Carbon Status of Indian Soils : An Overview

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Restoration of soil health through soil organic carbon (SOC) management is a major concern for tropical soils. The accelerated decomposition of SOC due to agriculture, resulting in loss of carbon to the atmosphere and its contribution to the green house effect, is a serious global problem. The contribution of SOC to improving soil physical, chemical and biological properties and maintaining soils integrity for sustaining soil productivity is well known. Important factors controlling SOC status include climate (especially rainfall and temperature), hydrology, parent material, soil fertility, biological activity, vegetation and land use (Jenny, 1941). Equally importantly, SOC is sensitive to human activities such as deforestation, biomass burning, land use changes and environmental pollution. It is estimated that the land use change results in the transfer of 1-2 Pg C yr^{-1} from terrestrial ecosystem to the atmosphere of which 15-17% C is contributed by decomposition of SOC (Humpton and Hackler., 1994).

It is important to note that organic matter (OM) preferentially accumulates in continuous paddy rice systems and that submerged soil systems store larger amounts of SOC as compared to their upland counterparts (Sahrawat, 2004, 2005 and 2007). The most important factor responsible for net accumulation and storage of OM in wetland paddy soils is the high net primary productivity of these systems (Sahrawat, 2004). Thus, slow decomposition of OM and higher net primary productivity of submerged paddy rice soils lead to net accumulation of organic matter and N in submerged soils and sediments.

To sustain quality and productivity of soils, information on SOC in terms of its amount and quality is essential. In recent years, agricultural-related global warming has created awareness on the role of C cycling in agroecosystems, especially, interest in storing atmospheric C in the soil (Velayutham *et al.*, 2000). The first comprehensive study on SOC status in Indian soils was conducted by Jenny and Raychaudhuri (1960). They collected 500 soil samples covering cultivated and forested soils under a wide range of total rainfall and its distribution. The results of this study demonstrated the dominant role of climate on SOC status and reserves in soils. However, these authors did not make any estimate of the total carbon reserves in the soils. The first attempt in estimating SOC stock was made by (Gupta and Rao, 1994), who reported SOC stock of 24.3 Pg for soils ranging from surface to an average depth of 44 to 186 cm using data from 48 soil series. However, this estimate was based on afforestation as a mechanism for enhancing SOC status of selected unproductive soils. Velayutham *et al.* (2000) made estimates of OC stocks in soils to varying depths using India-wide datasets.

The objective of this paper is to present an overview of the research carried out on SOC status of Indian soils using comprehensive datasets (Bhattacharyya *et al.*, 2000a, b, 2001, 2004, 2005, 2006, 2007a,b, c, d, e, f, 2008, 2009, 2010, Chandran *et al.*, 2009, Chivhane and Bhattacharyya., 2010, Pal *et al.*, 2000, Sahrawat *et al.*, 2005, Velayutham *et al.*, 2000, Wani *et al.*, 2007). We expect that the estimates based on these datasets would be helpful in setting out priorities of research for SOC management for sustainable productivity enhancement without degrading environmental quality.

Data Sets Used in the Study

For this synthesis, information on selected soils (Tables 1, 3-6) covering all regions in the country was collected from the existing primary datasets available at the NBSS&LUP, Nagpur (Bhattacharyya *et al.*, 1995, 1996, 2000a, 2007b, 2009, Jackson., 1973, Lal *et al.*, 1994, Murthy *et al.*, 1982, Pal *et al.*, 2000, Sehgal *et al.*, 1999 and Velayutham *et al.*, 2000). Generally, SOC is determined by the Walkley and Black's method (Jackson, 1973); the results are further used to generate SOC results on weight to volume basis. For soil inorganic carbon (SIC), the information available on calcium carbonate ($CaCO_3$) content in soils is used as the base. In this synthesis, the bulk density (BD) values were generated where they were not available (Bhattacharyya *et al.*, 2009).

Methodology Used in Estimating Carbon Stock of Soils

The data sets (SOC, SIC, BD, areal extent of soil series) were brought to the required format for 0 - 0.3, 0 - 0.5, 0 - 1.0 and 0 - 1.5 m of soil depth. The size of carbon stock was calculated following two steps. The first step involves calculation of SOC by multiplying SOC content (g g^{-1}), BD (Mg m^{-3}) and thickness of horizon (m) for individual soil profile with different thickness varying from 0 – 0.3, 0 – 0.5, 0 – 1.0 and 0 – 1.5 m. In the second step, the total SOC content determined by the first step was multiplied by the area (m ha) of the soil unit distributed in different agro-climatic zones (Anon., 1989). The total SOC content is expressed in Pg (1 Pg = 10^{15} g). The total SOC stock was thus calculated using following equation

$$\text{SOC stock in soil} = \frac{\text{C content (g g}^{-1}\text{) x BD (Mg m}^{-3}\text{) x Area (M ha) x Soil Depth (m)}}{10}$$

For the SIC, the same steps are followed using 12 parts of C present in $CaCO_3$ values. The sum of SOC and SIC stock gives the total carbon (TC) stock in soils.

Generating Thematic Maps

The maps of ACZ (Anon., 1989), AESR (Velayutham *et al.*, 1999), and bioclimatic systems (Bhattacharjee *et al.*, 1982) were digitized and used as base maps to generate thematic maps on soil carbon stock for different soil depth intervals using Arc-GIS (Ver.9.0) software. For brevity, the maps for 0-0.3 m depth are shown in this paper.

Carbon Stocks in Indian Soils

A. Carbon stocks in various soil orders and different types of soils: Soil carbon stocks (SOC, SIC and TC) in seven different soil orders are shown in Table 1. Vertisols, Inceptisols and Alfisols have the major share of SOC stocks in first 30 cm depth of soils. For similar depth, Aridisols show low SOC but very high (33%) level of SIC stock. For the purpose of this synthesis, Indian soils are broadly classified into five groups. The results showed that red soils (Alfisols and Ultisols), alluvial soils (Entisols and Inceptisols) and black soils (Vertisols) are found to store maximum organic carbon. Since carbon stock in soil is controlled mainly by carbon concentration and the areal extent of soils, in a soil even if the carbon content is high, the carbon stock could be lower due to smaller areal extent. This is the reason why brown forest soils, represented mostly by Mollisols, contain high carbon, yet show low carbon stock. Table 2 shows the stock of both organic and inorganic carbon in five major soils of India.

Table 1 : Carbon stock in Indian soils (Order-wise)*

Soil order	Soil depth (m)	Carbon stock (Pg)		
		SOC	SIC	TC
Entisols	0-0.3	0.62 (6)**	0.89 (21)	1.51 (11)
	0-1.5	2.56 (8)	2.86 (8)	5.42 (8)
Vertisols	0-0.3	2.59 (27)	1.07 (26)	3.66 (27)
	0-1.5	8.77 (29)	6.14 (18)	14.90 (23)
Inceptisols	0-0.3	2.17 (23)	0.62 (15)	2.79 (20)
	0-1.5	5.81 (19)	7.04 (21)	12.85 (20)
Aridisols	0-0.3	0.74 (8)	1.40 (34)	2.14 (16)
	0-1.5	2.02 (7)	13.40 (39)	15.42 (24)
Mollisols	0-0.3	0.09 (1)	0.00	0.09 (1)
	0-1.5	0.49 (2)	0.07 (0.2)	0.56 (1)
Alfisols	0-0.3	3.14 (33)	0.16 (4)	3.30 (24)
	0-1.5	9.72 (32)	4.48 (13)	14.20 (22)
Ultisols	0-0.3	0.20 (2)	0.00	0.20 (1)
	0-1.5	0.55 (2)	0.00	0.55 (1)
Total	0-0.3	9.55	4.14	13.69
	0-1.5	29.92	33.98	63.90

* Source : Bhattacharyya *et al.*, 2000b. ** Parentheses show percentage of total SOC, SIC and TC

Table 2 : Organic and inorganic carbon stock in commonly found Indian soils (0-0.3 m soil depth) (Values in Pg)*

Soil Carbon	Alluvial soils	Black soils	Arid soils	Brown forest soils	Red soils	Total Carbon
Organic	2.79	2.56	0.71	0.12	3.33	9.55
Inorganic	1.52	1.08	1.39	0.00	0.15	4.14
Total	4.30	3.64	2.11	0.12	3.52	13.69

*Source : Bhattacharyya *et al.* (2005)

B. Carbon stocks in the soils of various bioclimatic zones: An attempt was made to generalize the soil carbon storage in each bioclimatic system alongwith a comparison of the storage capacity of other two systems viz. agro-climatic zones (ACZs) and agro-ecological subregions (AESRs). The SOC and SIC storage have been reported to be related with climate (temperature and rainfall). The carbon storage values for different bioclimatic systems were collated, and are shown in Figure 1. The arid bioclimatic system is characterized by low annual rainfall (<500 mm). Since these areas do not support dense vegetation, the soils are low in organic carbon. This bioclimate is divided into two, namely cold arid and hot arid on the basis of atmospheric temperature. Within the cold arid bioclimate, the Ladakh plateau is colder than the north Kashmir Himalayas. Lower atmospheric temperature at subzero levels causes hyper-aridity and does not support vegetation, which is in contrast to western aspect of the Ladakh plateau and the north Kashmir Himalayas. This may be the reason why soils in the cold arid bioclimate contain higher SOC stock (Table 3). The arid bioclimate covers 15.8% of the TGA with a share of about 10% of the total SOC stock (Table 3).

