

Soil carbon storage capacity as a tool to prioritize areas for carbon sequestration

T. Bhattacharyya*, D. K. Pal, P. Chandran, S. K. Ray, C. Mandal and B. Telpande

National Bureau of Soil Survey and Land Use Planning, Amravati Road, Nagpur 440 010, India

Carbon dioxide (CO₂), one of the major components of greenhouse gases, is of major concern in terms of the global warming phenomenon. To mitigate the effect of atmospheric CO₂, carbon capture and storage (CCS) has been found to be an important tool. The present study aims at explaining the role of soils as one of the most important natural resources in enhancing CCS. Soils capture and store both organic and inorganic forms of carbon and thus act both as source and sink for atmospheric CO₂. The datasets developed on CCS of soils permit us to generate thematic maps on soil carbon stocks, which may serve as ready reckoners for planners in prioritizing C sequestration programmes.

Keywords: Carbon stock, capture, sequestration, soils, storage capacity.

SOIL carbon (both soil organic carbon, SOC and soil inorganic carbon, SIC) is important as it determines ecosystem and agro-ecosystem functions, influencing soil fertility, water-holding capacity and 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 CO₂.

To reduce the emission of CO₂, carbon capture and storage (CCS) has been found to be an important option. The technique consists of three basic steps, viz. (i) capturing CO₂ at large and stationary point sources, (ii) transporting CO₂ from a source to sink, and (iii) injecting CO₂ in suited geological reservoirs or sinks. CCS was generally regarded as an option during the first half of the 21st century, to bridge the gap posed by the urgent need to act against climate change and the time needed to fully develop an important renewable energy^{1,2}. Among the other known sources to enhance CCS, the role of soils as an important natural resource, in capturing and storing carbon has not been adequately explained.

The main issue of soil carbon management in India revolves around the fact that a few parts of the country have soils containing high amount of SOC³ and low amount of SIC, whereas other parts show a reverse

trend⁴⁻⁶. The most important fact is that soils act as a major sink and source of atmospheric CO₂ and therefore have a huge role to play in the 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 require basic information of CCS in the soils. The present study thus assumes importance, since knowledge on CCS of soils will facilitate in deciding areas for appropriate management techniques for carbon sequestration.

The most prudent approach to estimate the role of soils to capture and store carbon should require information on the spatial distribution of soil type, soil carbon (SOC and SIC) and the bulk density (BD). To estimate the CCS of soils in spatial domains we have used the agro-climatic zones (ACZs)⁷, bioclimatic systems (BCS) of India⁸ and the agro-ecosubregions (AESRs)^{9,10} maps as base maps. These three efforts of land area delineations have been used for various purposes at the national (Figures 1 and 2)^{7,8} and regional-level planning (Figure 3)⁹. We have, however, shown the utility of these maps for prioritizing areas for C sequestration in soils through a set of thematic maps on carbon stock. It will make a dataset for developmental programmes at both national and regional levels, to address the role of soils in capturing and storing elevated atmospheric CO₂ due to global climatic change.

Materials and methods

Materials

The necessary information about the selected soils (Tables 1–5) covering all the regions was collected from the existing primary datasets of NBSS&LUP, Nagpur^{6,9,11–17}. The quality of organic carbon data of soils depends on the sampling methods, exact season of collecting soils on different types of landscapes, kinds of vegetation and above all, the methods of soil analysis in the laboratory. The method of Walkley and Black¹¹ has been an acceptable analytical technique to generate SOC data by weight to volume. For SIC, the information on calcium carbonate (CaCO₃) content in the soils has been used as the base.

*For correspondence. (e-mail: tapas11156@yahoo.com)

During the present study some of the bulk density (BD) values were generated, where they were not available¹³.

Methods

Estimating carbon stock of soils

The datasets (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 (gg⁻¹), BD (mg m⁻³) and thickness of horizon (m) for individual soil profiles with different thicknesses varying from 0 to 0.3, 0 to 0.5, 0 to 1.0 and 0 to 1.5 m. In the second step, the total SOC content determined by the first step was multiplied by the area (mha) of the soil unit distributed in different agro-climatic zones⁷. The total SOC content is expressed in Pg (1 Pg = 10¹⁵ g). The total SOC stock was thus calculated using the following equation

$$\text{C content (g g}^{-1}\text{)} \times \text{BD (Mg m}^{-3}\text{)} \times \text{area (mha)} \times \text{soil depth (m)}$$

$$\text{SOC stock in soil} = \frac{\text{C content (g g}^{-1}\text{)} \times \text{BD (Mg m}^{-3}\text{)} \times \text{area (mha)} \times \text{soil depth (m)}}{10}$$

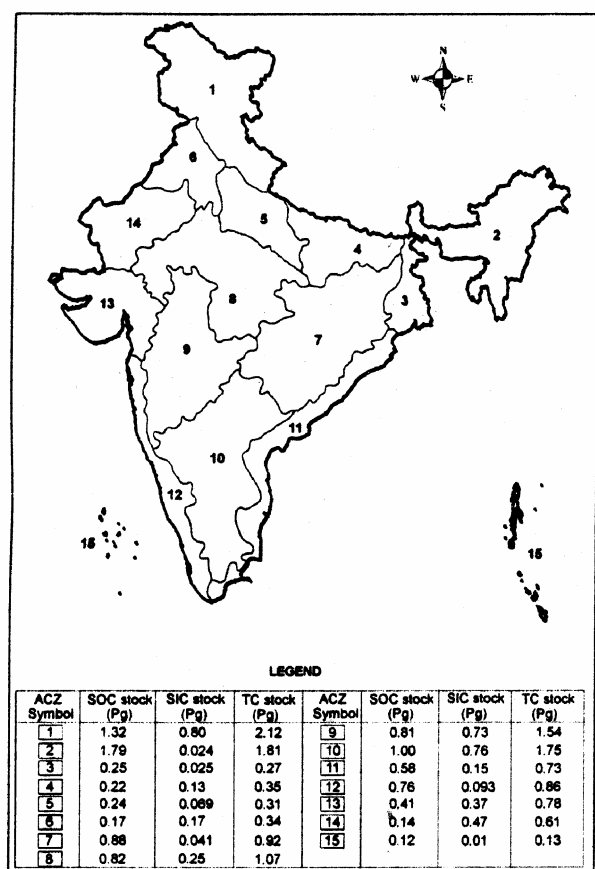


Figure 1. Agro-climatic zones of India (Planning Commission) showing soil carbon stocks (0–0.3 m soil depth).

