yield as wheat was the most common crop in the LTEs. Gross income was derived using minimum support price offered by Government of India for various commodities. The difference between gross income and total costs of inputs was considered as net income. Pathak et al. [~~111~~] based on such exercise reported that in 17 out of 26 LTEs, the NPK plus FYM treatment showed higher SOC and also higher net return than that under NPK treatment. They thus suggested that application of FYM with NPK is a cost effective, win–win technology in these LTEs. Indian farmers follow the FYM application, wherever it is feasible. However, Pathak et al. [112] reported that in the remaining 9 LTEs, SOC sequestration in the NPK plus FYM treatment showed a decreased net return because these LTEs received less than 10 Mg FYM ha^{-1}, an amount that helps in sequestering 0.33 Mg C ha^{-1} $year^{-1}$.Therefore, to include farmland as a potential option for C sequestration, additional financial support through incentives or transferable C credits under CDM may be a viable option [112] as soil C sequestration has been found to be the most cost-effective option [135] as compared to geological sequestration [136].

Concluding Remarks

Soil diversity in the tropics in general and in India in particular, is at least as large as that in the temperate zone relative to the variability in environmental factors that control soil formation as reflected in their taxonomic diversity. Generalizations possible about tropical soils made so far indicate that they are unlikely to have wider applicability in agriculturally progressive country like India. India's growing self-sufficiency in food production and stocks since independence has been made possible because of favourable natural endowment of soils that have capacity of sequestering C with an insignificant contribution to GWP through the emissions of GHGs. Major soil types (both zeolitic and non-zeolitic) remained highly responsive to management interventions made mainly by farming communities with the support from national and international institutions. The increase in SOC stock mainly in soils of dry climate seem due to improvement in physical and chemical properties through the dissolution of SIC ($CaCO_3$), which remains chemically inert, during its sequestration, but acts as a soil modifier during the reclamation of degraded soils. Tropical Indian soils have considerable amount of 2:1 layer silicates and soil modifiers that ensure good substrate quality. This shows their high potential for C sequestration under appropriate cropping and management. It is thus envisaged that the present SOC stock (around 30 Pg in the first 1.5 m) can further be increased by the use of recommended improved seeds, NPK fertilizers, micronutrients, FYM, and the inclusion of legumes in cropping systems. India being mainly as an agrarian society, soil care through recommended practices has been the engine of economic development, eliminating large portion of poverty and considerable transformation of rural communities. The synthesis of literature developed through this review may serve as guiding principles to improve and maintain soil health through adequate OC sequestration programmes in other tropical and sub-tropical parts of the world where as in Indian sub-continent such developments are either in progress or likely to take place soon in the twenty-first century.

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