Table 3 : Soil organic and inorganic carbon stock in different bioclimatic zones in India*

Bioclimatic Zones	Area		SOC		SIC		TC		Stock per unit area (Pg/M ha)	
	Coverage (M ha)	TGA (%)	Stock	% of total SOC stock	Stock	% of total SIC stock	Stock	% of total TC stock	SOC	SIC
Cold	15.2	4.6	0.6	6	0.7	17	1.3	10	0.039	0.046
Arid Hot	36.8	11.2	0.4	4	1.0	25	1.4	10	0.011	0.027
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

* Source: Revised from Bhattacharyya *et al.* (2000a, 2008).

It is interesting to note that cold arid bioclimate constituting 29% of the total arid ecosystem of the country, accounts for 60% of total SOC stock of arid bioclimate. Conversely hot arid system with about 71% area of the total arid bioclimate, contributes only 40% of the total SOC stock in the arid ecosystem (Table 3). Arid bioclimate has a SIC stock of 1.7 the first 30 cm depth of soil (Table 3) out of which 0.7 Pg is contributed by cold and 1.0 Pg by the hot arid ecosystem (Fig. 1).

Semi-arid bioclimate consists of major parts of central and south Peninsula, which extends upto western and north-western part of the country and comprises of 17 AESRs and 7 ACZs. By and large, temperature in semi-arid bioclimate ranges from 25^0 to 27^0 C and mean annual rainfall varies from 500 to 1000 mm. This bioclimate is characterized by a type of vegetation, which ranges from bushy thorns and grasses to deciduous forests. The total SOC stock in the semi-arid bioclimte is 2.9 Pg, which is nearly 30% of the total SOC stock

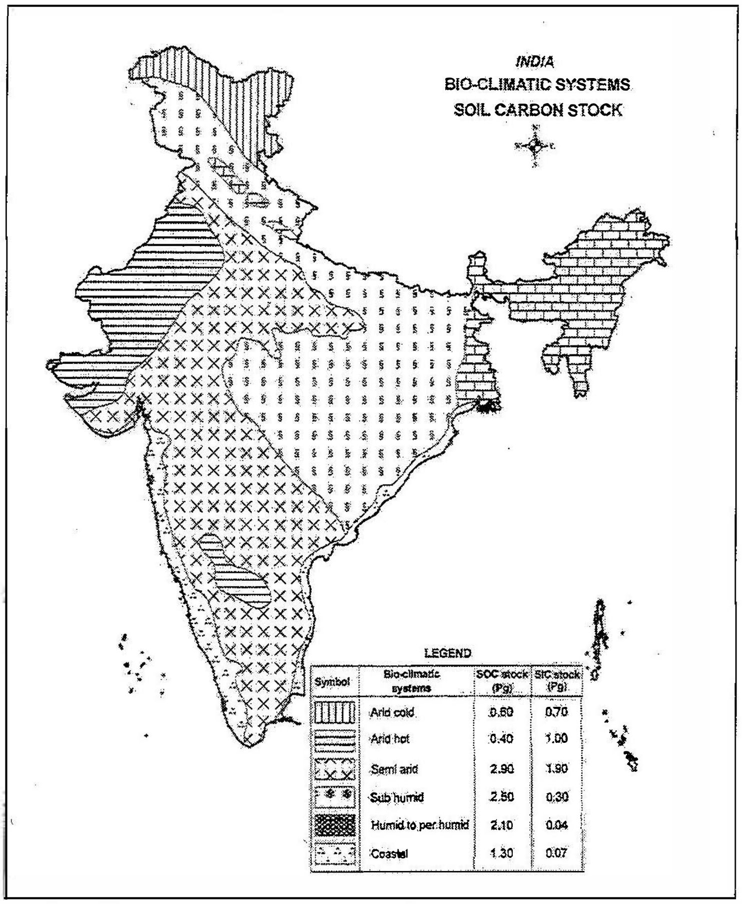


Fig.1. Carbon stock in major bioclimatic systems in India (0-0.3 m soil depth) (Source : Bhattacharyya *et al.* 2008).

of the country (Table 3). Semi-aridity helps in the formation of pedogenic $CaCO_3$, which is the source of 1.9 Pg SIC stock with a share of 47%. Total carbon (TC) stock of the semi-arid bioclimate has been estimated at 4.8 Pg, which is 35% of the total carbon stock of the country.

The calcium carbonate in calcic horizons (Soil Survey Staff, 2003) is reported to be generated by two processes (Pal *et al.*, 2000). First, carbonates may be physically derived from the rocks that act as the source of the soil or may be brought into the region by wind transport. Recrystallization may lead to the incorporation of atmospheric or soil CO_2 but the same amount of fossil CO_2 is liberated and the net balance for the carbon cycle is zero (Elberson *et al.*, 2000). These carbonates may be geogenic or non-pedogenic carbonates (NPC) (Pal *et al.*, 2000). By the second process, carbonates have been formed from the parent rocks by the combined influence of exchangeable calcium ions of soils liberated from the chemical weathering of minerals and overhead atmospheric/ soil CO_2 (Pal *et al.*, 2000, Elberson *et al.*, 2000). This pedogenic carbonate (PC) act as a sink for CO_2 (Elberson *et al.*, 2000). In many areas of the south western states and in the Deccan plateau, non-calcareous alluvium, including calcium-rich basaltic parent material is common. In such areas, calcium from the soil exchange deposited as carbonate in the basaltic alluvial soils, represents a sink for carbon (CO_2) from the atmosphere. Calcic horizons potentially represent the residue from large volumes of parent rock and may represent several metres of thickness. Large amount of PCs are stored in soils withdrawing CO_2 from the terrestrial carbon cycle for long periods. In the arid zone (ACZ 14), the main process of calcium carbonate formation in soils is through the accumulation of inherited carbonates (NPCs) mainly from calcareous dust. In contrast, in the semi-arid to subhumid zones with relatively good amount of water available for chemical weathering, more PCs are formed. Efforts were made to quantify the amounts of PCs over time which might indicate the amount of atmosphere/soil CO_2 sequestered by soil in inorganic form. The rate of formation of calcium carbonate was found to vary from soils depending on soil type and the zones represented by the soils. The representative soils of the IGP indicate 0.86 mg $100g^{-1}$ soil yr^{-1} of $CaCO_3$ formation. The black soils of central and western India register a range of 0.39 mg $100g^{-1}$ soil yr^{-1} to 2.12 mg $100g^{-1}$ soil yr^{-1}, while the ferruginous calcareous soils of southern India indicate a value of 0.20 mg $100g^{-1}$ soil yr^{-1} (Pal *et al.*, 2000).

The sub-humid bioclimate comprises of 14 AESRs and 5 ACZs. This ecosystem is characterized by transitional climatic phase between humid and semi-arid. The average annual temperature of this bioclimate is 22^0 to 29^0C with mean annual rainfall of 900-1700 mm. This bioclimate covers major part of the IGP and parts of southern Peninsula. Most of these areas are rich in vegetation and therefore SOC content of these soils is relatively high as compared to those in the semi-arid and arid bioclimate. The total SOC stock of the first 30 cm of the soils of this bioclimate is 2.5 Pg, which is 26% of the total SOC stock. It has been reported that barring few exceptions, the subhumid and humid bioclimates do not contain calcium carbonates in soils due to high rainfall. The subhumid bioclimate stores a meagre amount of 0.3 Pg SIC, constituting only 8% of total SIC reserves of the country. The relative contribution of SOC (89%) and SIC (11%) stocks indicates the effects of rainfall in building up of high SOC stock in this bioclimate.

The humid to perhumid bioclimatic system covers 34.9 M ha area (11% of TGA). In the first 30 cm depth of the soil, the SOC stock is estimated at 2.1 Pg. Many areas of this bio-climate are covered by Arunachal Pradesh, Meghalaya, Mizoram, Manipur and the hilly areas of Tripura where cooler winter months and higher rainfall have led to higher SOC stock (Bhattacharyya *et al.*, 2000a). The dominant soils in this bioclimate are non-calcareous as reflected by their contribution of meagre 1% SIC stock of the country. It is interesting to note that ACZ 2 is represented by a few soils which contain $CaCO_3$. Presence of inorganic carbon in the soils of this bioclimate characterized by high rainfall indicates that this $CaCO_3$ is non-pedogenic. Total carbon in this bio-climate is 2.14 Pg (15% of TC stock of the country) of which 98% is contributed by SOC (Table 3).

The coastal bioclimatic system covers an area of 20.4 m ha (6.2% of TGA). The SOC stock (1.3 Pg) of this system contributes 13% of the total SOC stock (Table 3). This system is represented by 10 AESRs and 3 ACZs. Total SIC stock of coastal bio-climate has been estimated 0.07 Pg, which represents 2% of the total SIC stock. In general, the soils in coastal bioclimate do not contain carbonates. However, there are exceptions in the soils of Kalathur, Thirunallur, Saili and Minicoy (Velayutham *et al.* 1999, 2000, Vadivelu and Bandyopadhyay 1997). However since SIC stock depends on the extent of geographical distribution of soils, the total SIC stock remains low in spite of presence of carbonates in some of the soils.