For SIC, the same steps were followed using 12 parts of C present in CaCO₃ values. The sum of SOC and SIC stock gave the total carbon (TC) stock in the soils.

Generating thematic maps

Maps of ACZ⁷, AESR⁸ and BCS¹⁰ were digitized and used as base maps to generate thematic maps on soil carbon stock for different soil depth intervals using the ArcGIS (ver.9.0) software. For brevity, the maps for 0–0.3 m depth are shown here.

Results and discussion

The estimated stocks of soil carbon in the ACZ are described below.

The Himalaya zones

Western Himalaya zone (ACZ1): This zone consists of three sub-zones: (a) Jammu and Kashmir, which covers

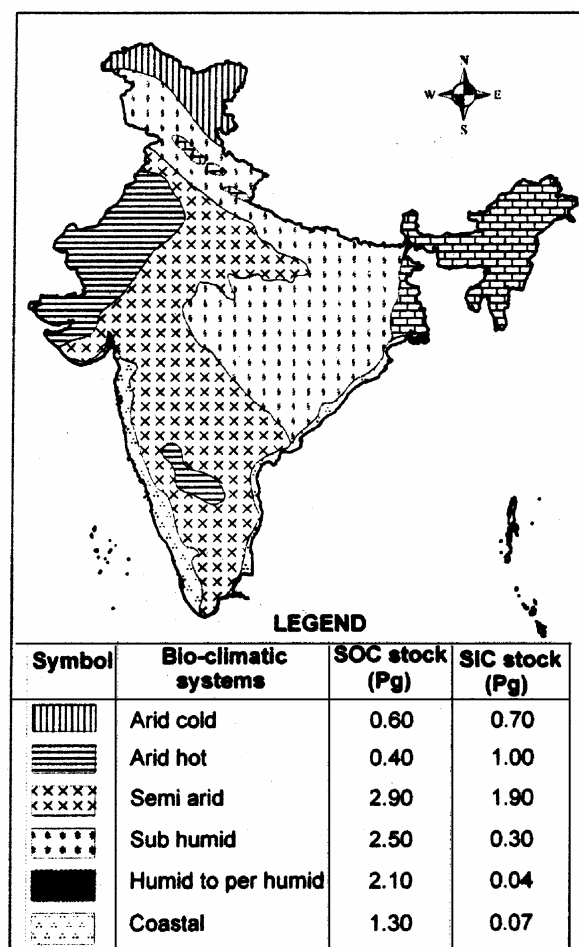


Figure 2. Carbon stock in major bioclimatic systems in India (0–0.3 m soil depth).

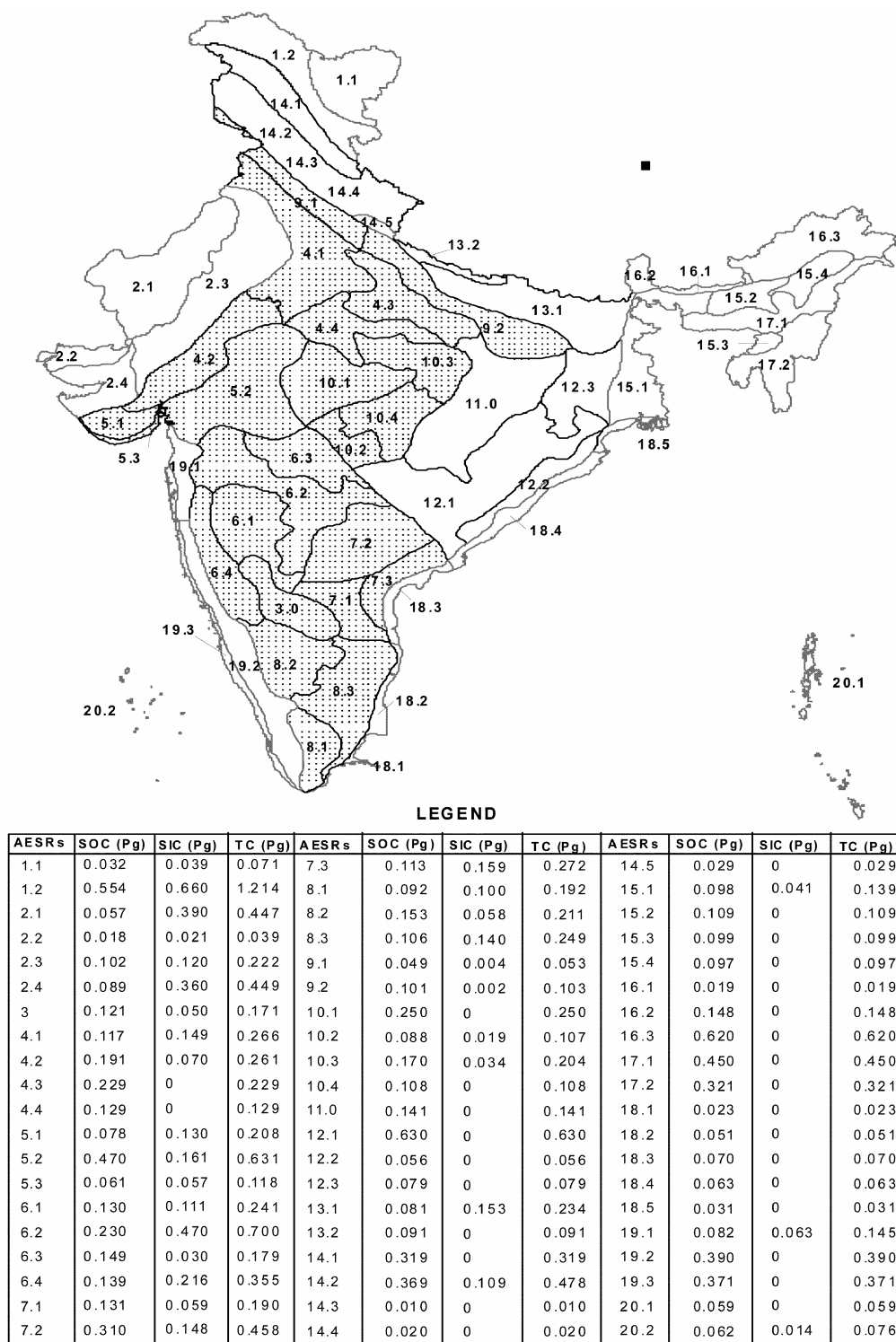


Figure 3. Soil carbon stock (in Pg) map in different agro-ecological subregions showing prioritized areas (shaded areas) for carbon sequestration (0–0.3 m soil depth).

