Processes Determining the Sequestration and Maintenance of Carbon in Soils: A Synthesis of Research from Tropical India

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Soil organic carbon (SOC) is the major determinant of soil quality, and it greatly influences global carbon cycling and climate change. This paper is a synthesis of the literature on soil carbon research in India, including soil organic and inorganic carbon stocks, in the form of thematic maps for national and regional level planning at bioclimatic systems and agroecological subregion levels in the country. The potential role of soils in mitigating the global warming effects of atmospheric CO_2 is discussed using results from Indian tropical soils. The database on Indian soils collected through natural resource inventory and soil carbon and crop modeling approaches show that sequestration of atmospheric CO_2 occurs as pedogenic carbonates and plays role as a soil modifier in enhancing soil organic carbon in the drier parts of the country through management interventions. Clearly, soils can act as a potential medium for sequestering atmospheric CO_2 to mitigate the global warming effect.

The role of soil as an important natural resource for sequestering and storing atmospheric CO_2 for mitigating climate change effects has been addressed by many researchers (Schlesinger, 1982; Victoria et al., 2008; Wang et al., 2010; Batjes, 2011; Powlson et al., 2011; Banwart et al., 2014; Bhattacharyya et al., 2014; van Noordwijk et al., 2014). There has been great interest in mitigating the climate change due to global warming by sequestering and storing carbon in soil and its influence on soil quality and agricultural productivity (Powlson et al., 2011; Banwart et al., 2014; Bhattacharyya et al., 2014). Soils provide important ecosystem services at both local and global levels and are the mainstay for crop production. Soils act both as sources and sinks for carbon (Bhattacharyya et al., 2008). With the challenge to feed a global population of 9 billion people by mid-century and beyond, it is essential to maintain the health and productivity of agricultural and rangeland soils (van Noordwijk et al., 2014). One way is to maintain, and wherever necessary, increase the soil organic carbon, especially in tropical soils. The term *carbon sequestration* has been used to describe the process of increasing organic carbon stores with appropriate land management interventions. The process could be natural and/or human-induced to harness CO_2 from the atmosphere and to store it in ocean or terrestrial environments (i.e., in vegetation, soils, and sediments) and in geologic formations (USGS, 2008; Powlson et al., 2011). The reduction of atmospheric CO_2 by sequestration has been reported to have a great potential for shifting greenhouse gases (GHG) emissions to mitigate climate change, and soil, as an ideal reservoir, can store organic carbon to a great extent (Wang et al., 2010). Interestingly, carbon sequestration has always been referred to in literature with respect to organic carbon, despite the fact that both organic and inorganic forms of carbon are involved in C sequestration. The aspects related to the formation of pedogenic $CaCO_3$ (PC), as an example of inorganic C sequestration, have a direct bearing to soil health (Bhattacharyya et al, 2004, 2008), especially in low quality, infertile soils in the semiarid tropical (SAT) environments. It is well known that vegetation and soils are the major sinks of atmospheric CO_2. Carbon stocks are not only critical for the soil to perform its productivity and environmental functions, but they also play an important role in the global C cycle. Soil C sequestration can improve soil quality and reduce the contribution of agriculture to CO_2 emissions.

Among the options to mitigate climate change (Jacobson, 2009), the sequestration of C in agricultural soils assumes added importance (Lal, 2011). At the Indian national level, little attention has been paid to study the potential of tropical soils to sequester

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Abbreviations: ESP, exchangeable sodium percentage; FYM, farm yard manure; GHG, greenhouse gases; MAR, mean annual rainfall; PC, pedogenic $CaCO_3$; QEV, quasi-equilibrium values; SAT, semiarid tropical; SCD, surface charge density; SIC, soil inorganic carbon; SOC, soil organic carbon.

and store atmospheric CO_2. Many think that tropical soils, as the soils of the hot and humid tropics, exemplified by deep, red and highly weathered soils (Eswaran et al., 1992), are dominated by clay minerals of advanced weathering stage (Schwertmann and Herbillon, 1992). Moreover, several reports indicate that low soil organic matter and the difficulty in maintaining adequate organic matter levels are the main constraints in maintaining soil fertility and quality of such tropical soils (Greenland et al., 1992). Slower output growth is expected to be a feature of agricultural production in both the developed and developing countries' agricultural sectors in the coming decade. Global agricultural production is projected to grow at 1.5% annually, on average, compared to 2.1% in the previous decade (OECD-FAO, 2013). This slower growth is expected to be exhibited by all crop sectors and livestock production. These trends reflect rising costs, growing resource constraints, and increasing environmental pressures, which are anticipated to inhibit supply response in virtually all regions. Higher production growth is expected from emerging economies that have invested in their agricultural sectors and where existing technologies offer good potential for closing the yield gap with the advanced economies, although yield and supply variability may be higher. The share of production from developing countries is expected to continue to increase during 2013 to 2022. This larger contribution from the developing countries indicates that most of the soils may not be infertile (Sanchez and Logan, 1992; Chandran et al., 2004). This can be exemplified by India's growing self sufficiency in food production and food stocks since its independence in 1947; moreover, during this time, the soils of major food growing regions of India in the SAT environments have maintained soil quality by sequestering atmospheric carbon (Bhattacharyya et al., 2007a).

As the tropics comprise approximately 40% of the land surface of the earth, more than one-third of the soils of the world represent tropical areas (Eswaran et al., 1992). The global extent of such soils suggests that agricultural management practices that are 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. In this context, it was decided to prepare a synthesis on the potential of Indian soils to accumulate atmospheric CO_2 as evidenced by SOC and soil inorganic carbon (SIC) stocks. Moreover, the information on the factors and practices that favor C sequestration under diverse land use are put into context.

Soil as a Source and Sink of Carbon

Soil carbon (SOC plus SIC) is a major determinant of agroecosystem functions; it greatly influences soil fertility, water holding capacity, and other soil quality parameters that influence overall productivity and sustainability. The main context for soil carbon management in tropical India is a relatively high amount of SOC (Jenny and Raychaudhuri, 1960) (Table 1) and low amount of SIC, whereas soils in rest of the regions show a reverse trend (Bhattacharyya et al., 2000). The soils sequester 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 carbonate) (Pal et al., 2000a). The sequestration of organic and inorganic carbon in soils and its estimation requires basic information on the processes that determine the C sequestration of soils. The most prudent approach to estimate the role of soils as both C source and sink is to develop the spatial distribution of SOC and SIC in various agroclimatic zones, bioclimatic systems, and agroecosystem subregions (Victoria et al., 2012; Batjes, 2011; Bhattacharyya et al., 2008). Carbon as SOC and SIC storage has been reported to be related to climate (temperature and rainfall). The carbon storage values for different bioclimatic systems have been collated and are shown in Fig. 1.

The arid bioclimatic system is characterized by low annual rainfall (<500 mm) (Bhattacharjee et al., 1982) and does not support dense vegetation, resulting in low organic C status of the soils. This bioclimate is divided into cold arid and hot arid on the basis of atmospheric temperature (Bhattacharyya et al., 2000) and

Table 1. Soil carbon stocks in different bioclimatic systems of India (0–0.3 m soil depth).

	Area		SOC‡		SIC‡		Total C			
Bioclimatic systems†	Coverage	Total area	Stock	Percent of total SOC	Stock	Percent of total SIC	Stock	Percent of total TC	SOC	SIC
	million ha	%	Pg	%	Pg	%	Pg	%	— Pg/million ha —	
Arid cold	15.2	4.6	0.6	6	0.7	17	2.7	20	0.0192	0.0327
Arid hot	36.8	11.2	0.4	4	1.0	25				
Semiarid	116.4	35.4	2.9	30	1.9	47	4.8	35	0.0249	0.0163
Subhumid	105.0	31.9	2.5	26	0.3	8	2.8	20	0.0238	0.0029
Humid to per humid	34.9	10.6	2.1	21	0.04	1	2.14	15	0.0602	0.0011
Coastal	20.4	6.2	1.3	13	0.07	2	1.37	10	0.0637	0.0034

† Ranges in rainfall: arid, <550 mm; semiarid, 550–1000 mm; subhumid, 1000–1500 mm; humid to per humid, 1200–3200 mm; coastal, 900–3000 mm (adapted from Bhattacharyya et al., 2008).

‡ SOC, soil organic carbon; SIC, soil inorganic carbon.