C. Carbon stocks in various agro climatic zones: The estimated stocks of soil carbon in the ACZ are briefly discussed in the following paragraphs:

The Himalaya Zones

Western Himalaya Zones (ACZ 1): These zones consist of 3 sub-zones (a) *Jammu and Kashmir* which covers cold arid region of Leh (~ 2000 m above mean sea level, MSL) to low altitude sub-tropical region of the southern plains (215 – 360 m above MSL), (b) *Himachal Pradesh* which consists of high hills (temperate dry and wet parts) to mid hills and subtropical uplands, and (c) *Uttar Pradesh Hills* which consists of valley, mid hills and high hills of the Western Himalayas (Anon., 1989). The Western Himalayan zones cover an area of 33.85 mha which constitutes 10% of the total geographical area (TGA) of the country. The soils contribute 14%, 19%, and 16% of SOC, SIC and TC stocks of the country, respectively (Figs. 2 and 3).

Eastern Himalaya Zones (ACZ 2): This zone is covered by Sikkim, part of West Bengal (Darjeeling, Jalpaiguri and Cooch Bihar districts), Arunachal Pradesh, Meghalaya, Nagaland, Assam, Manipur, Tripura and Mizoram. It is characterized by hills, mountains; plateau with near - tropical to alpine climate conditions. Mean annual rainfall is very high in areas under the forest. Many areas in Assam, West Bengal and Tripura represent cultivable lands. The soils contribute 19%, 1% and 13% of total SOC, SIC and TC stocks of the country, respectively (Figs. 2 and 3).

The Himalaya Zones (ACZs 1 and 2) cover nearly 19% area and contribute 33% of SOC reserves of the country largely due to the thick forest vegetation. The northern mountains of the country have maximum concentration of forest ecosystem except parts of central and western India. Eswaran *et al.* (1999) noted that about 40% of the total SOC stock of the global soils resides in forest ecosystems. The carbon stored in the upper soil horizons represents the pools most sensitive to changes, if the forest is used for agriculture or converted to pasture for ranching. It has been reported that the conversion of Amazonian forest to well-managed pastures causes an initial fall in the SOC reserves, followed by a slow rise. The estimates of SOC in any ecosystem represent a valuable baseline for evaluating the original status of SOC. The SOC stock of ACZ 1 and 2 may thus can act as a baseline dataset to assess the effects of land use changes in the Himalayan Range of India (Bhattacharyya *et al.*, 2008).

Gangetic Plains

Lower Gangetic Plains (ACZ 3): These plains represent four sub regions (i) barind plains, (ii) central alluvial plains (iii) alluvial coastal saline plains, (iv) rarh plains (Anon., 1989) and covers 3% of the TGA of the country. The soils contain 3%, 1%, and 2% of the total SOC, SIC and TC stocks of the country, respectively .

Middle Gangetic Plains (ACZ 4): Twelve districts of eastern Uttar Pradesh and twenty seven districts of Bihar Plains form this zone. It is sub-divided into two sub-zones (i) north-west alluvial (recent) plains, (ii) north-east alluvial (*tarai*) plains (Anon. 1989). This zone covers 5% of the TGA of the country. The dominant soils contribute 2%, 3% and 3% of the total SOC, SIC and TC stocks of the country.

Upper Gangetic Plains (ACZ 5): This zone consists of thirty two districts of Uttar Pradesh and covers 4% of the TGA of the country. This is sub divided into three sub-zones such as, (i) central plains (alluvial), (ii) north western plains (alluvial-*tarai*), and (iii) south western plains (alluvial). The dominant soils tribute 3%, 2%, and 3% of the SOC, SIC and TC stocks of the country, respectively.

Trans-Gangetic Plains (ACZ 6): This zone represents the states of Punjab, Haryana, Delhi, and part of Rajasthan (Shriganganagar district) covering 4% area of the country. It is divided into three sub-zones namely, (i) foothills of Shivalik and Himalayas, (ii) semi-arid plains, and (iii) arid zone bordering the Thar desert (Anon. 1989). The soils contribute 2%, 4%, and 3% of the SOC, SIC and TC stocks of the country, respectively.

The IGP is covered by 4 ACZs (ACZs 3, 4, 5 and 6) and occupying 15% area of the country (Anon. 1989). The Indo-Gangetic Plains (IGP) undergoes a gradual change in climate, physiography, natural vegetation and cropping systems. Total SOC, SIC and TC stocks in these plains are 9.0, 9.7, and 9.0% respectively. It was reported that the soils under hot humid and per-humid climates are deficient in SOC due to intensive agricultural practices (Bhattacharyya *et al.*, 2000b). Carbon sequestration in these soils is, however, possible through green manuring and application of farmyard manure in view of conducive soil and climatic conditions. A recent account on the changes in C storage in IGP soils shows an increasing trend (Bhattacharyya *et al.*, 2004). The predictive models (Century, IPCC-GEFSOC, Inter-governmental Panel on Climate Change – Global Environmental Facility Soil Organic Carbon) also show an increasing trend of SOC stock after an initial decline in the IGP (Bhattacharyya *et al.*, 2007a). Most part of the humid and subhumid regions of the IGP punctuated by a 2-3 cooler winter months dominated by non-calcareous soils fall under the sufficient zones of SOC content (Velayutham *et al.*, 2000). It has been reported that the soils of the arid and semi-arid climates occupying more than one-third area of the IGP are poor in SOC content and are thus prone to be calcareous and sodic (Pal *et al.*, 2000). Proper rehabilitation programmes can make these sodic soils resilient and can thus form an important step for carbon sequestration for improving the soil quality (Gupta and Rao., 1994, Bhattacharyya *et al.*, 2004, Pal *et al.*, 2000).

Plateau and Hills

Eastern Plateau and Hill (ACZ 7): This zone is formed by five sub-zones namely, (i) Wainganga, Madhya Pradesh Eastern Hills and Orissa Island, (ii) Northern Orissa, Madhya Pradesh Eastern Hills and Plateau, (iii) North Chhota Nagpur and Eastern Hills and Plateau, (iv) South Chhota Nagpur and West Bengal Hills and Plateau, and (v) Chhattisgarh and South Western Orissa Hills (Anon., 1989). It covers 13% of the TGA of the country. The soils (Table 4) contribute 9%, 1%, and 7% of the SOC, SIC and TC stocks of the country, respectively.

Central Plateau and Hills Region (ACZ 8): This zone comprises of forty six districts of Madhya Pradesh, Uttar Pradesh and Rajasthan. It has been sub-divided in 14 sub-zones (i) Bundelkhand (Uttar Pradesh), (ii) Bundelkhand (Madhya Pradesh), (iii) north hills, (iv) Kymore plateau and Satpura hills, (v) Vindhya plateau, (vi) Satpura plateau, (vii) Central narmada valley, (viii) Gird, (ix) South eastern plains, (x) Southern plains, (xi) Transitional plains, (xii) Southern plains and Aravalli hills, (xiii) Semi-arid eastern plains, and (xiv) Floodprone eastern plains. These sub-zones are characterized by different physiography of low hills, mounds, valleys, and ravines (Anon., 1989). Nearly 30% of this zone is not available for cultivation. The climate is dry in western part and sub-humid in eastern part of this zone. It covers 11% of the TGA of the country. The soils contribute 9%, 6%, and 8% of the SOC, SIC and TC stocks of the country, respectively.

Western Plateau and Hills Region (ACZ 9): Major part of Maharashtra, part of Madhya Pradesh, and one district (Jhalawar) of Rajasthan represents this region. It has been divided into 4 sub-zones (i) hill, (ii) scarcity, (iii) plateau north, and (iv) plateau south (Anon., 1989). The region occupies 10% of the TGA of the country. The dominant soils contribute 9%, 18%, and 11% of the SOC, SIC and TC stocks of the country, respectively.

Southern Plateau and Hills region (ACZ 10): This region consists of thirty five districts of Andhra Pradesh, Karnataka and Tamil Nadu and covers 12% area of the country. These have been sub-divided into six sub-zones. The dominant soils contribute 10%, 18%, and 13% of the SOC, SIC and TC stocks of the country, respectively.

Four ACZs consisting of 7, 8, 9, 10 constitute the plateau and hills region. This region occupies nearly 45% area of the country and covers the semi-arid tropics (SAT) of the Indian subcontinent. The black soils (Vertisols and their intergrades with some inclusions of Entisols) are dominant in SAT along with the associated red soils (Entisols and Alfisols). The carbon storage capacity of soils depends on the quality of soil substrate and its surface charge density (SCD). The increase of SOC again enhances the SCD of soils and the ratio of internal/external exchange sites. The soils in these hills and plateau are dominated by smectites and smectite-kaolinite minerals. This region is reserve to maximum amount of carbon in soils, which could be due to large areal coverge as well as greater carbon sequestration potential of these soils (38%, 43%, and 39% SOC, SIC and TC, respectively – Fig. 3).