the cold arid region of Leh (~2000 m amsl) to the low-altitude sub-tropical region of the southern plains (215–360 m amsl); (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 consist of valley, mid hills and high hills of the Western Himalayas⁷. The Western zone covers an area of 33.85 mha, which constitutes 10% of the total geographi-

Table 1. Dominant soils and their characteristics in the Himalaya zones

Soil series	Soil taxonomy*	Organic carbon (%)		Calcium carbonate (%)	
		0–0.3 m	0–1.5 m	0–0.3 m	0–1.5 m
ACZ 1 (Western Himalaya zone)					
Ladakh	Typic Cryorthids	0.11	0.06	1.30	2.10
Kibber	Typic Cryorthids	1.40	0.57	13.80	17.30
Kalpa	Typic Haplustepts	0.75	0.42	0**	0
Gogjipather	Typic Haplustalfs	0.33	0.23	0.20	11.50
Wahthora	Mollic Haplaquepts	0.63	0.40	0.10	0
Mataur	Typic Hapludepts	0.40	0.20	0	0
Chinwali	Lithic Udorthents	1.01	0	0	0
Haldi	Typic Hapludolls	0.71	0.38	0	0
ACZ 2 (Eastern Himalaya zone)					
Mahimabari	Aeric Haplaquepts	0.85	0.40	0	0
Barak	Umbric Haplustepts	1.84	1.40	0	0
Seoraguri	Typic Haplaquepts	1.32	0.77	0	0
Jaihing	Typic Haplustepts	1.29	0.90	0	0
Singvita	Umbric Haplustepts	1.41	0.82	0	0
Nimbong	Typic Haplustepts	3.20	1.68	0	0
Lankaparahat	Umbric Haplustepts	3.56	0	0	0
Sukna	Typic Haplustepts	2.90	0	0	0
Mebo	Typic Hapludalfs	1.33	0.73	0	0
Yakimoli	Typic Hapludalfs	2.70	2.22	0	0
Salsekgiri	Typic Hapludalfs	2.37	1.58	0	0
Digingru	Typic Paleudalfs	1.90	1.23	0	0
Dialong	Ultic Hapludalfs	1.74	1.00	0	0
Barjola	Typic Hapludalfs	0.92	0.64	0	0
Shibbari	Typic Kandihumults	1.36	0.94	0	0
Bijaynagar	Typic Paleudults	1.35	0.85	0	0

*Soil Survey Staff²⁹.

**Many soils in these ACZs are non-calcareous and thus calcium carbonate is not a source of soil inorganic carbon.

cal area (TGA) of the country. The soils (Table 1) contribute 14, 19, and 16% of SOC, SIC and TC stocks of the country respectively (Table 6).

Eastern Himalaya zones (ACZ 2): This zone covers 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 and plateaus with near-tropical to alpine climate conditions. Mean annual rainfall is high in areas under the forest. Many areas in Assam, West Bengal and Tripura represent cultivable lands⁷. The soils (Table 1) contribute 19, 1 and 13% of total SOC, SIC and TC stocks of the country respectively (Table 6).

The Himalaya zones (ACZ 1 and ACZ 2) cover nearly 19% area and contribute 33% of SOC reserves of the country, largely due to the thick forest vegetation (Figures 4 and 5). The northern mountains of the country have maximum concentration of forest ecosystem, except parts of central and western India. Eswaran *et al.*¹⁸ 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 pool 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 the Amazonian forest to well-managed pastures will cause an initial fall in the SOC reserves followed by a slow rise¹⁹. The estimates of SOC in any ecosystem represent a valuable baseline for evaluating the original status of SOC²⁰. The SOC stock of ACZ 1 and ACZ 2 may thus act as a baseline dataset to assess the effects of land-use changes in the Himalayan range of India¹⁴.

Indo-Gangetic Plains (IGP)

Lower Gangetic Plains (ACZ 3): These plains represent four sub-regions: (i) barind plains, (ii) central alluvial plains, (iii) alluvial coastal saline plains, and (iv) rare plains⁷, covering 3% of the TGA of the country. The soils (Table 2) constitute 3, 1, and 2% of the total SOC, SIC and TC stocks of the country respectively (Table 6).

Middle Gangetic Plains (ACZ 4): Twelve districts of eastern Uttar Pradesh (UP) and 27 districts of Bihar Plains form this zone. It is sub-divided into two sub-zones: (i) northwest alluvial (recent) plains, and (ii) northeast alluvial (tarai) plains⁷. This zone covers 5% of the TGA of the country. The dominant soils (Table 2) contribute 2,