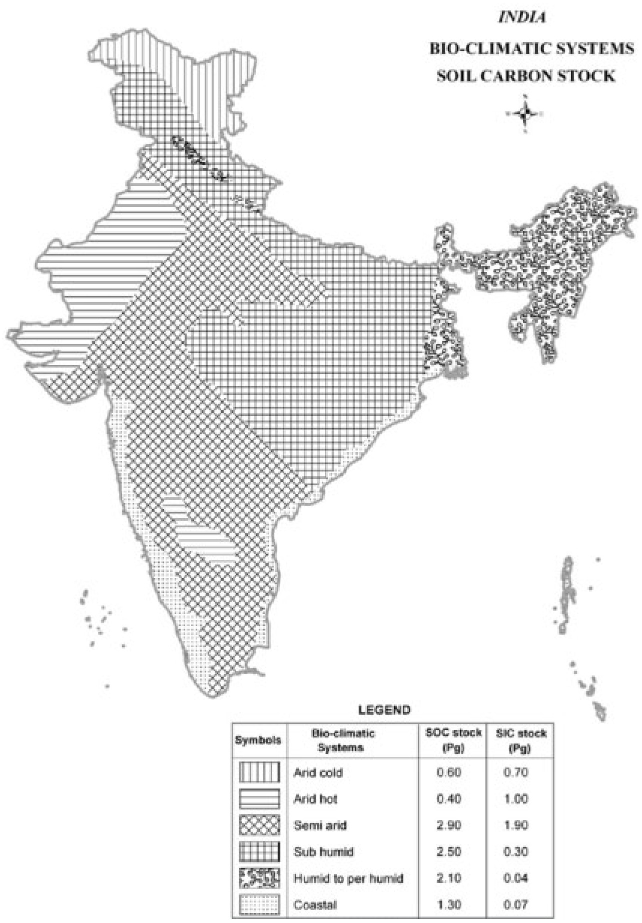


Fig. 1. Carbon stocks in major bioclimatic systems in India (0–0.3 m soil depth). SIC, soil inorganic carbon; SOC, soil organic carbon. (Source: Bhattacharyya et al., 2008.)

within the cold arid bioclimate, the Ladakh plateau is colder than the northern Himalayas. Lower atmospheric temperature at the subzero levels that cause hyper-aridity does not support vegetation, which is in contrast to that found in the western region of the northern Himalayas. This is the reason for more SOC stock in the cold arid bioclimate (Table 1).

Following U.S. soil taxonomy (Soil Survey Staff, 2006), total SOC stock of Indian soils in the first 1.5-m depth is estimated at ~30 Pg, whereas that of SIC as ~34 Pg (Table 2). The SOC and SIC stocks in five bioclimatic zones (Bhattacharyya et al., 2008) show that SOC stock is two and one-half times greater than the SIC stock in first 0- to 0.3-m soil depth (Table 2). Although the presence of $CaCO_3$ in the humid and per-humid region is due to inheritance from strongly calcareous parent material, usually on young geomorphic surfaces (Velayutham et al., 2000), the SIC stock in dry bioclimates is relatively large (Bhattacharyya et al., 2008). The SIC stock increases with depth (Table 2) in all soil orders (except for the Ultisols) of dry climates, which cause more calcareousness in the subsoil (Pal et al., 2000a).

Distribution of Soil Carbon in Different Soil Orders of Tropical India

The majority of India falls between the Tropic of Cancer and Tropic of Capricorn, and the soils therein are termed *tropical soils*. India has five distinct bioclimatic systems (Bhattacharjee et al., 1982) with varying mean annual rainfall (MAR). These are arid cold and hot (MAR < 550 mm), semiarid (MAR 550–1000 mm), subhumid (MAR 1000–1500 mm), humid to per-humid (MAR 1200–3200 mm), and coastal (MAR 900–3000 mm). The major soils of India are Inceptisols, Entisols, Alfisols, Vertisols, Aridisols, Ultisols, and Mollisols, and cover 39.4, 23.9, 12.8, 8.1,

Table 2. Distribution of soil organic carbon (SOC) and soil inorganic carbon (SIC) stocks in different soil orders.†

Soil order (area in million ha)	Soil depth range	Carbon stock					
		SOC		SIC		Total C	
	m	Pg	Pg/million ha	Pg	Pg/million ha	Pg	Pg/million ha
Entisols (79)	0–0.3	0.60	0.0076	0.89	0.011	1.49	0.019
	0–1.5	2.56	0.0324	2.86	0.036	5.42	0.069
Vertisols (27)	0–0.3	2.59	0.096	1.07	0.040	3.66	0.135
	0–1.5	8.77	0.325	6.14	0.227	14.90	0.552
Inceptisols (129)	0–0.3	2.17	0.017	0.62	0.005	2.79	0.022
	0–1.5	5.81	0.045	7.04	0.054	12.85	0.099
Aridisols (13)	0–0.3	0.74	0.057	1.40	0.108	2.14	0.165
	0–1.5	2.02	0.155	13.40	1.031	15.42	1.186
Mollisols (1.6)	0–0.3	0.09	0.057	0.00	0.000	0.09	0.056
	0–1.5	0.49	0.306	0.07	0.044	0.56	0.350
Alfisols (42)	0–0.3	3.14	0.075	0.16	0.004	3.30	0.078
	0–1.5	9.72	0.231	4.48	0.107	14.20	0.338
Ultisols (8.4)	0–0.3	0.20	0.024	0.00	0.000	0.20	0.024
	0–1.5	0.55	0.065	0.00	0.000	0.56	0.065
Total	0–0.3	9.55	–	4.14	–	13.69	–
	0–1.5	29.92	–	33.98	–	63.90	–

† Adapted from Bhattacharyya et al. (2008, 2009, 2013).

4.1, 2.6, and 0.5%, respectively, of the total geographical area of the country (Bhattacharyya et al., 2009). The baseline information indicates that except for the Ultisols and Aridisols, the other five soil orders exist in more than one bioclimatic zones of India, suggesting that soil diversity exists in the geographic tropics of India. The soil carbon stocks (Table 1) show that Vertisols, Inceptisols, and Alfisols have the major share of SOC stocks in the first 0.3-m depth of soil. Interestingly, the SOC stock of different soils expressed as per unit area shows that Mollisols, in spite of low SOC stock, contain more SOC per unit area than Entisols, Ultisols, and Aridisols (Table 1). Under natural vegetation, SOC values tend to attain quasi-equilibrium values (QEVs) with varying duration of 500 to 1000 yr in a forest system (Dickson and Crocker, 1953), 30 to 50 yr in agricultural systems after forest cutting (Johnson, 1995; Batjes, 2001), and 5 to 15 yr in agricultural systems after forest cutting in red soils (Saikh et al., 1998). Further, the shrink–swell soils in the subhumid tropics in India under forest and horticultural systems were reported to attain a QEV of 0.8 and 0.7% over a period of 30 yr and centuries, respectively (Naitam and Bhattacharyya, 2004).

Continuous cultivation of cotton (*Gossypium hirsutum* L.) (as a sole crop) for 20 yr and cotton plus pigeonpea [*Cajanus cajan* (L.) Huth] for 50 yr drastically reduced the QEV, suggesting that when shrink–swell soils are put to agricultural use, the QEV of SOC may decrease. Since all these soils have similar clay mineral suites, it seems that the variation in QEV in these soils is primarily due to differences in land use systems. The similarity in substrate quality indicates that the soils under agricultural system have the potential to attain QEVs similar to those observed in agricultural and forest systems (Fig. 2). This could be achieved through the addition of farm yard manure (FYM) or other green manures (Bhattacharyya et al., 2011), which could potentially increase the present QEV from 0.44 to 0.51% in soils

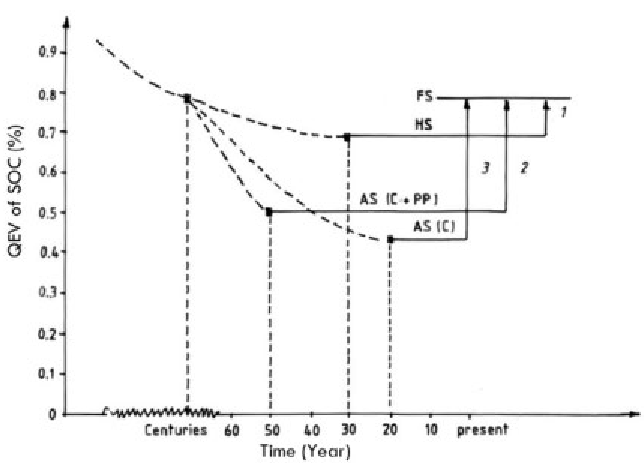


Fig. 2. Quasi-equilibrium values (QEV) of soil organic carbon (SOC) in swell–shrink soils vs. time under different systems and their scope for improvement in terms of increasing QEV in the first 0.3-m soil depth (source: Naitam and Bhattacharyya, 2004).

of agricultural system to the 0.70 to 0.80% observed in the soils of horticultural and forest systems in the subhumid tropical climate of India.