Coastal Plains

The Indian coasts vary in their characteristics and structure. The west coast is narrow except around the Gulf of Cambay and the Gulf of Kutch. In the extreme south, however, it is somewhat wider along with the characteristic features of this coast. The coastal plains in the east, in contrast, are broader due to depositional activities of the east-flowing rivers due to the change in their base levels. Extensive deltas of the Mahanadi, Godavari, Krishna and Kaveri are the characteristic features of this coast. These plains cover nearly 10% area (Figs. 2 and 3).

East Coast Plains and Hill (ACZ 11): This zone consists of six sub-zones in the east coast of the country and covers 6% area of the country. These are: (i) north Orissa coast, (ii) north coastal Andhra Pradesh, (iii) south coastal Andhra Pradesh, (iv) north coastal Tamil Nadu, (v) Tanjavur and (vi) south coastal Tamil Nadu. The soils contribute 6%, 4%, and 5% of the SOC, SIC and TC stocks of the country, respectively (Figs. 2 and 3).

West Coast Plains and Ghat Region (ACZ 12): This zone covers the coastal areas of Tamil Nadu, Kerala, Karnataka, Maharashtra and Goa with different types of vegetations (plantation crops and spices) and soils. It is sub-divided into 4 sub-zones namely, (i) coastal hill, (ii) coastal midland, (iii) midland, and (iv) hilly (Anon. 1989) It covers 4% area of the country. The dominant soils contribute 8%, 2% and 6% of the SOC, SIC and TC stocks of the country, respectively (Figs. 2 and 3).

Gujarat Plains and Hills (ACZ 13): Nineteen districts of Gujarat represent this zone, which is divided into 7 sub-zones: (i) south Gujarat A, (ii) south Gujarat, (iii) middle Gujarat, (iv) north Gujarat, (v) north-west arid, (vi) north Saurashtra, and (vii) south Saurashtra. It covers 6% of the total geographical area of the country. The representative soils contribute 4%, 9% and 6% of the SOC, SIC and TC stocks of the country, respectively (Figs. 2 and 3).

Western Dry (ACZ 14): Nine districts of Rajasthan characterized by hot sandy desert, erratic rainfall (average annual rainfall 395 mm) and very low vegetation represent this zone. The dominant soils of this zone are Thar, Shobhasar, and Kolu. It covers 5.4% of the TGA of the country. The dominant soils contribute 1%, 11% and 6% of the SOC, SIC and TC stocks of the country, respectively (Figs. 2 and 3).

The Islands (ACZ 15): This zone is represented by the island territories of the Andaman and Nicobar islands and Lakshadweep, which are typically equatorial with mean annual rainfall of 3000 mm. These two groups of islands: the Arabian Sea islands and the Bay islands differ significantly in origin and physical characteristics. The Arabian Sea islands (Lakshadweep, Minicoy, etc.) are the remnants of

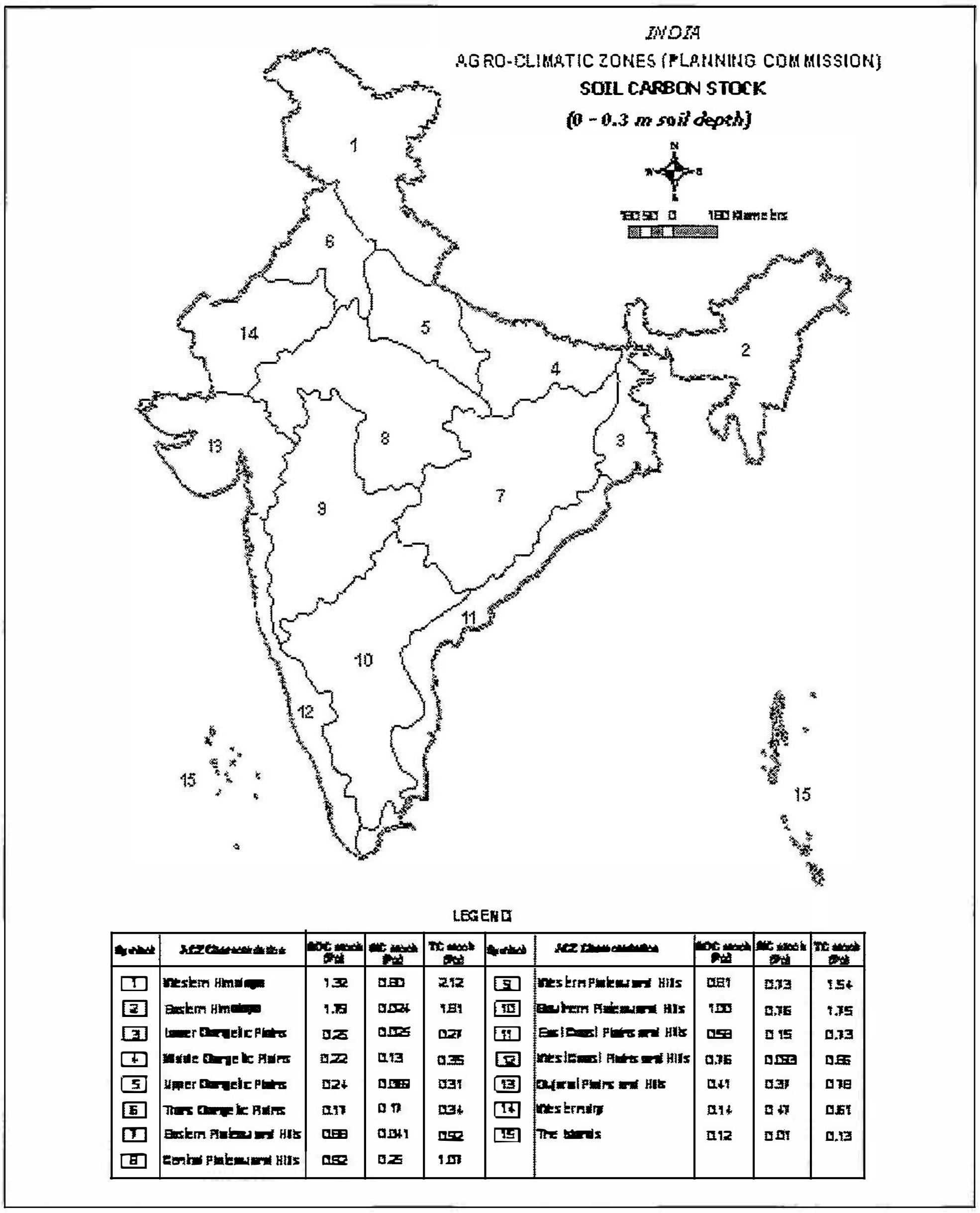


Fig. 2. Agro-climatic zones of India (Planning Commission) showing soil carbon stocks (0-0.3 m soil depth) (Source : Bhattacharyya *et al.*, 2008).

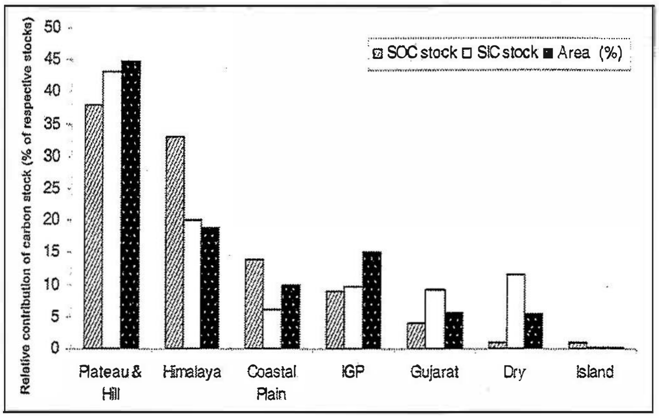


Fig. 3. SOC and SIC stocks and areal extent of seven major agro-climatic zones of India
(Source : Bhattacharyya *et al.*, 2008)

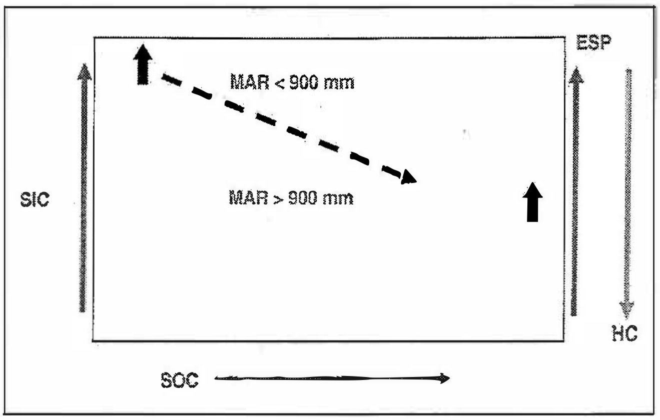


Fig. 4. Schematic diagram showing relation between SIC, SOC and other soil and climatic parameters
(Source : Bhattacharyya *et al.*, 2000a, 2004)

the old land mass and subsequent coral formations. On the other hand, the Bay islands lie about 220 km away from the nearest point on the main land mass and extend about 590 km with a maximum width of 58 km. This zone covers 0.3% of the TGA of the country. The dominant soils contribute 1%, 0.34% and 1% of the SOC, SIC and TC stocks of the country, respectively (Figs. 2 and 3).