Table 2. Dominant soils and their characteristics in the Gangetic Plains

Soil series	Soil taxonomy*	Organic carbon (%)		Calcium carbonate (%)	
		0–0.3 m	0–1.5 m	0–0.3 m	0–1.5 m
ACZ 3 (Lower Gangetic Plains)					
Sasanga	Typic Ustifluvents	0.47	0**	0.49	0
Konarpara	Typic Fluvaquents	0.36	0.21	0	0.87
Hanrgram	Vertic Endoaquepts	0.62	0.28	0	0
Amarpur	Typic Ustochrepts	0.40	0.21	0	0
Madhpur	Typic Endoaqualfs	0.29	0.19	0.34	1.60
Sagar	Typic Haplaquepts	0.69	0.35	0	0
ACZ 4 (Middle Gangetic Plains)					
Keserganj	Typic Ustifluvents	0.20	0.17	6.02	5.05
Bahraich	Typic Ustifluvents	0.16	0.18	0	7.02
Sivapande	Fluventic Ustochrepts	0.19	0.17	0	8.01
ACZ 5 (Upper Gangetic Plains)					
Basiaram	Udic Ustochrepts	0.34	0.16	0.10	0.11
Itwa	Aeric Ochraqualfs	0.32	0.22	0.10	16.52
Simri	Fluventic Ustochrepts	0.15	0.26	0	0
Akbarpur	Typic Natrustalfs	0.43	0.14	0	0
Pantanagar	Aquic Hapludolls	2.70	1.41	0	4.02
Haldi	Typic Hapludolls	0.71	0.38	0	0
ACZ 6 (Trans Gangetic Plains)					
Dhoda	Aquic Ustochrepts	0.32	0.18	0	0
Jagjitpur	Typic Ustochrepts	0.30	0.12	1.01	11.02
Bhanra	Typic Ustipsamments	0.10	0.08	0	0
Berpura	Udic Ustochrepts	0.27	0.24	0	0
Nabha	Typic Ustochrepts	0.36	0.24	0.10	0.10
Sadhu	Vertic Ustochrepts	0.49	0.32	0.30	0.32
Zarifa Viran	Typic Natrustalfs	0.30	0.18	0.93	8.12
Fatehpur	Typic Ustochrepts	0.11	0.05	0	0.10
Phaguwala	Typic Ustochrepts	0.23	0.16	2.65	5.20
Ghabdan	Aquic Natrustalfs	0.17	0.13	8.40	7.80

*Soil Survey Staff²⁹.

**Soils which are non-calcareous and do not contribute inorganic carbon show calcium carbonate value as zero.

3 and 3% of the total SOC, SIC and TC stocks of the country respectively (Table 6).

Upper Gangetic Plains (ACZ 5): This zone consists of 32 districts of UP and covers 4% of the TGA of the country. This is sub-divided into three sub-zones: (i) Central Plains (alluvial), (ii) Northwestern Plains (alluvial–tarai), and (iii) Southwestern Plains (alluvial)⁷. The dominant soils (Table 2) constitute 3, 2, and 3% of the SOC, SIC and TC stocks of the country respectively (Table 6).

Trans-Gangetic Plains (ACZ 6): This zone represents Punjab, Haryana, Delhi and part of Rajasthan (Shriganganagar District) covering 4% of the TGA 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 desert⁷. The soils (Table 2) contribute 2, 4, and 3% of the SOC, SIC and TC stocks of the country respectively (Table 6).

The IGP covers four ACZs (3–6) and occupies 15% of the TGA of the country⁷ (Figure 5). The IGP is undergo-

ing 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 (Figure 4). It was reported that the soils under hot, humid and per-humid climates are deficient in SOC due to intensive agricultural practices¹⁴. 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 trend²¹. 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 in the IGP after an initial decline²⁰. Most parts of the humid and sub-humid regions of the IGP punctuated by 2–3 months of cooler winter, dominated by non-calcareous soils fall under the sufficient zone of SOC content⁶. It has been reported that the soils of the arid and semi-arid climate occupying more than one-third area of the IGP are poor in SOC content and are thus prone to be calcareous and sodic¹⁷.

Table 3. Dominant soils and their characteristics in the plateau and hills

Soil series	Soil taxonomy*	Organic carbon (%)		Calcium carbonate (%)	
		0–0.3 m	0–1.5 m	0–0.3 m	0–1.5 m
ACZ 7 (Eastern plateau and hills region)					
Chhal	Udic Rhodustalfs	0.12	0.10	0**	0
Arang	Entic Chromusterts	0.39	0.24	0	0
Chaugel	Plinthustalfs	0.64	0.41	0	0
Ekma	Typic Haplustalfs	0.50	0.10	0	0
Pusaro	Typic Paleustalfs	0.24	0.12	0	0
Hatiapather	Typic Ochraqualfs	0.50	0.24	0	0
Bhubaneswar	Typic Haplustults	0.60	0.47	0	0
Parichhal	Aquic Haplustalfs	0.40	0.15	0	0
ACZ 8 (Central plateau and hills region)					
Pali	Lithic Camborthids	0.22	0	0	0
Bijapur	Udic Ustochrepts	0.16	0.15	0	0
Hirapur	Aeric Haplaquepts	0.30	0.19	0	6.00
Marha	Chromic Haplusterts	0.41	0.29	0	0.20
Saunther	Typic Haplusterts	0.82	0	0	0
Kheri	Typic Haplusterts	0.41	0.29	0	2.30
Linga	Udic Haplusterts	0.49	0.42	2.90	5.70
Khursapar	Typic Ustorthents	0.94	0.57	4.00	3.00
Jamra	Chromic Haplusterts	0.73	0.61	3.90	8.30
Sundra	Chromic Haplusterts	0.64	0.37	0.56	0.72
Bishramganj	Lithic Ustorthents	0.90	0	0	0
Amgaon	Typic Plinthustalfs	0.60	0	0	0
Bhendala	Typic Haplusterts	0.20	0.70	0	5.20
ACZ 9 (Western plateau and hills region)					
Pargaon	Lithic Ustorthents	0.20	0	12.20	0
Sawargaon	Typic Calcicusterts	0.64	0	3.80	0
Gulbarga	Typic Haplusterts	0.45	0.30	3.00	0
Pargaon	Lithic Ustorthents	0.20	0	12.20	0
Nimone	Typic Haplusterts	0.40	0.40	5.00	9.30
Dharangaon	Lithic Ustorthents	0.50	0	0	0
Jambha	Typic Haplusterts	0.46	0.40	2.00	2.10
Pargaon	Lithic Ustorthents	0.20	0	12.20	0
Sawargaon	Typic Calcicusterts	0.64	0	3.80	0
Achmatti	Sodic Haplusterts	1.23	0.92	13.70	14.30
ACZ 10 (Southern plateau and hills region)					
Garnimitta	Typic Rhodustalfs	0.32	0.11	0	0
Raichure	Typic Haplusterts	0.80	0.66	3.30	3.40
Sidiganmala	Ustollic Calciorthisds	0.31	0.51	11.90	14.70
Sunkadkallu	Typic Camborthids	0.37	0.35	0	0
Bodur 1	Typic Haplargids	0.87	0.52	0	0
Bodur 2	Typic Paleargids	0.68	0.46	0	1.10
Dindhar	Ustollic Calciorthisds	0.27	0.21	12.20	11.30
Patancheru	Udic Rhodustalfs	0.83	0.52	0	0
Kasireddipalli	Sodic Haplusterts	0.66	0.40	6.00	6.50
Palathurai	Typic Haplustalfs	0.71	0	1.80	0
Coimbatore	Vertic Ustropepts	0.37	0.35	8.00	11.80
Channasandra	Kandic Paleustalfs	0.68	0.46	0	0
Tyamagondalu	Kandic Paleustalfs	0.48	0.45	0	0
Irugur	Typic Rhodustalfs	0.15	0.13	0	0
Dandupalya	Typic Kandicustalfs	0.54	0.36	0	0
Giriyappanamane	Kandic Paleustalfs	1.64	0.97	0	0
Idugundi	Ustic Palehumults	2.41	1.04	0	0
Koladabigodu	Ustic Haplohumults	1.32	0.71	0	0
Kalatmadu	Kanhaplic Haplustults	1.15	0.48	0	0
Bejjavalli	Kanhaplic Rhodustalfs	3.23	1.74	0	0
Kargudi	Typic Argiudolls	2.55	0.84	0	0
Teppakadu	Typic Hapludolls	1.53	0.83	0	0
Kambakkaddu	Typic Argiustolls	1.04	0.94	0	0
Vadavayal	Mollic Paleudalfs	2.25	1.20	0	0
Malaperahatti	Rodic Paleustalf	1.09	0.66	0	0
Avalanchi	Typic Haplohumults	5.50	1.94	0	0