The qualitative nature of the soil substrate and their quantitative proportion of surface reactivity, referred as surface charge density (SCD), control the rate of SOC sequestration. Increase in organic C enhances SCD of the soil and the ratio of internal/external exchange sites (Poonia and Niederbudde, 1990). It may be mentioned that the dominant soils in SAT environments are black soils (Vertisols and their intergrades, with some inclusions of Entisols in the hills) and associated Alfisols. All these soils are dominated by smectites (Bhattacharyya et al., 1993; Pal et al., 2000b). The presence of smectites increases SCD, which offers greater potential for carbon sequestration in these soils. Black soils, therefore, may reach a QEV of more than 2%, as reported in the representative soils developed in basaltic alluvium.

While discussing the role of soil colloids in carbon accumulation in soils, Bhattacharyya and Pal (2003) estimated that the total proportion of soil organic pools (i.e., moderately oxidized, strongly oxidized, physically sequestered, and chemically sequestered) are controlled by clay minerals to the extent of 18, 20, 20, and 20%, respectively. This suggests that a minimum 78% of the total organic matter in soil is controlled by inorganic substrate (precisely phyllosilicates minerals with higher surface area in the finer fractions). Bhattacharyya et al. (2006) reported the SOC content of black soils to the tune of 2 to 3% while explaining the formation and persistence of Mollisols in the humid tropical climate.

Dalal and Conter (2000) have also indicated the scope of higher SOC content in the shrink–swell soils of Australia. The importance of SCD, rainfall, and their combined influence indicates an inverse pyramid relation of SOC with soil taxonomy (Fig. 3). Humid and subhumid regions of the Indo-Gangetic Plains, punctuated by 2 to 3 mo of cooler winter and dominated by noncalcareous soils, fall under the sufficient zones of SOC (Bhattacharyya et al., 2013). It was argued that the lower limit of QEV of SOC should be 1% since that is the limit of SOC in the mollic epipedon of Mollisols. In view of the higher SCD of the dominant soils of the semiarid tropics, fixing a QEV of SOC of 2% in the first 0.3-m soil depth, the SOC stock was 10.5 Pg for an area of 116.4 million ha. This value is three times greater than the present SOC stock of the semiarid tropics in India. This fact assumes importance since it points to enormous scope for organic C sequestration in the SAT with appropriate land management techniques.

Results from a long-term heritage watershed experiment at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India under rainfed conditions supported the hypothesis that an improved system of catchment management in combination with an appropriate cropping system can sustain increased productivity and improve the soil quality of Vertisols. The management strategies involved soil and water conservation

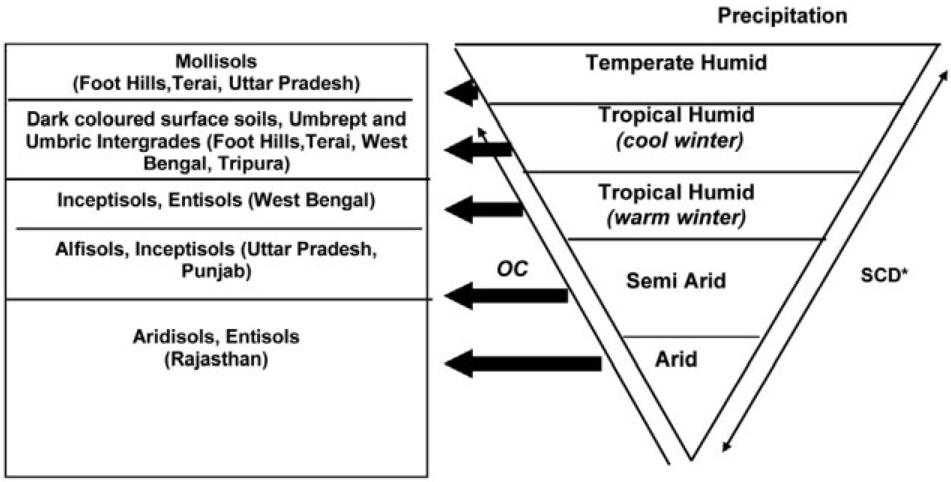


Fig. 3. Inverse pyramid relation with accumulation of organic carbon (OC) in soils grouped following U.S. Soil Taxonomy as influenced by precipitation, temperature, and substrate quality (* SCD, surface charge density) (source: Bhattacharyya et al., 2000, 2004).

practices (Wani et al., 2003). This experiment showed a fivefold increase in the yield over that in the traditional system. Increase in SOC sequestration was evident by a gain of about 7.3 t C ha^{-1} over a 24-yr period ending in 2000. The results of other long-term experiments with different cropping patterns in Vertisols indicated that legume-based cropping was more sustainable than those with cereals (Wani et al., 1995). The sequestering of atmospheric CO_2 in the soil is a win–win situation since it both improves the soil quality and maintains environmental quality (Wani et al., 2007).

Organic Carbon Sequestration in Soils of Tropical Climate

The Mollisols in the temperate world, even in agricultural land use system, contain high organic matter with soft (mollus) soil structure. The cold climate slows down the decomposition and loss of organic matter. In the humid tropics, the soils under agricultural lands are subjected to high atmospheric temperature and are not able to build up and store enough organic matter to be grouped under Mollisols. Interestingly, Mollisols have been reported in subtropical parts of northern India developed in micaceous alluvium of the Indo-Gangetic Plains. These soils are formed in environments similar to the temperate climates in the United States and Europe. Mollisols have also been reported from hilly regions of the southern peninsular and north-eastern India (Krishnan et al., 1996; Das et al., 1996; Shiva Prasad et al., 1998). However, Mollisols of the humid tropical climatic conditions of the Western Ghats and Satpura Range developed on Deccan basalt are acidic and fairly weathered (Bhattacharyya et al., 2006; Table 3). This is in contrast to the commonly reported calcareous Mollisols (Fanning and Fanning, 1989). The Indian Mollisols of humid tropical climate contain Ca-zeolites, which

Table 3. Selected soil parameters of Mollisols in humid tropical climate in India.

Horizon	Depth	Clay	pH (water)	Linear extensibility	Organic matter	Clay CEC	Zeolite in clay (2–0.2 μm)†
	m	%			%	cmol(+) kg^{-1}	%
Vertic Haplustoll, Madhya Pradesh (Forest: *Tectona grandis, Madhuca indica*)							
A1	0–0.06	30	5.9	11	6.1	173	16
A2	0.06–0.20	39	5.8	12	5.2	154	22
Bw1	0.20–0.37	29	5.8	11	3.5	207	17
Bw2	0.37–0.74	31	5.9	14	2.1	216	16
Bw3	0.74–1.06	31	5.6	16	1.4	232	18
Bw4	1.06–1.50	28	5.5	16	0.9	264	18
Vertic Argiudoll, Maharashtra (Forest: *Syzgium cuminii, Terminalia chebula, Carissa caranadas, Ficus glomerata*)							
A1	0–0.15	51	5.7	10	3.5	37	–
Bw	0.15–0.40	53	5.7	14	2.1	34	–
Bt1	0.40–0.74	61	5.7	16	1.2	31	–
Bt2	0.74–1.08	61	6.1	17	0.7	31	–
Bt3	1.08–1.46	59	6.1	15	0.5	32	–
BC1	1.46–1.75	53	6.1	13	0.2	38	–
BC2	1.75–1.90	51	6.1	13	0.2	39	–

† Zeolite present in sand and silt fractions in Vertic Haplustoll and only in sand in Vertic Argiudoll (Source: Bhattacharyya et al., 2006).

act as a source of base-rich heulandites that helps them persist even in adverse humid tropical climate with mean annual rainfall ranging from 1,400 to 3,300 mm (Bhattacharyya et al., 2006). The loss of bases during the leaching of soils has thus been continuously replenished by the steady supply of bases from heulandites (Ca-zeolites). This process develops a chemical environment that prevents the formation of kaolinitic and/or oxidic clay minerals, characteristic of typical advanced stage of soil weathering. These zeolitic minerals act as protectors against further soil degradation and help maintain a base saturation level (>50%) sufficiently high enough to keep these soils moist, soft, and dark even with subdominating proportion of smectites in the present day humid tropical climate.