Usefulness of soil carbon stocks datasets:

The relation between SOC and SIC with soil depth is negative. The role of SIC seems to be huge in dry climates in controlling SOC (Bhattacharyya *et al.*, 2000a). In the ecoregion of high rainfall, virtually there is no role of SIC in accumulation of SOC. This further strengthens the fact indicated earlier (Pal *et al.*, 2000) that with aridity (in terms of decreasing rainfall and increasing atmospheric temperature), the natural degradation in terms of formation of pedogenic $CaCO_3$ (SIC) with a concomitant formation of sodicity (ESP), increase in soil pH, reduction in hydraulic conductivity (HC) will reduce the possibility of growing successful crops making the soils impoverished in SOC. This is schematically presented in Fig. 4.

Current arid and semi-arid environments prevailing in central and southern Peninsular India are a part of global warming phenomena (Eswaran and Van den Berg., 1992). It is in this respect that tropical soils of the Indian subcontinent require immediate attention for better carbon management. In view of large areal extent and the specific soil properties, the drier parts (mostly SAT) offer a better scope for carbon sequestration. Effective carbon management can thus help not only in building up the SOC stock to a level of 14.02 Pg from the existing 2.8 Pg but also help to dissolve SIC stock to the tune of 2.0 Pg much to the benefit of growing plants (Table 3). Such approach will restore the productivity of vast areas under semi-arid tract and will also keep climatic hazards at bay.

Climate change, resulting in rising temperature and shrinking annual rainfall in some areas of the country, poses a potential threat for tropical soils of the Indian subcontinent (Jenny and Raychaudhuri 1960, Sombroek *et al.*, 1993). Therefore, the arid climate will continue to remain as a bane for Indian agriculture since it will cause soil degradation in terms of depletion of OC, formation of pedogenic $CaCO_3$ with the concomitant development of sodicity and/or salinity (Pal *et al.*, 2000). To combat such situation, the restoration of OC and efforts to enlarge the soil carbon pool by appropriate management techniques should form the strategic perspective to sustain the soil health. The most unfavourable natural endowment is the climatic adversity, which will place greater demands on resources to support targetted yields in Indian agriculture and thus may retard the pace of rehabilitation programme required to restore the soil productivity. Despite this fact, research attention for soils of arid and semi-arid climates sponsored through national agenda needs to be an immediate concern. In absence of such programme, deforestation will continue to increase the area under agriculture and obviously this may reduce the carbon level of soils. Thus the information of carbon stocks can act as a single-most important parameter in judging the soil health to prioritize areas for better management of soils.

(i) Identification of systems for carbon sequestration: Threshold values of SOC: Huge analytical datasets of the black and associated red soils allowed us to identify 22 systems (Table 4) which fulfill the minimum SOC stock as described earlier.

Table 4 : Selected soil parameters for identifying systems for carbon sequestration (0-30 cm) in various bioclimatic systems*

Sl. No.	Pedon No. (Soils)	Soil Series	Land use systems (Crops)	BD ($g\ cm^{-3}$)	SOC (%)	SIC (%)	SOC stock (Pg/M ha)
			Sub-humid (moist)				
1.	P5 (Black)	Nabibagh	Agriculture (HM) (Soybean-Wheat)	1.30	0.75	0.66	0.029
2.	P15 (Black)	Boripani	Forest (Teak)	1.35	0.810	0.48	0.032
3.	P24 (Red)	Dadarghugri	Forest (Teak) (*Tectona grandis*)	1.22	2.42	0.00	0.078
4.	P25 (Red)	Karkeli	Forest (Sal) (*Shorea robusta*)	1.734	1.09	0.00	0.056
			Sub-humid (dry)				
5.	P1 (Black)	Linga	Horticulture (*Citrus spp.*)	1.50	0.75	0.762	0.034
6.	P3 (Black)	Linga	Agriculture (FM) (Soybean-Wheat/Gram)	1.40	0.86	0.870	0.036
7.	P8 (Black)	Sarol	Agriculture (FM) (Soybean-Wheat)	1.40	0.76	0.780	0.032
8.	P48 (Black)	Nipani	Agriculture (FM) (Cotton+Pigeonpea)	1.57	0.82	3.04*	0.039
			Semi-arid (moist)				
9.	P12 (Black)	Asra	Agriculture (HM) (Cotton+Pigeonpea/Soybean-Gram)	1.50	0.92	0.64	0.041
10.	P18 (Red)	Vijaypura-1	Agriculture (HM) (Finger millet)	1.52	0.81	0.00	0.037
11.	P42 (Black)	Bhatumbra	Agriculture (FM) (Sorghum+Pigeonpea/Blackgram-Chickpea)	1.36	0.88	1.12	0.036
			Semi-arid (dry)				
12.	P13 (Black)	Paral	Agriculture (LM) (Cotton+Pigeonpea/Sorghum)	1.60	0.63	1.19	0.030
13.	P29 (Black)	Semla	Agriculture (Cotton/Groundnut-Wheat)	1.40	0.756	1.99	0.032
14.	P37 (Red)	Hayatnagar	Agriculture (HM) (Sorghum-Castor)	1.51	0.93	0.00	0.042
15.	P38 (Red)	Hayatnagar	Agriculture (LM) (Sorghum-Castor)	1.52	0.96	0.00	0.044
16.	P39 (Black)	Kasireddipalli	Agriculture (HM) (Soybean+Pigeonpea)	1.60	0.76	0.53	0.036
17.	P41 (Red)	Patancheru	Permanent Fallow (Grassland)	1.60	1.42	0.00	0.068
18.	P43 (Black)	Teligi	Agriculture (LM) (Paddy-Paddy)	1.40	1.03	1.39	0.043
19.	P44 (Black)	Teligi-1	Agriculture (HM) (Paddy-Paddy)	1.56	0.80	0.96	0.037
20.	P47 (Black)	Kalwan	Agriculture (HM) (Sugarcane/Jowar-Wheat/Gram)	1.40	0.90	0.37	0.038
			Arid				
21.	P51 (Black)	Nimone	Agriculture (HM) (Cotton-Wheat/Chickpea)	1.39	0.76	1.71	0.0320
22.	P52 (Black)	Nimone-1	Agriculture (FM) (Sugarcane/Soybean-Wheat/Chickpea)	1.31	0.76	2.64	0.0300

* Source : Bhattacharyya *et al.* (2007b)

A closer look at the data shows that Paral soils (under cotton and pigeonpea/sorghum systems) have minimum SOC content of 0.63% with maximum BD (1.60 g cm^{-3}) (Fig. 5). Thus Paral soils under agricultural system provide a minimum threshold of SOC where organic carbon has been sequestered @0.030 Pg Mha^{-1}. The minimum SOC and maximum BD values have been found to be associated with the presence of $CaCO_3$ (1.19% SIC) (Bhattacharyya *et al.*, 2007a). It may be mentioned that although these values of SOC and BD provide systems sequestering appreciable amount of SOC, yet the increased SIC and reduction in soil drainage due to compaction might create other associated problems (Bhattacharyya *et al.*, 2000a, 2004, Pal *et al.*, 2000).

(ii) Prioritization of area of carbon sequestration: Carbon stock in soil depends largely on the a real extent of the soils besides other factors such as carbon content, depth and bulk density of soils. Even with a relatively small amount of SOC content (0.2-0.3 per cent), the SOC stock of arid and semi-arid system is very large. This is due to large area of the dry tracts. Therefore, the carbon stock per unit area (Pg/M ha) should ideally be considered to identify the influence of soil and/or management parameters for carbon sequestration in soils. A threshold value of 0.03 Pg SOC / M ha has been found to be effective in finding out systems (agriculture, horticulture, forestry) that sequester significant quantities of organic carbon in soils (Bhattacharyya *et al.*, 2007b).

Criteria such as SOC stock per unit area as well as point data for individual soil indicate that the vast areas in the arid (AESR 3, part of ACZ 10), semi-arid and drier part of sub-humid bioclimatic systems (AESRs 4.1-4.4, 5.1-5.3, 6.1-6.4, 7.1-7.3, 8.1-8.3, 9.1, 9.2, 10.1-10.4; ACZs 4,7,8,9,10,13 and part of 2,3,5,6,11 and 12) (Fig. 6) of the subcontinent are low in SOC and high in SIC stock (Bhattacharyya *et al.*, 2008) and thus should get priority for organic carbon management. The total prioritized area has been worked out as 155.8 M ha (arid: 4.9 M ha, semi-arid: 116.4 M ha and subhumid: 34.5 M ha) (Fig. 6).