*Soil Survey Staff²⁹.

**Soils which are non-calcareous and do not contribute inorganic carbon show calcium carbonate value as zero.

Table 4. Dominant soils and their characteristics in the coastal plains and Gujarat plains

Soil series	Soil taxonomy*	Organic carbon (%)		Calcium carbonate (%)	
		0–0.3 m	0–1.5 m	0–0.3 m	0–1.5 m
ACZ 11 (East coast plains and hills)					
Madukkur	Vertic Hapludalfs	0.76	0.28	0**	0
Kalathur	Sodic Haplusterts	0.57	0.26	8.30	9.10
Tirunallar	Typic Haplusterts	1.00	0.55	2.00	2.30
Andhra Pradesh Coast	Typic Ustifluvents	0.80	0.80	0	0
Sunugarh	Aquic Ustochrepts	0.45	0.36	0	0
Motto	Vertic Haplaquepts	0.70	0.31	0	0
Palada	Typic Humitropepts	3.80	3.22	0	0
ACZ 12 (West coast plains and ghat region)					
Saili	Vertic Ustochrepts	0.86	0.53	9.00	13.10
Athal	Typic Haplusterts	0.72	0.59	0	0
Trivandrum	Ustoxic Dystrypepts	1.10	0	0	0
Kunnamangalam	Typic Halploorthoxs	1.63	0.82	0	0
Palode	Oxic Dystrypepts	2.19	1.37	0	0
Ambalapuzha	Typic Sulfaquents	6.10	7.80	0	0
Kyadagi	Oxic Ustrophepts	0.81	0.52	0	0
Ramanthali	Ustic Haplohumults	2.11	0.68	0	0
Nayabazar	Ustic Kandihumults	1.26	0.91	0	0
Nellikunnam	Ustic Kanhaplohumults	1.22	0.67	0	0
Koliyoor	Typic Kandistults	1.09	0.54	0	0
Agali	Pachic Argiustolls	1.13	0.65	0	0
Medumgayam	Pachic Haplustolls	1.67	0.99	0	0
Vanibetta	Ustic Palehumults	2.67	1.40	0	0
Zaimolo	Typic Paleustults	1.44	0.98	0	0
Bandoli	Typic Haplustults	2.39	1.52	0	0
ACZ 13 (Gujarat plains and hills)					
Lakhpat	Typic Natrargids	0.21	0.17	2.00	2.40
Padana	Typic Calciorhithids	0.34	0.43	11.20	35.00
Bhola	Vertic Ustrophepts	0.66	0.38	18.30	23.00
Amipur	Halic Calcicusterts	1.20	0.86	12.60	15.00
Rinawada	Sodic Calcicusterts	1.20	0.82	13.80	23.20
Nabhamota	Fluventic Ustrophepts	0.60	0.49	1.85	2.30
Kamliakheri	Vertic Ustrophepts	0.77	0.50	0	0
Sarol	Typic Haplusterts	0.36	0.31	1.95	2.50
Chambal	Chromic Haplusterts	0.33	0.33	6.20	5.90

*Soil Survey Staff²⁹.

**Soils which are non-calcareous and do not contribute to inorganic carbon show calcium carbonate value as zero.

Table 5. Dominant soils and their characteristics in the western dry and islands zone

Soil series	Soil taxonomy*	Organic carbon (%)		Calcium carbonate (%)	
		0–0.3 m	0–1.5 m	0–0.3 m	0–1.5 m
ACZ 14 (western dry)					
Thar	Typic Torripsamments	0.10	0.06	6.00	6.80
Sobhasar	Typic camborthids	0.01	0.15	6.00	7.00
Kolu	Typic Paleorthids	0.18	0.05	0.40	15.40
ACZ 15 (islands)					
Dhanikhari	Fluventic Sulfaquults	3.20	3.60	0**	0
Garacharma	Troporthents	0.21	0.21	0	0
Phargaon	Typic Haplustepts	0.84	0.57	0	0
Minicoy 1	Typic Ustipsamments	4.20	2.80	100.00	819.00
Minicoy 2	Typic Tropopsamments	7.40	0	943.00	0
Minicoy 3	Typic Tropofluvents	8.90	0	956.00	0
Minicoy 4	Typic Tropopsamments	18.20	13.20	923.00	945.00

*Soil Survey Staff²⁹.