Carbon Sequestration in Waterlogged Soils

Accumulation of organic matter under submerged conditions is the basis of maintenance of organic matter and fertility in wetland rice (*Oryza sativa* L.) soils compared to their arable counterparts (Sahrawat, 2004, 2005). Lowland rice systems (rice–rice) stored higher organic carbon and nitrogen compared to other systems in the semiarid tropics (Table 4). Soils under wetland rice had a tendency to show wider SOC/N ratio compared to those under other cropping patterns. This indicates a change in the quality of organic matter in sites under wetland rice compared to the sites with a narrow C/N ratio under arable cropping. The SOC/N ratio of soils increases with the intensity of irrigated rice, and the ratio is wider in soils under double- and triple-crop rice than in soils under dry land rice or rice–soybean [*Glycine max* (L.) Merr.] system (Sahrawat et al., 2005). In the lowland rice double-crop system the SIC/N ratio is relatively narrow (Table 5). A comparative evaluation of C/N ratios suggests that the narrower values of rice soils indicate a better and healthy pedo-environment, which keeps the deteriorating effect of $CaCO_3$ formation and concomitant sodicity at bay in these soils (Pal et al., 2000a). Soils under lowland rice systems preferentially accumulate organic matter, and they are important for sequestering atmospheric C. Soil submergence, as practiced in lowland rice systems, also seems to retard the rate of formation of $CaCO_3$. The temporal data (Fig. 4) support this suggestion (Bhattacharyya et al., 2007b).

It is noted that the SOC estimates for the Indo-Gangetic Plains differed by 8% (0–30 cm) and 25% (0–100 cm) from earlier estimates (Bhattacharyya et al., 2004): 630 Tg C for 0 to 30 cm and 1560 Tg C for 0 to 100 cm as compared to estimates made by IGP-SOTER (Batjes et al., 2007). Possible reasons for these differences are: (i) all soil components were characterized by a single soil unit/profile in IGP-SOTER, whereas the underlying soil associations have been described by two to three soil types on the source maps (Chandran et al. (2005), p. 42–44); (ii) somewhat different boundaries have been used for the Indo-Gangetic Plains, India, in various studies (Chandran et al., 2005); (iii) missing bulk density data have been estimated using different procedures; and (iv) the SOTER-based estimates are 95% confidence intervals for median SOC stocks as opposed to average stocks (Bhattacharyya et al., 2004). The other probable reasons are the huge differences in SOC stocks in a few spots like Fatehpur and Jagjitpur soils where earlier SOC data showed very low SOC. Data uncertainty and methods of estimation of SOC in different laboratories might also cause such differences. Soils under lowland rice systems preferentially accumulate organic matter and are important for sequestering atmospheric C. Soil submergence thus prevents or slows down degradation of calcareous soils, such as non-sodic Vertisols, to its sodic counterpart.

It has been observed that some soils (Entisols, Inceptisols, Alfisols, Vertisols) under various short- or long-term agricultural land

Table 4. Site and soil characteristics in rice growing areas in semiarid tropics of India.†

Soils (state)	Soil	Crops	MAR	SOC	SIC	SOC/N	SIC/N
			mm	——— % ———			
Jhalipura (Rajasthan)	Typic Haplusterts	rice–wheat	842	0.53	1.10	12: 1	25: 1
Jajapur 1 (Andhra Pradesh)	Vertic Haplustepts	rice–rice	792	0.88	0.26	11: 1	3: 1
Teligi (Karnataka)	Calcic Haplusterts	rice–rice	632	1.03	1.30	17: 1	21: 1
Paral (Maharashtra)	Sodic Haplusterts	cotton+pigeonpea/sorghum	794	0.60	1.19	17: 1	33: 1
Kovilpatty (Tamil Nadu)	Gypsic Haplusterts	cotton+blackgram	660	0.40	0.85	14: 1	30: 1

† Source: Sahrawat et al. (2005). Last two non-paddy soils are shown here for comparison. MAR, mean annual rainfall; SOC, soil organic carbon; SIC, soil inorganic carbon.

Table 5. Characteristics of pedogenic and nonpedogenic calcium carbonates in soils.†

Pedogenic calcium carbonates	Non-pedogenic calcium carbonates
· occurs as coating, fillings and nodules · micritic, microsparitic or sparitic · affects weathering of primary minerals · fabric similar to adjacent soil fabric, i.e., inclusion of primary minerals · occurs together with alluvial clay pedofeatures	· sharp boundary with soil matrix · relatively pure without inclusion of primary minerals · coarse-textured · free from other pedogenic features like illuviated clay

† Source: Pal et al. (2000a), Srivastava (2001).

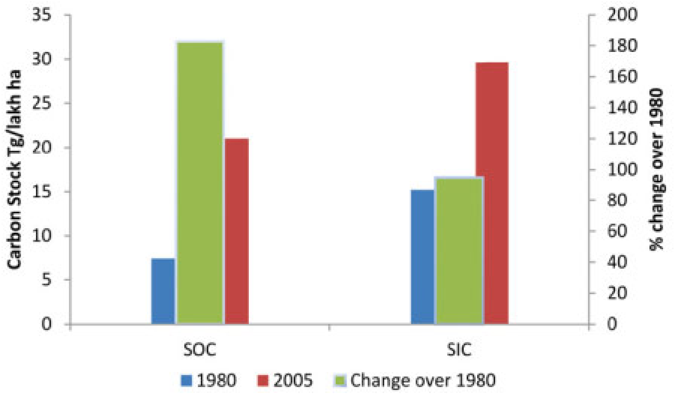


Fig. 4. Temporal changes in soil organic carbon (SOC) and soil inorganic carbon (SIC) over two different time periods (source: Bhattacharyya et al., 2007a).

uses (agriculture, agri-horticulture, and forestry) showed potential to sequester organic C under both arable and submerged rice conditions (Wani et al., 2003; Sahrawat, 2004; Sahrawat et al., 2005; Bhattacharyya et al., 2007a,b; Majumder et al.,2008a,b; Mandal et al., 2008; Chandran et al., 2009), and soils continue to show potential to sequester organic C even in humid climates (Mandal et al., 2008). Under the SAT environments, the results on Vertisols indicated that legume-based improved management even without applying FYM and gypsum could sequester organic C at the rate of 5 mg yr^{-1} in the first 1-m soil depth (Pal et al., 2011). Vertisols showed further potential to sequester an additional amount of 330 kg organic C ha^{-1} yr^{-1} (Pathak et al., 2011a) when FYM was applied (10 Mg FYM ha^{-1}) along with 100% of recommended doses of NPK.

Soil degradation and loss of organic matter and fertility is a widespread problem, especially in the rainfed areas of the semiarid regions (Pathak et al., 2011b; Jat et al., 2012). To arrest soil degradation and loss of fertility, it is essential to implement appropriate soil and water conservation practices, including appropriate site-specific components of conservation agriculture, especially no-till, retaining crop residues on the soil surface, and inclusion of legumes in production, among others, for the conservation of the natural resource and to maintain soil quality and productivity in the longer term (for a detailed discussion see Jat et al., 2012). Research has demonstrated that an integrated approach, in which soil and water conservation and balanced, integrated nutrient management practices are implemented, can sustainably increase the agricultural productivity of drier areas under rainfed conditions (for a review, see Pathak et al., 2011b; Sahrawat et al., 2011).

Inorganic Carbon Sequestration in Soils of Tropical India

In India, the climate changed from humid to semiarid in the rainfed areas during the Holocene period (Pal et al., 2009a,b). It is quite likely that due to this shift of climate from humid to semiarid, parts of India might experience adverse changes in physical and chemical properties of soils (Brevik, 2012). Detailed studies on Indian Vertisols and other alluvial and ferruginous soils in India and elsewhere in the world (Lal and Kimble, 2000a,b; Breecker et al., 2009; Hua, 2011) indicate that the drier climate is the primary factor responsible for the depletion of Ca^{2+} ions from the soil solution due to the formation of $CaCO_3$ (Pal et al., 2000a; Bhattacharyya et al., 2004; Breecker et al., 2009; Srivastava et al., 2013). Formation of $CaCO_3$, as PC, enhances the pH and also increases the relative abundance of Na^+ ions in both soil exchange sites and solution. Thus, the formation of $CaCO_3$ accentuating inorganic C sequestration has a deleterious effect on soil quality since it affects soil pH, exchangeable sodium percentage (ESP), and hydraulic properties (Bhattacharyya et al., 2008).