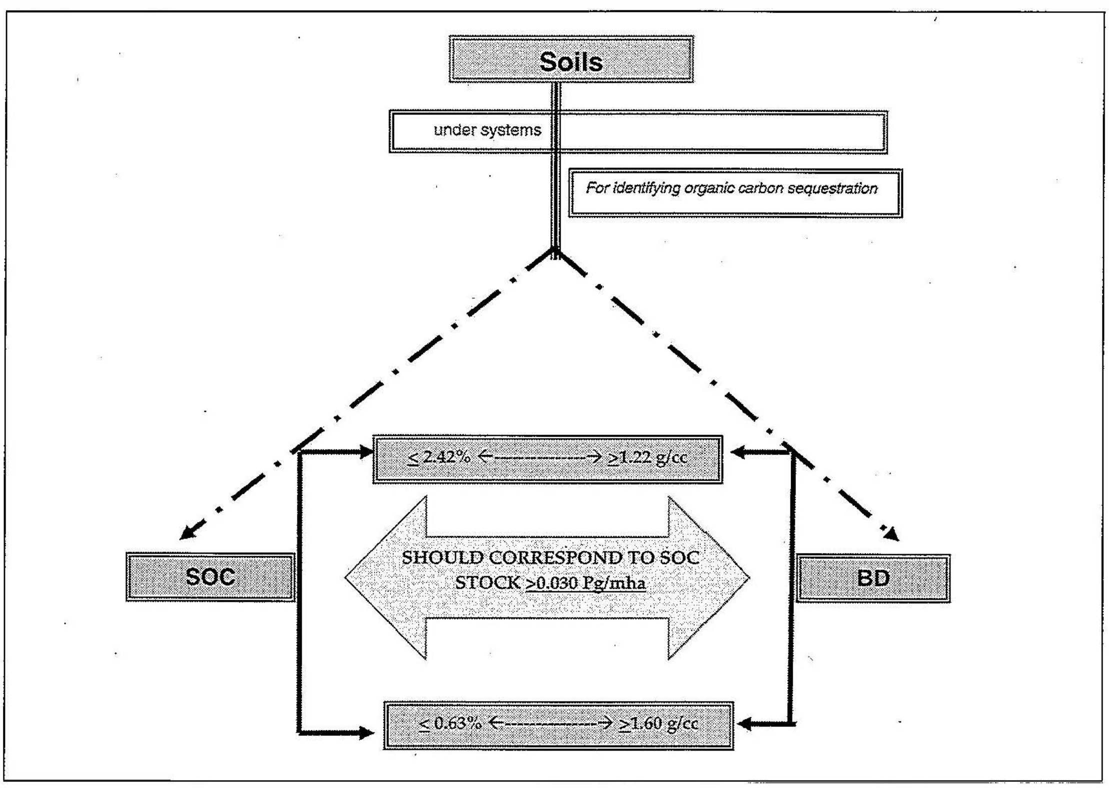
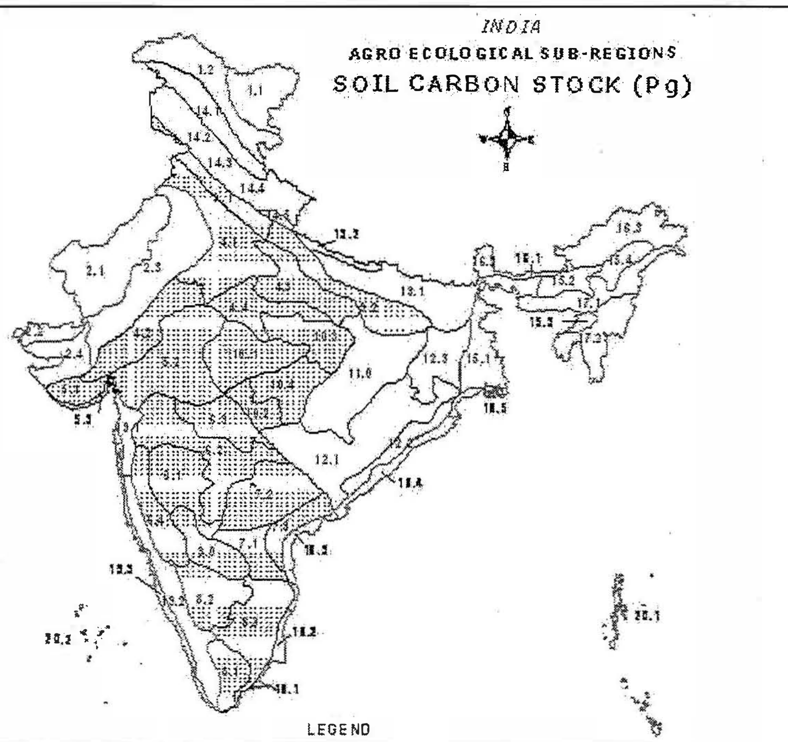


Fig. 5. Conditions to identify systems for organic carbon sequestration in black and associated red soils of SAT, India (SOC and BD values are of 0-30 cm) (Source : Bhattacharyya *et al.*, 2007c).



AESR	SOC (Pg)	SIC (Pg)	TC (Pg)	AESR	SOC (Pg)	SIC (Pg)	TC (Pg)	AESR	SOC (Pg)	SIC (Pg)	TC (Pg)
1.1	0.032	0.039	0.071	7.3	[illegible]	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	0.091	0	0.091
2.4	0.083	0.360	0.449	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	0.103	16.3	0.520	0	0.520
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	0.635	0	0.635	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	0.019	0	0.019	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	0.700	13.2	0.091	0	0.091	19.1	0.052	0.063	0.115
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	0.311	0	0.311
7.1	0.131	0.059	0.190	14.3	0.010	0	0.010	20.1	0.059	0	0.059
7.2	0.310	0.148	0.458	14.4	0.020	0	0.020	20.2	0.062	0.014	0.076

Fig.6. Soil carbon stocks in different agro-ecological subregions showing prioritized areas (shaded areas) for carbon sequestration (0-0.3 m soil depth) (Source : Bhattacharyya *et al.*, 2008).

Soil systems attain a quasi-equilibrium stage after accumulation of dry matter as well as loss of SOC over time and this quasi-equilibrium stage depends on land-use systems. 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. This way, the SOC is stabilized 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 increase in OC enhances the substrate quality of soils. It may be mentioned that the dominant soils in the semi-arid tropics (SAT) are black soils (Vertisols and their associated red soils) and these are dominated by smectites (Pal *et al.*, 2000). Presence of smectite also results in improving substrate quality so important for carbon sequestration in soil. Recent studies indicated that smectite-rich black soils could sequester 2-3 per cent organic carbon (Bhattacharyya *et al.*, 2006, Dalal and Conter, 2000). In view of better substrate quality of these dominant soils in the arid (southern India, AESR 3), semi-arid and dry sub-humid tracts of the country, a modest SOC content of 2 per cent gives an estimate of SOC stock as 14.02 Pg. This value is 3.7 times more than the existing SOC stock of the prioritized area (Fig. 6). Recent studies on changes of carbon in soils of the SAT have shown that over a period of nearly 25 years, SOC has increased by 34 to 118 per cent (Bhattacharyya *et al.*, 2007e). This has been possible due to the adoption of the management interventions (Bhattacharyya *et al.*, 2004, 2007b). Thus, appropriate management interventions that maintain the capability of productive soils and also raise the productivity of less productive soils, are capable of enhancing organic carbon storage of Indian soils. Such management interventions have helped in the dissolution of native SIC ($CaCO_3$) due to increase in pCO_2 in the soil and contributed partly to the overall pool of SOC following the C transfer model (Bhattacharyya *et al.*, 2004) that works better in the drier part of the country. This pathway of C transfer from inorganic (atmospheric CO_2) to organic (CH_2O) and organic (CH_2O) to inorganic (CO_2 in soil and then to $CaCO_3$) which indirectly helps in better vegetative growth (organic) in improved soil management (good structure, better drainage) is largely active in soil systems of the dry climate (Bhattacharyya *et al.*, 2008).

(iii) As a tool for carbon capture and storage: Soil carbon (both SOC and SIC) is important as it determines ecosystem and agro-ecosystem function, influencing soil fertility, water holding capacity and many other soil parameters. It is also of global importance because of its role in the global carbon cycle and therefore, the part it plays in the mitigation of atmospheric levels of greenhouse gases (GHGs) with special reference to CO_2. To reduce the emission of CO_2, carbon capture and storage (CCS) has been found to be an important option. The technique consists of three basic steps viz. (i) capturing CO_2 at large and stationary point sources, (ii) transporting the CO_2 from a source to sink, and (iii) injecting the CO_2 in suitable geological reservoirs or sinks. The CCS is generally regarded as an option during the first half of the 21st century, that can help bridging the gap posed by the urgent need to act against climate change and the time needed to fully develop renewable energy systems (Anon, 2007; Goel, 2007). Among the other known sources to enhance CCS, the role of soils, as an important natural resource, in capturing and storing carbon has been adequately explained (Bhattacharyya *et al.*, 2008). The main issue of soil carbon management in India revolves around the fact that a few parts of the country are dominated by soils containing very high amount of SOC (Jenny and Raychaudhuri., 1960) and low amount of SIC whereas the other parts show an opposite trend (Dadhwal and Nayak., 1993, Gupta and Rao., 1994, Velayutham *et al.*, 2000, Bhattacharyya *et al.*, 2008). The most important fact is that soils act as a major sink and source of atmospheric CO_2 and therefore have a huge role to play in carbon capture and storage (CCS) activity. The soils capture and store both organic (through photosynthesis of plants and then to soils as decomposed plant materials and roots) and inorganic carbon (through the formation of pedogenic calcium carbonates). The sequestration of organic and inorganic carbon in soils and its follow-up requires basic information of CCS in soils.