**Soils which are non-calcareous and do not contribute inorganic carbon show calcium carbonate value as zero.

Table 6. Carbon stock in different ACZs for four different soil depths

Type of carbon	Carbon stock (Pg)				Type of carbon	Carbon stock (Pg)			
	Depth range (m)					Depth range (m)			
	0–0.3	0–0.5	0–1.0	0–1.5		0–0.3	0–0.5	0–1.0	0–1.5
ACZ 1 (Western Himalaya)					ACZ 9 (Western plateau and hills)				
SOC	1.326 (14)*	2.032	3.140	4.387	SOC	0.815 (9)	1.034	1.691	1.376
SIC	0.806 (19)	1.250	4.068	6.763	SIC	0.734 (18)	1.079	3.232	3.063
TC	2.132 (16)	3.282	7.208	11.150	TC	1.549 (11)	2.113	4.923	4.439
ACZ 2 (Eastern Himalaya)					ACZ 10 (Southern plateau and hills)				
SOC	1.792 (19)	2.932	4.626	5.427	SOC	1.002 (10)	1.490	2.580	2.914
SIC	0.024 (1)	0.005	0.025	0.048	SIC	0.763 (18)	1.182	2.810	3.093
TC	1.817 (13)	2.937	4.651	5.475	TC	1.759 (13)	2.662	5.374	5.990
ACZ 3 (Lower Gangetic Plains)					ACZ 11 (East coast plains and hills)				
SOC	0.252 (3)	0.415	0.651	0.785	SOC	0.580 (6)	0.969	1.609	1.983
SIC	0.025 (1)	0.036	0.091	0.145	SIC	0.159 (4)	0.357	0.812	1.103
TC	0.278 (2)	0.451	0.742	0.930	TC	0.738 (5)	1.326	2.421	3.086
ACZ 4 (Middle Gangetic Plains)					ACZ 12 (West coast plains and hills)				
SOC	0.223 (2)	0.359	0.556	0.985	SOC	0.767 (8)	1.115	1.946	2.260
SIC	0.136 (3)	0.438	1.037	1.708	SIC	0.093 (2)	0.161	0.409	0.564
TC	0.359 (3)	0.797	1.593	2.693	TC	0.860 (6)	1.275	2.355	2.823
ACZ 5 (Upper Gangetic Plains)					ACZ 13 (Gujarat plains and hills)				
SOC	0.248 (3)	0.371	0.659	0.968	SOC	0.411 (4)	0.592	1.002	1.056
SIC	0.069 (2)	0.149	0.588	1.151	SIC	0.375 (9)	0.714	2.671	4.490
TC	0.317 (3)	0.521	1.247	2.119	TC	0.786 (6)	1.306	3.673	5.545
ACZ 6 (Trans Gangetic Plains)					ACZ 14 (Western dry)				
SOC	0.170 (2)	0.269	0.442	0.659	SOC	0.142 (1)	0.232	0.318	0.525
SIC	0.173 (4)	0.271	1.175	2.162	SIC	0.475 (11)	0.698	3.011	5.403
TC	0.343 (3)	0.540	1.617	2.821	TC	0.617 (6)	0.931	3.329	5.928
ACZ 7 (Eastern plateau and hills)					ACZ 15 (Islands)				
SOC	0.881 (9)	1.900	2.480	3.484	SOC	0.121 (1)	0.131	0.183	0.371
SIC	0.041 (1)	0.105	0.341	0.591	SIC	0.014 (0.3)	0.025	0.056	0.034
TC	0.922 (7)	2.005	2.822	4.074	TC	0.135 (1)	0.156	0.239	0.405
ACZ 8 (Central plateau and hills)					Total				
SOC	0.825 (9)	1.234	2.157	2.743	SOC	9.550	15.074	24.040	29.920
SIC	0.251 (6)	0.566	2.137	3.666	SIC	4.140	7.036	22.461	33.983
TC	1.076 (8)	1.800	4.294	6.409	TC	13.690	22.110	46.501	63.903

*Values in parentheses indicate percentage of respective stocks, i.e. SOC, SIC and TC. For example, SOC content 1.326 % in ACZ1 is 14% of total SOC of 9.55 (1.326/9.55*100 = 14%).

Proper rehabilitation programmes can make these sodic soils resilient and can thus form an important step for carbon sequestration to improve the soil quality^{5,21,22}.

Plateau and hills

Eastern plateau and hills region (ACZ 7): This zone is formed by five sub-zones: (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 Southwestern Orissa Hills⁷. It covers 13% of the TGA of the country. The soils (Table 3) con-

tribute 9, 1, and 7% of the SOC, SIC and TC stocks of the country respectively (Table 6).

Central plateau and hills region (ACZ 8): This zone comprises 46 districts from Madhya Pradesh (MP), UP and Rajasthan. It has been sub-divided into 14 sub-zones: (i) Bundelkhand (UP), (ii) Bundelkhand (MP), (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,

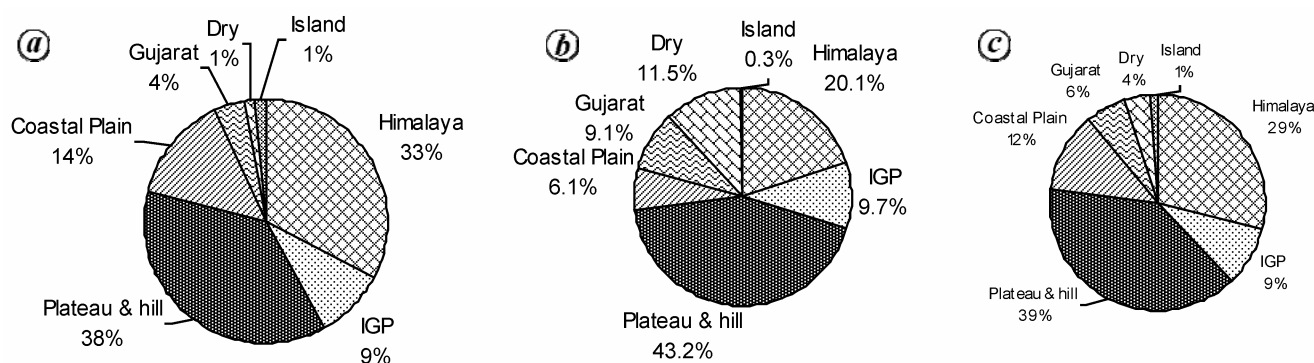


Figure 4. Relative contribution of soil carbon in seven major zones in India. (a) SOC, (b) SIC and (c) TC (fifteen agro-climatic zones (ACZs) were clubbed to seven major zones, namely Himalayas, Indo-Gangetic plains, (IGP), plateau and hill, coastal plains, Gujarat, dry and island).