Despite the availability of various estimates of the world storage of SOC, there has been very little effort to estimate the carbon stored in inorganic form, primarily as calcium carbonate. Efforts have, however, been made to estimate the stock of the inorganic carbon mass in desert soils and in the soils of the world generally (Batjes, 1996). The soils that store large quantities of carbonates play an important role in global carbon cycle (Lal and Kimble, 2000a,b). However, the role of these carbonates as a probable source of calcium nutrition in soils of India was reported in a proposed model of C transfer (Bhattacharyya et al., 2004). Calcareous soils have $CaCO_3$ content varying from a small amount in some part of the profile to an appreciable amount occurring throughout the profile. This $CaCO_3$ often occupies much of the soil mass, especially in the thick calcic or petrocalcic horizons (calcretes). Reaction to hydrochloric acid (HCl) does not distinguish the $CaCO_3$ in soils that might have formed through the action of several models of genesis—fluvial, lacustral, pedogenic, and groundwater (Dhir, 1995).

Although arid and semiarid climates are the most conducive environments for the conversion of $Ca(HCO_3)_2$ to $CaCO_3$ in soils (Balpande et al., 1996), a wide occurrence of strongly developed carbonate-rich horizons in dry regions has commonly been attributed to steady aeolian deposition of carbonates and to their pedogenic origin (Pal et al., 2000a). Even in soils of the extreme arid climate of Rajasthan, the role of Aeolian dust was discounted by Choudhari (1994), who described the presence of carbonates as a pedogenic process that redistributed the calcareous material in soils. With the availability of broader datasets of soils (NAIP-C-4, http://www.geosis-naip-nbsslup.org/, accessed 10 June 2014), we have revised the map of calcareous soils to identify areas where inorganic C was sequestered (Fig. 5). It is, however, difficult to reconcile with the supposition that $CaCO_3$ in soils is entirely of pedogenic origin. Pal et al. (2000a) and Srivastava (2001) identified the typical characteristics of pedogenic and nonpedogenic carbonates, based on micromorphological studies along with the stable isotopic composition of soils belonging to the different age groups that correlate well with the types of vegetation specific to both the arid and humid climates that

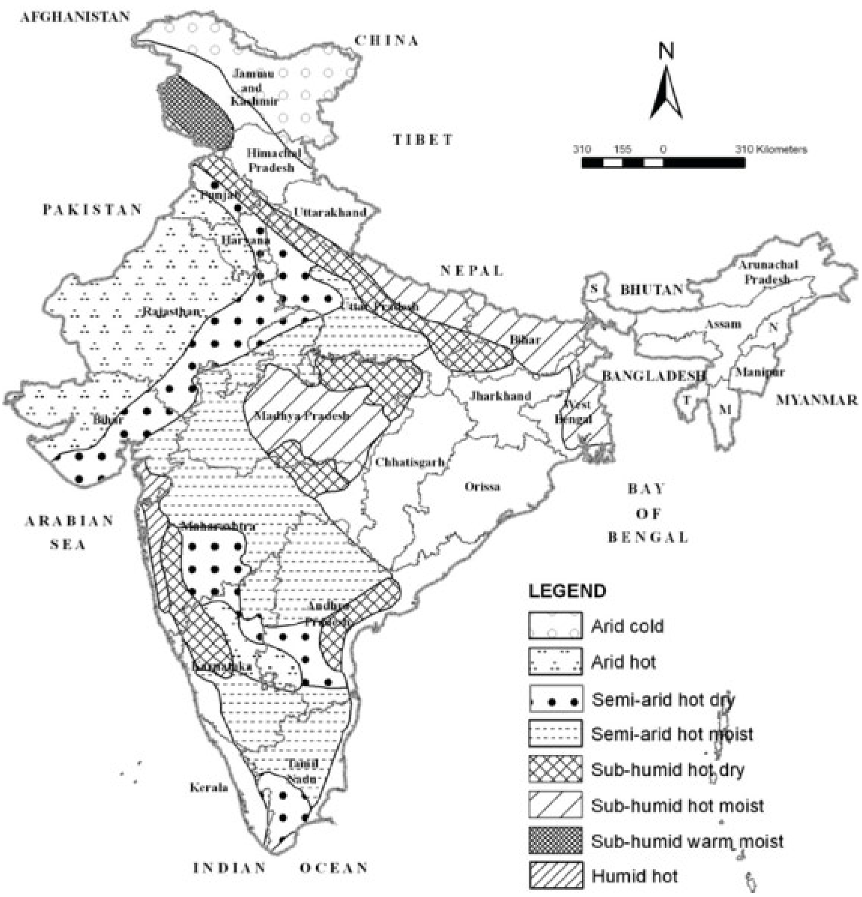


Fig. 5. Distribution of calcareous soils in different bioclimatic regions of India. Note: Part of Orissa, Kerala, Assam, and Tripura also contain $CaCO_3$ (T: Tripura; M: Mizoram; N: Nagaland; S: Sikkim) (NAIP-C-4, http://www.geosis-naip-nbsslup.org/, accessed 10 June 2014).

prevailed during the Holocene. The essential features of these two forms of carbonates are shown in Table 5.

In an aqueous solution open to CO_2 gas, the dissolution and precipitation of $CaCO_3$ can be shown in the following equations:

$$CO_2(g) + H_2O \rightleftharpoons H_2CO_3(\text{or } CO_2\text{, aqueous}) \quad [1]$$

$$H_2CO_3 \rightleftharpoons H^+ + CO_3^{2-} \quad [2]$$

$$CaCO_3 + H^+ \rightleftharpoons Ca^{2+} + HCO_3^- \quad [3]$$

We can summarize Eq. [1], [2], and [3] by a single equation:

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

The above shows that as the pCO_2 of a system increases, the solubility of $CaCO_3$ in that system also increases. As a result of microbial respiration during the decomposition of organic materials and respiration of plant roots, the pCO_2 of soil air is much greater than that in the atmosphere. This causes an increase in calcite solubility. Once the $CaCO_3$ is dissolved and is in solution as HCO_3^-, carbonate precipitation is generally induced by either the lowering of pCO_2 or by evaporation. Thus, water loss through evapotranspiration is considered to be the primary mechanism in the precipitation of PCs (Rabenhorst et al., 1984). Through its effect on evapotranspiration, temperature also plays an important role in controlling water flow in the soil (Ahmad, 1978). This has been particularly true in soils of dry (subhumid to arid) regions of India, as evidenced by the presence of pedogenic $CaCO_3$ (Pal et al., 2000a, 2013). In a discussion of inorganic carbon sequestration and its consequences to soil sodicity, Bhattacharyya et al. (2000, 2004) reported a threshold limit for MAR of 850 mm, below which the soils become more calcareous, alkaline, and sodic. With the help of the RothC model, a similar threshold limit was observed in research aimed at determining the SOC turnover rate (Bhattacharyya et al., 2011) (Fig. 6).

The soluble $Ca(HCO_3)_2$ helps restore the soluble and exchangeable Ca levels in soils, decreasing ESP and improving soil structure to increase hydraulic conductivity. The CO_2 evolved goes back to the atmosphere and thus makes the cycle complete (Fig. 7). This cycle is largely active in all the bioclimatic systems in India, with drier climate showing more inorganic carbon sequestration. Inorganic carbon sequestration in soils through the formation of pedogenic $CaCO_3$ is a problem and requires management interventions. Chemical treatments of soils along with vegetative cover (either plantation and/or crops) help in dissolving the native $CaCO_3$ as explained above. This may save these soils from further degradation (Fig. 8).

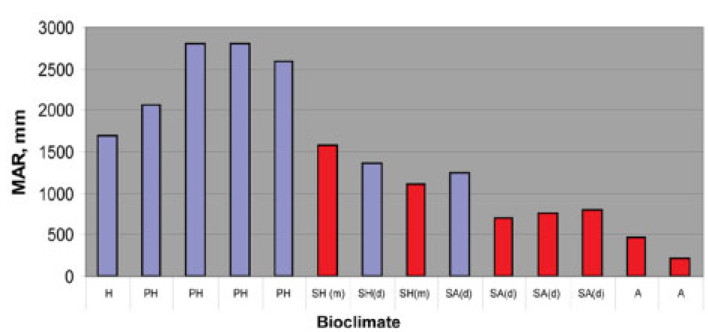


Fig. 6. Different bioclimatic systems showing accumulation of $CaCO_3$ (red areas) (revised from Bhattacharyya et al., 2004). (MAR, mean annual rainfall; H, humid; PH, per humid; SH(m), subhumid moist; SH(d), subhumid dry; SA(d), semiarid dry; A, arid; blue areas are noncalcareous).