Although the unique role of soil as a potential substrate in mitigating the effects of atmospheric CO_2 has been recognized for some time (Schlesinger., 1982, Batjes., 1999), the role of sequestration of atmospheric CO_2 in the form of SIC (pedogenic carbonate) and its subsequent enhancement of SOC in the drier parts of the country through management interventions (Bhattacharyya *et al.*, 2004, 2008) has been studied only recently. The study points out a fact that the soil can act as a potential medium for CCS. It is hoped that this tool (thematic maps on soil C stock) will help the planners in prioritizing C sequestration programmes in different bioclimatic systems representing various ACZs and AESRs (Fig. 6).

(iv) Soil health monitoring using soil C stock datasets

a. Threshold limits for green belt concept: Soil Information System (SIS) of Tripura developed by NBSS&LUP has been found to be helpful to determine soil health using SOC stock datasets. In Tripura, SOC concentration varies from 0.34 to 1.88%. Relatively high SOC is found in deep to very deep, well to excessively drained loamy hill soils. North-Eastern Region in India has been declared as a green belt. Earlier SOC level of 1.0% was shown as a threshold limit for soils showing good health (Soil Survey Staff, 2003, Bhattacharyya *et al.*, 2008).The SIS of Tripura helps to estimate SOC stock to show nearly 58% area in Tripura to have more than 45 kg ha^{-1} SOC stock in first 30 cm depth of soils. Total SOC stock in India and Tripura is 9.55 Pg and 0.05 Pg, respectively (Table 5). It shows that SOC stock in Tripura is maintained at 0.046 Pg/M ha as compared to all India average of 0.029 Pg/M ha. Earlier, using Planning Commission's 14 agro-climatic zones (AEZs), SOC stock of AEZ 2, representing the entire NER was estimated at 0.064 Pg/M ha (Bhattacharyya *et al.*, 2008) (Table 5). Such threshold values of SOC stock ranging from 0.05 to 0.06 Pg/M ha should, therefore, be maintained in the areas declared as green belt to protect natural ecosystems.

Table 5 : SOC stock (0-30 cm) in Tripura and India – a comparison to fix threshold value for green belt*

Region	SOC stock (Pg)	SOC stock Pg/M ha
India	9.550	0.029
ACZ 2	1.792	0.064
Tripura	0.05	0.046

**ACZ 2 (Agroclimatic Zone 2 representing entire North-Eastern Region – also see Bhattacharyya *et al.*, (2010).

b. Carbon stock in India and World: Total SOC and SIC stocks in the IGP are 9.0 and 9.7%, respectively. It was reported that the soils under hot, humid and per-humid climates are deficient in SOC due to intensive agriculture (Bhattacharyya *et al.*, 2000a). SOC stocks in the IGP dominated by rice-wheat cropping system were earlier estimated as 0.63 and 2.00 Pg in the first 0.3 and 1.5 m soil depth, respectively (Table 6).

Table 6 : Carbon stocks in the IGP and other parts of the world (values in Pg)

Region	Soil depth (m)	
	0 – 0.3	0 – 1.5
IGP, India*	0.63 (6.45/0.3/0.09)**	2.00 (6.67/0.32/0.08)
India***	9.55	29.92
Tropical Regions****	201-213	616-640
World*****	684-724	2376-2456*****

* Bhattacharyya *et al.* (2004), ** Parentheses show % of stock in India, Tropical regions and world respectively; *** Bhattacharyya *et al.* (2008), **** Batjes (1996), ***** For 0-2.0 m soil depth

Based on SOC content, nearly 70% area in the IGP falls under deficient zones (Velayutham *et al.*, 2000). Besides, SOC stock in terms of IGP share is only 0.4% of the tropical regions indicating scope to sequester organic carbon. Revisiting nearly 37 benchmark spots to estimate SOC stock indicated 0.88 Pg C in the first 20 cm soils (Table 7).

The IGP has been traditionally considered as a rice growing area. Century model estimates 0.66 Pg SOC in lowland rice soils. Soil C estimated using IPCC method showed little change over 1967-2030. IPCC method rests on classification of land area into distinct management and land use categories to determine C stocks (Bhattacharyya *et al.*, 2007a). Here, changes in SOC are controlled by changes in the distribution of area of land use systems over time. There is relatively little land use change in IGP over the period of modelling since almost all the areas are under intensive agriculture. Century model estimates a 21% decrease in SOC stocks in IGP from 1967 to 2030, with a dynamic equilibrium reached during 1990 and changed little thereafter (Fig. 7).

Table 7 : Soil organic carbon stock estimates for the IGP, India

Study	System	Method	Year of stocks	SOC stock (Pg)
Bhattacharyya *et al.* (2004)	Benchmark soil series	Laboratory and cartography	1980	0.66*
GEFSOC (field work)	Benchmark soil series	Laboratory and cartography	2005	0.88*
Batjes *et al.* (2006)	Benchmark soil series	Extrapolation from secondary data based on Chandran *et al.* (2005)	1990	0.572 – 0.587**
GEFSOC	IPCC	Soil, climate and land use classification method	2000	0.97**
GEFSOC	Century model	Model simulation	2000	1.44*

* For the first 20 cm soil depth; ** For the first 30 cm soil depth

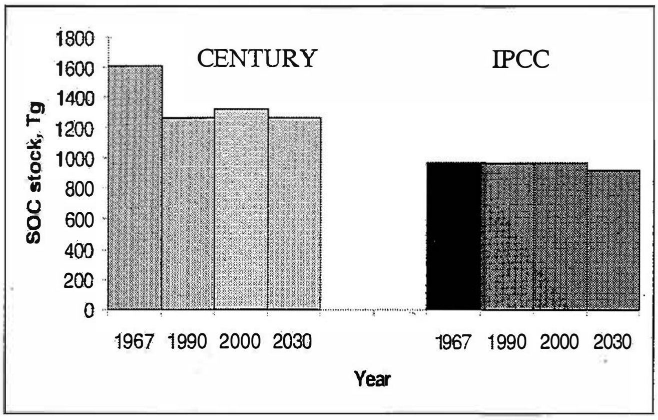


Fig. 7. GEFSOC modelling systems (IPCC & Century) to assess SOC stocks in IGP (Source : Bhattacharyya *et al.*, 2007a).

c. Changes in levels of carbon in soils: It is realized that the carbon content in soils changes depending on land use system and time. There is an increasing concern about the decline in soil productivity and the impoverishment of soil organic carbon (SOC) caused by intensive agriculture. The National Bureau of Soil survey and Land Use Planning (NBSS&LUP) of the Indian Council of Agricultural Research (ICAR), through organized research initiatives, sponsored by National and International organizations, developed data sets of soil organic (SOC) and inorganic carbon (SIC) for two important crop production zones viz. the Indo-Gangetic Plains (IGP) and the black soil region (BSR) in the semi-arid tropics (SAT). The datasets for 1980 and 2005 indicate an overall increase in SOC stock in the Benchmark spots under agriculture practiced for the last 25 years although the level of SIC has increased indicating an initiation of chemical degradation (Tables 8 and 9). This suggests that the agricultural management practices advocated through the National Agricultural Research System (NARS) for the last 25 years did not cause any decline in SOC in the major crop growing zones of the country (Bhattacharyya *et al.*, 2007c).

Table 8 : Changes in carbon stock over years in the selected Benchmark Spots in the IGP, India (0-150 cm)*

Bioclimatic System	Soil Series	SOC stock (Tg/lakh ha)		SOC change over 1980 (%)	SIC stock (Tg/lakh ha)		SIC change over 1980 (%)
		1980	2005		1980	2005	
Semi-arid	Phaguwala	3.36	5.48	63	13.10	26.14	99
	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

* Source : Bhattacharyya *et al.* (2007c).

Table 9 : Changes in carbon stock over years in the selected Benchmark Spots of the BSR (0-150 cm)*

Bioclimatic System	Soil Series	SOC stock (Tg/lakh ha)		SOC change over 1980 (%)	SIC stock (Tg/lakh ha)		SIC change over 1980 (%)
		1980	2005		1980	2005	
Arid	Sokhda	11.19	9.20	-18	23.63	60.92	158
	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
Semi-arid	Kaukantla	4.71	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

* Source : Bhattacharyya *et al.* (2007c).

Future Areas of Research

We have made a good start in estimating soil organic and inorganic C stocks; however, the following aspects require attention.

i) Role of soils in inorganic C sequestration.

ii) Role of soil physical, chemical, biological and mineralogical properties to sequester both organic and inorganic carbon.

iii) Role of naturally-occurring soil modifiers viz. gypsum, zeolites, palygorskite, pedogenic carbonates, non-pedogenic carbonates in influencing both organic and inorganic C sequestration in soils.

iv) Total organic carbon (TOC) has been considered as an important and robust soil quality parameter (SQP), only a portion of TOC is available to plant. In view of the recent research findings, active pool of TOC should be a logical SQP for soil quality and its health (Chivhane and Bhattacharyya., 2010).

v) Role of both organic and inorganic C in soil resilience through various types of remediation.

vi) Role of soil moisture in estimating soil C turnover and its measurement through various model approaches.

vii) Developing an indigenous and comprehensive total soil carbon model.