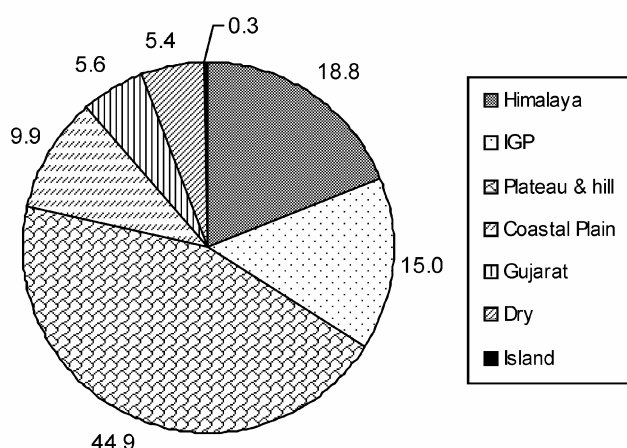


Figure 5. Area (%) occupied by the major (ACZs) of India (fifteen ACZs were clubbed to seven major zones namely Himalayas, IGP, plateau and hill, coastal plains, Gujarat, dry and island).

valleys, and ravines⁷. Nearly 30% of this zone is not available for cultivation. The climate is dry in the western part and sub-humid in eastern part of this zone⁷. It covers 11% of the TGA of the country. The soils (Table 3) contribute 9, 6, and 8% of the SOC, SIC and TC stocks of the country respectively (Table 6).

Western plateau and hills region (ACZ 9): A major part of Maharashtra, part of MP, and one district (Jhalawar) of Rajasthan represent this region. It has been divided into four sub-zones: (i) Hill, (ii) Scarcity, (iii) Plateau north, and (iv) Plateau south⁷. The region occupies 10% of the TGA of the country. The dominant soils (Table 3) contribute 9, 18, and 11% of the SOC, SIC and TC stocks of the country respectively (Table 6).

Southern plateau and hills region (ACZ 10): This region consists of 35 districts of Andhra Pradesh (AP), Karnataka and Tamil Nadu (TN) and cover 12% of the TGA of the country. It has been sub-divided into six sub-zones. The dominant soils (Table 3) contribute 10, 18, and 13% of the SOC, SIC and TC stocks of the country respectively (Table 6).

Four ACZs (7–10) constitute the plateau and hills region. This region occupies nearly 45% of the TGA of the country (Figure 5) and covers the semi-arid tropics (SAT) of the Indian subcontinent. Black soils (vertisols and their intergrades with some inclusions of entisols) are dominant in SAT along with the associated red soils (entisols and alfisols). It has been shown that 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 sites²³. The soils in these hills and plateau are dominated by smectites and smectite-kaolinite minerals^{17,24–28}. This region has maximum reserves of carbon in the soil, which could be due to large areal coverage as well as greater carbon sequestration potential of the soils (38, 43, and 39% SOC, SIC and TC respectively; Figure 4).

Coastal plains

The Indian coasts vary in their characteristics and structures. 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 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% of the TGA of the country (Figure 5).

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 AP, (iii) south coastal AP, (iv) north coastal TN, (v) Tanjavur, and (vi) south coastal TN⁷. The soils (Table 4) contribute 6, 4, and 5% of the SOC, SIC and TC stocks of the country respectively (Table 6).

West coast plains and ghat region (ACZ 12): This zone covers the coastal areas of TN, Kerala, Karnataka, Maharashtra and Goa with different types of vegetation (plantation crops and spices) and soil. It is sub-divided into four sub-zones, namely (i) coastal hill, (ii) coastal midland, (iii) midland, and (iv) hilly⁷ and covers 4% area of the country. The dominant soils (Table 4) contribute 8, 2 and 6% of the SOC, SIC and TC stocks of the country respectively (Table 6).

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) northwest Arid, (vi) north Saurashtra, and (vii) south Saurashtra⁷. It covers 6% of the TGA of the country. The representative soils (Table 4) contribute 4, 9 and 6% of the SOC, SIC and TC stocks of the country respectively (Table 6).

Western dry (ACZ 14): Nine districts of Rajasthan characterized by hot sandy desert, erratic rainfall (average annual rainfall 395 mm) and less vegetation represent this zone. The dominant soils of this zone are: Thar, Shobhasar and Kolu (Table 5). It covers 5.4% of the TGA of the country (Figure 5). The dominant soils (Table 5) contribute 1, 11 and 6% of the SOC, SIC and TC stocks of the country respectively (Table 6).

The islands (ACZ 15): This zone is represented by the Andaman and Nicobar Islands and Lakshadweep, which are typically equatorial with mean annual rainfall of 3000 mm. These two groups of islands, i.e. the Arabian Sea Islands and the Bay Islands differ significantly in origin and physical characteristics. The Arabian Sea islands (Lakshadweep, Minicoy, etc.) are remnants of 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 (Figure 5). The dominant soils (Table 5) contribute 1, 0.34 and 1% of the SOC, SIC and TC stocks of the country respectively (Table 6).

Soil carbon stock in bioclimatic systems

An attempt has been made to generalize the soil carbon storage in each BCS along with a comparison of the storage capacity of other two systems, viz. ACZ and AESR (Table 7). SOC and SIC storage has been reported to be related with climate (temperature and rainfall). The carbon storage values for different zones, subregions and BCS have been collated and shown in Figures 1–3. The arid BCS is characterized by low annual rainfall (<500 mm)⁸. Since these areas do not support dense vegetation, the soils are low in organic carbon. This bioclimate is di-

vided into cold arid and hot arid on the basis of atmospheric temperature¹⁰. Within the cold arid bioclimate, the Ladakh plateau is colder than the north Kashmir Himalayas. Lower atmospheric temperature at subzero levels causing hyper-aridity does not support vegetation, which is in contrast to the western aspect of the Ladakh plateau and the north Kashmir Himalayas. This may be the reason why the cold arid bioclimate contains more SOC stock (part of ACZ 1 and AESRs 1.1, 1.2, Table 7). The arid bioclimate covers 15.8% of the TGA, with a share of about 11% of the total SOC stock (Table 7). It is interesting to note that the cold arid bioclimate constituting 29% of the total arid ecosystem of the country has a share of 60% of total SOC stock of the 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 7). The arid bioclimate has SIC stock of 1.7 Pg in the first 30 cm depth of soil (Table 7), out of which 0.7 Pg is contributed by cold and 1.0 Pg by the hot arid ecosystem (Figure 4).