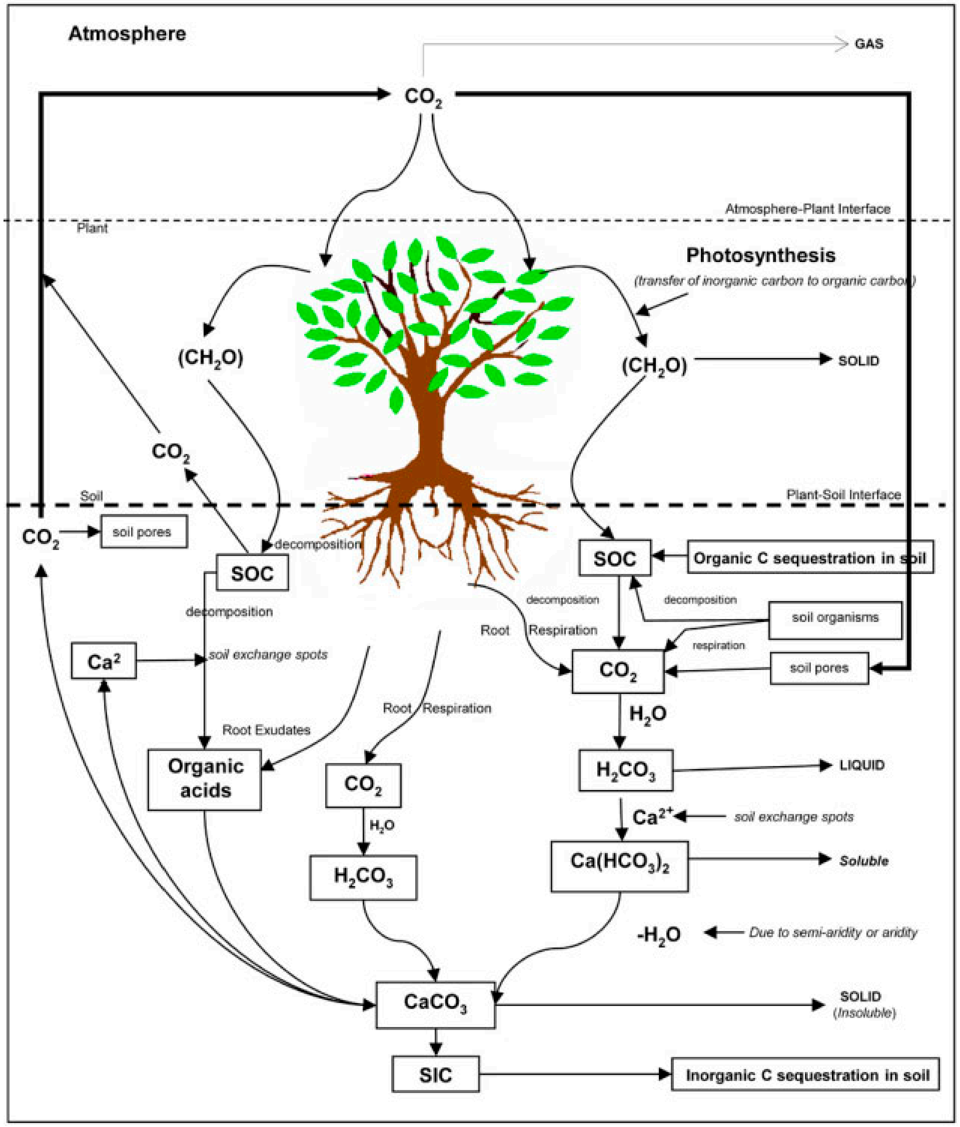


Fig. 7. Carbon transfer model showing organic and inorganic carbon sequestration in soil (source: Bhattacharyya et al., 2004).

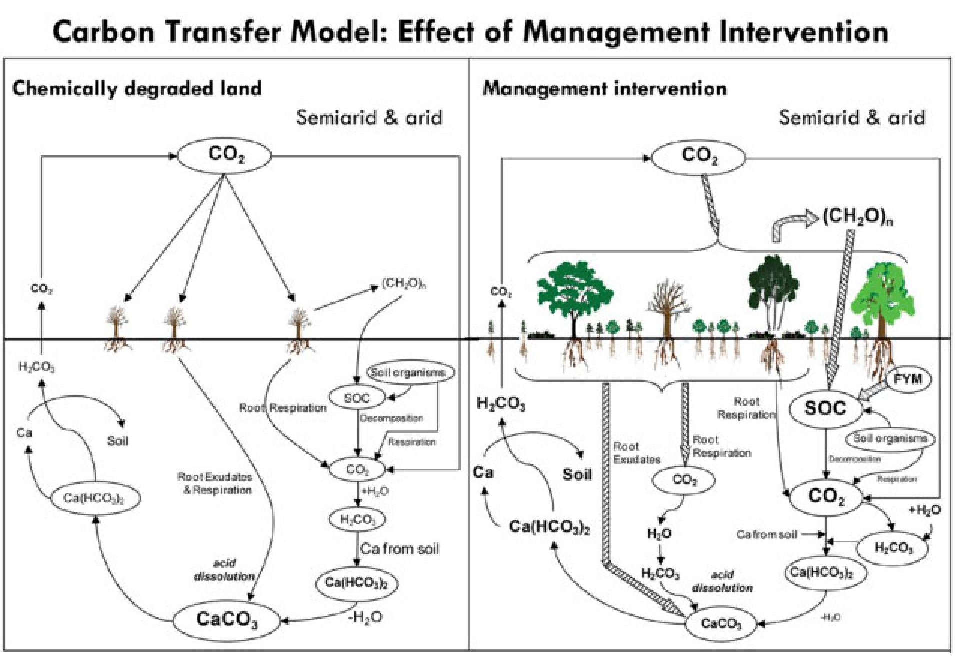
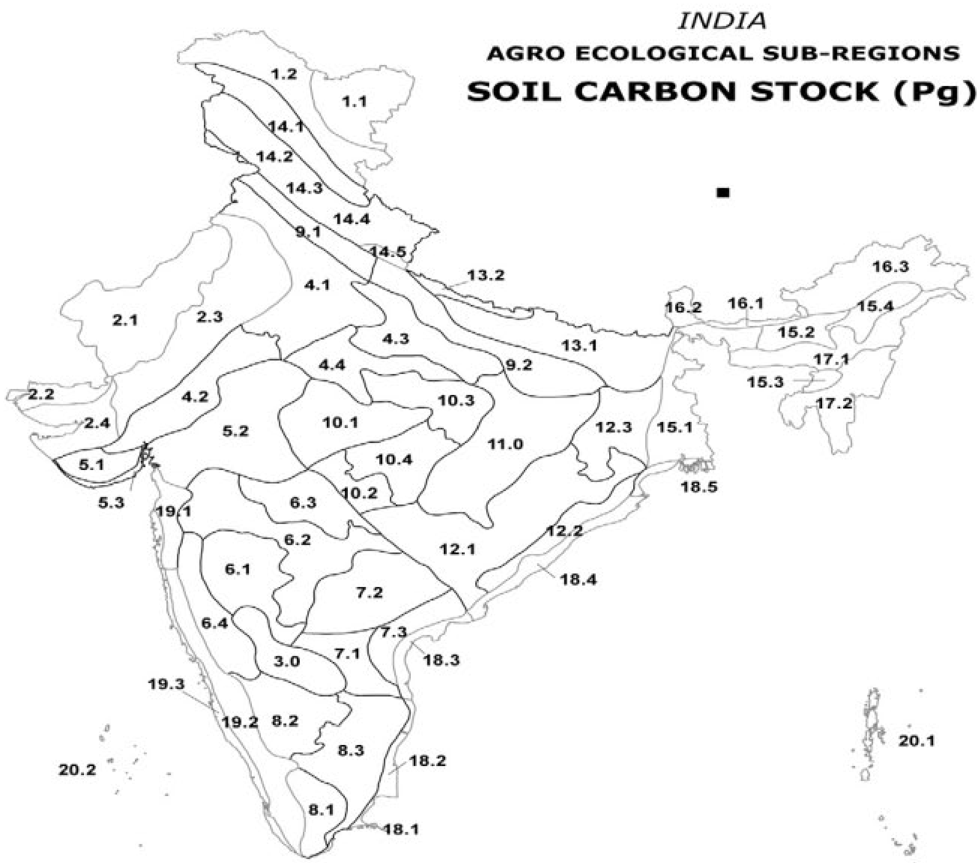


Fig. 8. Carbon transfer in semiarid and arid bioclimatic systems of chemically degraded land and areas showing management intervention (the size of circle and letters indicate relative proportion of individual component) (source: Bhattacharyya et al., 2004).