References:

Anonymous., 1989. Agro-climatic regional planning (an overview). Planning Commission, Government of India, New Delhi, p.144.

Batjes NH., 1996. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science 47:151-163.

Batjes NH., 1999. Management options for reducing CO_2-concentration in the atmosphere by increasing carbon sequestration in the soil. Report 410-200-031. Dutch National Research Programme on Global Air Pollution and Climate Change, Bitthoven.

Batjes NH., 2001. Options for increasing carbon sequestration in West African soils : An exploratory study with special focus on Senegal. Land Degradation and Development 12:131-142.

Bhattacharjee JC, Roychaudhury C, Landey RJ and Pandey S. 1982. Bioclimatic analysis of India. NBSS&LUP Bull. No. 7, Nagpur, p.21 + map.

Bhattacharyya T, Das TA, Dubey PN, Baruah U, Gangopadhyay SK and Dileep Kumar. 1995. Soil Survey Report of Morigaon district, Assam (1:50,000 scale). NBSS&LUP, Regional Centre, Jorhat, Assam, No. 527.

Bhattacharyya T, Sehgal JL and Sarkar D. 1996. Soils of Tripura for optimizing land use : their kinds, distribution and suitability for major field crops and rubber. NBSS&LUP Publ. 65 (Soils of India Ser. 6), Nagpur, p.154.

Bhattacharyya T, Pal DK, Velayutham M, Chandran P and Mandal C. 2000a. Total Carbon stock in Indian soils: Issues, priorities and management. In Special Publication of the International Seminar on Land Resource Management for Food, Employment and Environmental Security (ICLRM), New Delhi, 8-13 November, 2000 pp. 1-46.

Bhattacharyya T, Pal DK, Mandal C and Velayutham M. 2000b. Organic carbon stock in Indian soils and their geographical districution. Current Science 79:655-660.

Bhattacharyya T, Pal DK, Chandran P, Mandal C, Ray SK, Gupta RK and Gajbhiye KS. 2004. Managing soil carbon stocks in the Indo-Gangetic Plains, India, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, pp.44.

Bhattacharyya T, Pal DK, Chandran P, Ray SK and Mandal C. 2005. Bharatbarsher maatir jaiba ebrog ajaiba cabon, Vigyanmela, 2005 (Nov-Dec), 7-9.

Bhattacharyya T, Pal DK, Lal S, Chandran P and Ray SK. 2006. Formation and persistence of Mollisols on zeolitic Deccan basalt of humid tropical India. Geoderma, 136:609-620.

Bhattacharyya T, Pal DK, Easter M, Williams S, Paustian K, Milne E, Chandran P, Ray SK, Mandal C, Coleman K, Falloon P, Powlson DS and Gajbhiye KS. 2007a. Evaluating the Century C model using long-term fertilizer trials in the Indo-Gangetic Plains, India. Agriculture Ecosystems and Environment 122:73-83.

Bhattacharyya T, Chandran P, Ray SK, Pal DK, Venugopalan MV, Mandal C, Wani SP, Manna MC and Ramesh V. 2007b. Carbon sequestration in red and black soils III. Identifying systems through carbon stock and bulk density of soils. Agropedology, 17:26-34.

Bhattacharyya T, Chandran P, Ray SK, Pal DK, Venugopalan MV, Mandal C and Wani SP. 2007c. Changes in levels of carbon in soils over years of two important food production zones of India. Current Science., 93:1854-1863.

Bhattacharyya T, Ray SK, Pal DK, Chandran P, Mandal C and Wani SP. 2009. Soil carbon stocks in India – issues and priorities. Journal of Indian Society of Soil Science. 57:461-468.

Bhattacharyya T, Sarkar Dipak, Pal DK, Mandal C, Baruah U, Telpande B and Vaidya RH. 2010. Soil information system for resource management – Tripura as a case study. Bulletin NBSS & LUP, Nagpur.

Chandran P, Ray SK, Durge SL, Raja P, Nimkar AM, Bhattacharyya T and Pal DK. 2009. Scope of horticultural land use system in enhancing carbon sequestration in ferruginous soils of the semi-arid tropics. Current Science, 97:1029-1046.

Chivhane SP and Bhattacharyya T. 2010. Effect of land use and bio-climatic system on organic carbon pool of shrink-swell soils of Vidarbha region, Maharashtra. Agropedology, 20:145-156.

Dadhwal VK and Nayak SRI. 1993. A preliminary estimate of biogeochemical cycle of carbon for India. Science and Culture 59:9-13.

Dalal RC and Canter JU. 2000. Soil organic matter dynamics and carbon sequestration in Australian Tropical soils. In Global climatic Change and Tropical Ecosystems (R. Lal, J.M. Kimble and B.A. Stewart, Eds.), Boca Raton, pp.283-314.

Elberson GWW, Davies GR, Van Recuwijk and Janssen RPT. 2000. Quantification of the incorporation of atmospheric CO_2 in calcic horizons. In Global Climate Change and Pedogenic Carbonates (eds. Lal R, Kimble JM, Eswaran H and Stewart BA), Lewis Publishers, FL, USA, pp.87-95.

Eswaran H and van den Berg 1992. Impact of building of atmospheric CO2 on length of growing season in the Indian sub-continent. Pedologie 42:289-296.

Eswaran, H., van den Berg, E. and Reich, P. (1993) Organic carbon in soils of the world. Soil Science Society of America Journal 57, 192-194.

Gupta RK and Rao DLN. 1994. Potential of wastelands for sequestering carbon by reforestation. Current Science 66:378-380.

Houghton RA and Hackler JL. 1994. The net flux of carbon from deforestation and degradation in south and southeast Asia. In Effects of Land-Use Change on Atmospheric CO_2 concentrations : South and Southeast Asia as a Case Study (V. Dale, ed.), Springer Verlag, New York, pp.301-327.

Jackson ML., 1973. Soil Chemical Analysis, Prentice Hall of India Pvt. Ltd., New Delhi, p.498.

Jenny H and Raychaudhuri SP. 1960. Effect of climate and cultivation on Nitrogen and organic Matter Reserves in Indian soils, ICAR, New Delhi, India, p.126.

Lal S, Deshpande SB and Sehgal J. 1994. Soil Series of India. NBSS&LUP, Nagpur, p. 684.

Murthy RS. (eds) 1982. Benchmark soils of India. NBSS&LUP, Nagpur, India, p. 374.

Pal DK, Dasog DS, Vadivelu S, Ahuja RL and Bhattacharyya T. 2000. Secondary calcium carbonate in soils of arid and semi-arid region of India In (Lal, R., J.M. Kimble, H. Eswaran and B.A. Stewart, eds.) Global Climate Change and Pedogenic carbonates. CRC Press, Boca Raton, pp. 149-185.

Sahrawat KL., 2004. Organic matter accumulation in submerged soils. Advances in Agronomy 81:169-201.

Sahrawat KL, Bhattacharyya T, Wani SP, Chandran P, Ray SK, Pal DK and Padmaja KV. 2005. Long-term lowland rice and arable cropping effects on carbon and nitrogen status of some semi-arid tropical soils. Current Science, 89:2159-2163.

Sahrawat KL, 2007. Soil fertility advantages of submerged rice cropping systems: A review. Journal of Sustaianble Agriculture 31:5-23.

Schlesinger WH. 1982. Carbon storage in the caliche of arid soils : a case study of Arizona. Soil Sci., 133:247-255.

Sehgal JL, Mandal DK, Mandal C and Vadivelu S. 1999. Agro-Ecological Regions of India, NBSS&LUP, Bull. No. 24, Nagpur, India, p.130.

Soil Survey Staff 2003. Keys to Soil Taxonomy. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC, 9th edn.

Sombroek WG, Nachtergache FD and Habel A. 1993. Amounts, dynamics and sequestration of carbon in tropical and subtropical soils. Ambio 22:417-427.

Vadivelu S and Bandyopadhyay AK. 1997. Characteristics, genesis and classification of soils of Minicoy Island, Lakshadweep. Journal of Indian Society of Soil Science, 45:796-800.

Velayutham M, Mandal DK, Mandal C and Sehgal J. 1999. Agro-ecological sub-regions of India for Development and Planning, NBSS&LUP, Nagpur, Publication 35, p.452.

Velayutham M, Pal DK and Bhattacharyya T. 2000. Organic carbon stock in soils of India. In Global Climatic Change and Tropical Ecosystems (R. Lal, J.M. Kimble and B.A. Stewart, Eds.) Lewis publishers, Boca Raton, F.L. pp.71-96.

Wani SP, Sahrawat KL, Sreedevi TK, Bhattacharyya T and Rao Ch. Srinivasa. 2007. Carbon sequestration in the semi-arid tropics for improving livelihoods. International Journal of Environmental Studies, 64:719-727.