Prioritized agroecosystem subregions for organic C sequestration (Fig. 9) are SIC enriched, but the majority of soils therein have sodicity either in the subsoil or throughout the soil depth (Pal et al., 2000a). Calcareous sodic soils cover nearly 3.7 million ha area of the country. These chemically degraded and organic C–impoverished soils exhibit good potential to sequester organic C when ameliorative management practices are implemented. Following the specific management practices for Typic Natrustalfs of the Indo-Gangetic Alluvial Plains (Abrol and Fireman, 1977) and Sodic Haplusterts of southern India (Wani et al., 2003; Pal et al., 2011), a substantial gain in organic C stock was observed for both soil types (Wani et al., 2003; Bhattacharyya et al., 2007a).The enhanced potential for sequestering organic C is due to high rate of dissolution of PC (SIC) in these soils. After 30



LEGEND

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	0.449	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	0.107	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	0.079	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	0.082	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	0.010	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. 9. Map showing areas prioritized for organic carbon sequestration in soils (source: Bhattacharyya et al., 2008) (soil organic C stock values for 0–0.3 m soil depth).

mo of reclamation of sodic soils (Typic Natrustalfs) in the Indo-Gangetic Plains, an increase in exchangeable Ca^{+2} and Mg^{+2} and a decrease in ESP, pH, sodium adsorption ratio, and electrical conductivity of saturation extract were observed. But, the decrease in native $CaCO_3$ to a considerable depth indicated an improvement in chemical environment. During 30 mo of these cultural practices, the rate of dissolution of SIC ($CaCO_3$) was 254 mg 100 g^{-1} soil in the top 1 m of the profile (Pal et al., 2000a). Similar trends in chemical changes were also observed in Vertisols (Sodic Haplusterts). After 30 yr of improved management, the saturated hydraulic conductivity in the first 1 m of the profile increased by almost 2.5 times due to the reduction in ESP through the dissolution of $CaCO_3$. The rate of dissolution of $CaCO_3$ was 21 mg yr^{-1} in the first 1 m of the profile (Pal et al., 2011). Release of Ca^{2+} ions during the dissolution of $CaCO_3$ (8.4 mg per 100 g soil yr^{-1} in 1-m deep profile) in the improved management system was higher than immobilization of Ca^{2+} ions during the formation of $CaCO_3$ (0.10 mg per 100 g soil yr^{-1} in 1-m profile). This caused the improvement of saturated hydraulic conductivity to store and release more soil water during dry spells between rainfall events in the growing season, resulting in better crop productivity and higher organic C sequestration (Pal et al., 2012a).

Chemical changes and the concomitant increase in potential to sequester greater organic C during the resilience of sodic soils suggest that with time SIC gets dissolved through the release of cations of acidic root exudates and carbonic acid (H_2CO_3). This results in the formation of soluble Ca $(HCO_3)_2$, which supplies soluble and exchangeable Ca ions in the soils. This indirectly helps in better vegetative growth (organic) due to improved soil environment (good structure and better drainage).This works in sodic soils of both the Indo-Gangeic Plains and Black Soil Region in India.. These observations on C transfer validate the operation of the soil C transfer model (Fig. 7) of Bhattacharyya et al. (2004). This model also highlights the unique role of SIC, which remains chemically inert (Pal et al., 2000a) during its sequestration (Sahrawat, 2003), but acts as soil modifier during the amelioration of sodic soils (Pal et al., 2011, 2012a,b). The improvement in soil properties is also reflected in the classification of these soils. The sodic soils of the Indo-Gangetic Plains (Typic Natrustalfs) are now ameliorated, as evidenced by its revised grouping (Typic Haplustalfs) (Pal et al., 2011). These results are similar to those for the Vertisols with subsoil sodicity (Sodic Haplusterts) getting reclaimed (Typic Haplusterts) (Pal et al., 2011, 2012a). Therefore, the implementation of the improved management practices would make these sodic soils resilient, with increased potential for organic C sequestration. Thus, C sequestration may be promoted as one of the important mitigation strategies to cope with the impact of climate change by reducing the atmospheric concentration of CO_2 (Lal, 2004), and by improving the resilience of soils.

Soil Carbon Modeling

To make appropriate management decisions, we need to predict how SOC stocks change under different climate change scenarios. Several methods are used for the prediction at the benchmark spots for various long-term fertilizer experiments. Although these efforts are site-specific, keeping in view the similarity in the soil type (soil series) and bioclimatic systems, a broad level of generalization is possible. There are several models available to estimate soil organic C turnover (Smith et al., 1997). We used the RothC (26.3) and Century models (4.0) because these models are able to simulate long-term fertilizer experimental datasets consistently as well as site-specific data over a range of different land uses. The RothC and Century models were evaluated in four selected long-term fertilizer experiments sites representing contrasting bioclimatic systems: subhumid (moist), subhumid (dry), semiarid (dry), and arid (Bhattacharyya et al., 2011) (Table 6). RothC follows the trends of experimental set up in terms of different management interventions in all these sites represented by various bioclimatic systems. Even with usual soil carbon loss in semiarid climate, addition of manure in these sites causes increases in total organic carbon. An example of Sarol spot (Vertisols) is shown in Fig. 10. It seems substrate (clay) quality and quantity can possibly mitigate the effect of loss of total organic carbon by increased atmospheric temperature. This observation assumes importance, as it relates soil substrate and carbon sequestration (Fig. 3).

Evaluation of the Century model showed that these models can work in selected benchmark spots. It can simulate the treatment effects of the different bioclimatic systems in terms of predicting SOC change. The model was more successful when applied to subhumid climate (Nabibagh, Vertisols) than those in drier climate represented by soils with high amount of cracking clay (Akola, Teligi). The prediction of soil carbon status in subhumid bioclimatic (Sarol) system (Fig. 11) was similar when Century carbon models were used.

The relative performance of the RothC and Century model shows Century performs better (in terms of RMSE) except in Akola (Table 7) (Bhattacharyya and Tiwary, 2013). The modeling of Akola with high clay and semiarid climate could not simulate the field observation (Bhattacharyya et al., 2007a). The control treatment assumes greater importance in determining the relative efficiency of RothC and Century carbon models since no fertilizers and organic amendments are used in these treatments. It is interesting to find that Sarol spots (subhumid moist) capture similar modeled values during the experimental period and thereafter (Table 7). This is in sharp contrast to the drier spots (arid) at Teligi and Akola (semiarid). It seems that RothC and Century predict carbon changes and its turnover similarly in the subhumid (Sarol) spot. The simulation results of the crop models can be helpful in understanding the effect of climate change and in formulating mitigation strategies through management

Table 6. Comparative evaluation of RothC and Century models for predicting soil C at various long-term experimental sites.†

Spot (Bioclimate)	MAR	MAT_{max}	Soil	Treatments	Details of treatments	Simulation error RMSE RothC	RMSE Century	*t* RothC	*t* Century
	mm	°C							
Nabibagh (subhumid moist)	1148	31.7	Fine, smectitic, hyperthermic Typic Haplusterts	T1	Control, no fertilizer and manure	7.33	1.56	0.27	–0.82
				T2	N:P:K = 20:60:20 kg ha^{-1}	9.32	1.99	0.05	–1.95
				T5	N:P:K = 12.2: 15: 10 kg ha^{-1} + FYM @ 5 t ha^{-1}	4.70	5.63	0.35	–2.67
				T6	N:P:K = 12.2: 15: 10 + PM @ 10 t ha^{-1}	8.03	3.25	0.07	0.83
Sarol (subhumid dry)	1053	32.3	Very fine, smectitic, hyperthermic Typic Haplusterts	T1	Control, no fertilizer and manure	13.88	8.31	0.28	–2.65
				T2	N 20–40	11.50	4.57	0.16	–1.21
				T5	N 30 + FYM	15.01	5.55	0.67	0.25
				T6	FYM + N10–20	13.64	6.96	0.03	2.06
Akola (semiarid dry)	793	26.4	Fine, smectitic, hyperthermic Typic Haplusterts	T1	Control	1.79	1.74	0.98	–0.11
				T2	50% NPK	3.26	39.05	0.47	0.25
				T13	100% NPK + FYM @ 10 t ha^{-1}	8.01	18.01	0.31	1.40
				T14	FYM @ 10 t ha^{-1}	6.08	17.58	0.05	0.97

† MAR, mean annual rainfall; MAT, mean annual temperature; FYM, farm yard manure. Source: Bhattacharyya et al. (2011).

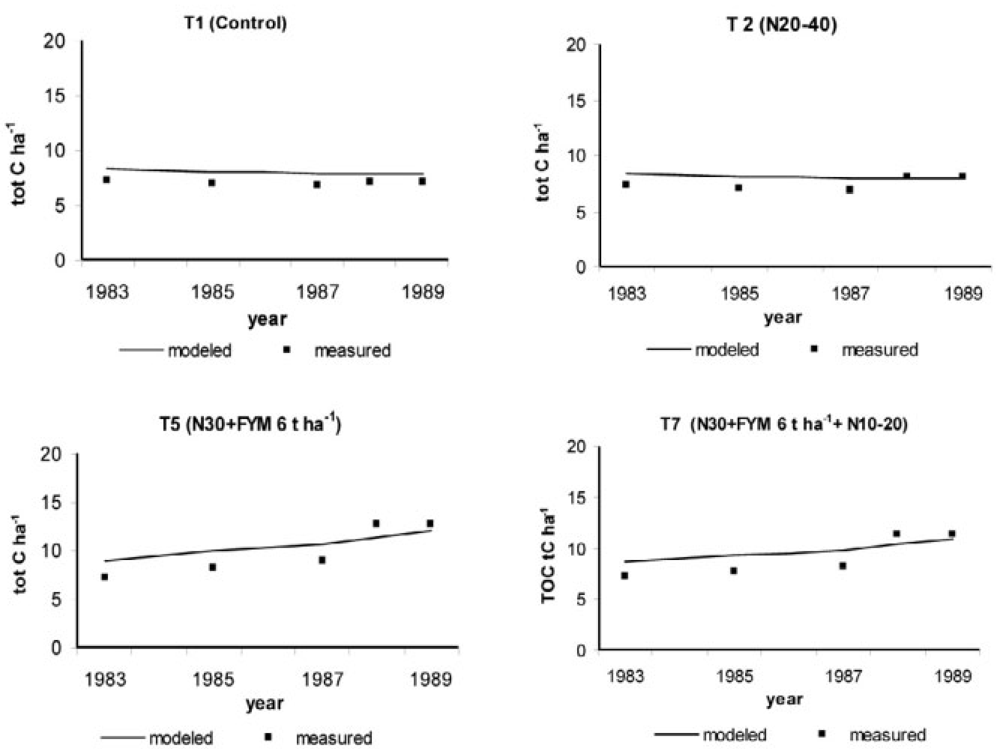


Fig. 10. Modeled organic carbon contents (tot C ha^{-1}: total soil carbon per hectare) in the RothC model of the surface horizon (0–23 cm) of soils from four treatments on the long-term fertilizer experiments site of Sarol (N, nitrogen; FYM, farm yard manure) (source: Bhattacharyya and Tiwary, 2013).

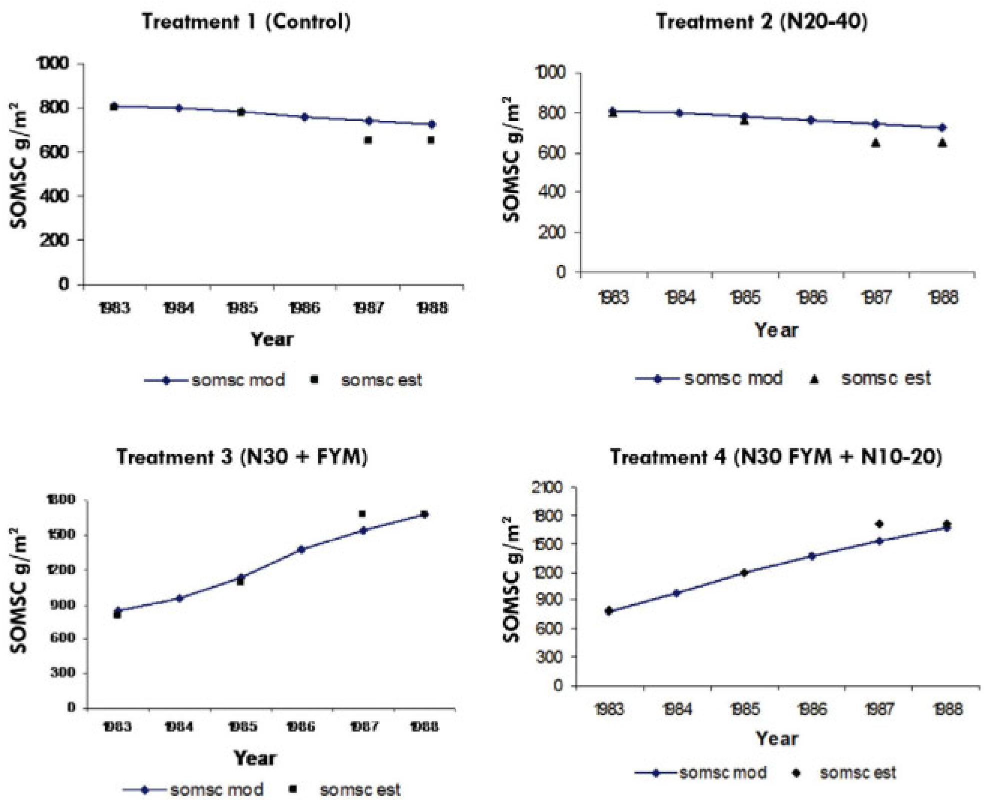


Fig. 11. Modeled and estimated soil carbon over time in Century model for Treatment 1 (control, no fertilizer, no manure), Treatment 2 (N20–40), Treatment 3(N30+FYM), and Treatment 4 (N30FYM+N10–20) in long term fertilizer experiment trial at Sarol, Madhya Pradesh, India (N, nitrogen; FYM, farm yard manure) (source: Bhattacharyya and Tiwary, 2011).

Table 7. Predicted Total organic carbon trend for selected long-term fertilizer experiments sites using RothC and Century C model.†

	RothC		Benchmark spots and cropping systems		Century	
1990	2000	2050		1990	2000	2050
			Sarol (soybean–safflower)			
	t C ha^{-1}				t C ha^{-1}	
6.25	6.24	6.15	Control	6.99	6.30	5.93
6.27	6.27	6.31	NPK	6.60	5.95	5.76
12.97	18.20	31.88	NPK + FYM	18.12	24.21	34.11
			Teligi (paddy–paddy)			
6.13	6.08	6.05	Control	15.66	14.67	11.33
6.13	6.14	6.20	NPK	15.57	14.61	14.82
8.84	13.83	27.86	NPK + FYM	17.46	17.98	19.58
			Akola (soybean–wheat)			
7.90	6.97	5.55	Control	9.81	4.00	2.64
8.26	7.79	7.46	NPK	10.08	6.51	7.47
13.74	21.76	40.50	NPK + FYM	12.08	14.00	20.60
			Nabibagh			
12.92	12.47	12.34	Control	12.09	12.57	12.78
13.31	13.12	13.63	NPK	11.67	14.75	17.08
14.85	16.86	22.44	NPK + FYM	9.37	17.11	22.51

† NPK, nitrogen, phosphorus, potash (added through fertilizers); FYM, farm yard manure. Source: Bhattacharyya and Tiwary (2013).

interventions and development of new technologies, such as development of tolerant crop varieties adapted to SAT.

Concluding Remarks

Soils of the tropical Indian environments are endowed with diverse, generally good substrate quality, and they are under favorable environmental conditions, as is evident from their considerable potential to absorb atmospheric CO_2 as SOC. The formation of pedogenic $CaCO_3$ (as SIC) and its subsequent role in enhancing the potential of soils to sequester SOC in the drier regions of the country illustrates a unique process involved in sequestering atmospheric CO_2. Major soil types generally show resilience to spring back to normal productive state with appropriate management interventions by farming communities with the support from national and international institutions. These soils have provided a sustainable foundation for India's growing self sufficiency in food production, and they generally maintain a positive organic C balance in the longer term. In view of a good potential for C sequestration by major zeolitic and nonzeolitic soils, the present SOC stock of about 30 Pg can be further increased under improved management of soil, water, crop, and nutrients in various diverse production systems. These case studies indeed may serve as a model elsewhere under similar soil and climatic conditions in the tropical world to maintaining soil heath and productivity under climate change through C sequestration.

Acknowledgments

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