Semi-arid bioclimate consists of major parts of the central and south peninsula, which extends up to the western and northwestern parts of the country and comprises 17 AESRs and 7 ACZs (Table 7). By and large, temperature in the semi-arid bioclimate ranges from 25°C to 27°C and mean annual rainfall 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 bioclimate is 2.9 Pg, which is nearly 30% of the total SOC stock of the country (Table 7). Semi-aridity helps in the formation of pedogenic CaCO₃ which is the source of 1.9 Pg SIC stock with a share of 47%. TC stock of semi-arid bioclimate has been established as 4.8 Pg, which is 35% of the TC stock of the country.

Calcium carbonate in calcic horizons²⁹ has been reported to be generated by two processes^{17,30}. First, carbonates may be physically derived from the rocks that act as a source of the soil or may be brought into the region by wind transport. Recrystallization may lead to the incorporation of atmospheric or soil CO₂, but the same amount of fossil CO₂ is liberated and the net balance for the carbon cycle is zero³⁰. These may be geogenic or non-pedogenic carbonates (NPCs)¹⁷. By the second process^{17,30}, 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 CO₂. The pedogenic carbonates (PCs) act as a sink³⁰ for CO₂. In many areas of southwestern United States³¹ and the Deccan Plateau¹⁷, non-calcareous alluvium, including calcium-rich basaltic parent material is common. In such areas, calcium from the soil exchanger deposited as carbonate in the basaltic alluvial soils represents a sink for carbon from the atmosphere³¹. Calcic horizons potentially represent the residue from large volumes of parent rock and may represent

RESEARCH ARTICLES

Table 7. Soil carbon stocks in different bioclimatic systems (BCS), ACZs and agro-ecosubregions (AESRs) of India

BCS*	ACZ**	AER (AESR)***	Area		SOC		SIC		TC		Pg/mha	
			Coverage (mha)	TGA (%)	Stock	Percentage of total SOC	Stock	Percentage of total SIC	Stock	TC	Percentage of total	
											SOC	SIC
Arid cold	1 (45%)	1 (1.1, 1.2)	15.2	4.6	0.6	6	0.7	17	2.7	20	0.0192	0.0327
Arid hot	6 (40%), 10 (30%), 14 (100%)	2 (2.1, 2.2, 2.3, 2.4), 3	36.8	11.2	0.4	4	1.0	25				
Semi arid	5 (75%), 6 (35%), 9 (100%), 10 (70%), 11 (30%), 12 (30%), 13 (100%)	4 (4.1, 4.2, 4.3, 4.4), 5 (5.1, 5.2, 5.3), 6 (6.1, 6.2, 6.3, 6.4), 7 (7.1, 7.2, 7.3), 8 (8.1, 8.2, 8.3)	116.4	35.4	2.9	30	1.9	47	4.8	35	0.0249	0.0163
Sub humid	2 (45%), 3 (25%), 4 (100%), 5 (25%), 6 (25%), 7 (100%), 8 (100%)	9 (9.1, 9.2), 10 (10.1, 10.2, 10.3, 10.4), 11, 12 (12.1, 12.2, 12.3), 13 (13.1, 13.2), 14 (14.1, 14.2)	105.0	31.9	2.5	26	0.3	8	2.8	20	0.0238	0.0029
Humid to per humid	1 (55%), 2 (55%), 3 (75%)	14 (14.3, 14.5, 14.5), 15 (15.1, 15.2, 15.3, 15.4), 16 (16.1, 16.2, 16.3), 17 (17.1, 17.2)	34.9	10.6	2.1	21	0.04	1	2.14	15	0.0602	0.0011
Coastal	11 (70%), 12 (70%), 15 (100%)	18 (18.1, 18.2, 18.3, 18.4, 18.5), 19 (19.1, 19.2, 19.3), 20 (20.1, 20.2)	20.4	6.2	1.3	13	0.07	2	1.37	10	0.0637	0.0034

*Ranges in rainfall: Arid, <550 mm; Semi-arid, 550–1000 mm; Sub-humid, 1000–1500 mm; Humid to per humid, 1200–3200 mm; Coastal, 900–3000 mm.

**Values in parentheses show areas of BCS matching with ACZs. For example, 45% ACZ1 falls in arid cold while the remaining 55% matches with humid to per humid BCS. For a few ACZs (14, 6, 13, 7, 8 and 15) 100% area matches with arid hot, semi-arid, sub-humid and coastal bioclimatic system respectively.

***Values in parentheses show the AESRs. For example, arid cold BCS is represented by AER1 or by AESRs 1.1 and 1.2.

several metres of thickness. Large amounts of PC are stored in soils¹⁷, withdrawing CO₂ 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 sub-humid zones with relatively good amount of water available for chemical weathering, more PCs are formed. Efforts were made to quantify the amount of PC over time, which might indicate the amount of atmosphere/soil CO₂ sequestered by soil as inorganic form.

The rate of formation of calcium carbonate varies for soils depending on soil type and the zones represented by these soils. The representative soils of the IGP indicate 0.86 mg/100 g soil/yr of CaCO₃ formation. The black soils of central and western India register a range of 0.39 mg/100 g soil/yr to 2.12 mg/100 g soil/yr, while the ferruginous calcareous soils of southern India indicate a value of 0.20 mg/100 g soil/yr^{17,22}.

The sub-humid bioclimate comprises 14 AESRs and 5 ACZs (Table 7). This ecosystem is characterized by transitional climatic phase between humid and semi-arid. The average annual temperature of this bioclimate is 22–29°C, with mean annual rainfall of 900–1700 mm. This bioclimate covers a major part of the IGP and parts of the southern peninsula. Most of these areas are rich in vegetation and therefore SOC content of these soils is relatively high compared to 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 (Table 7). It has been reported that barring a few exceptions, the sub-humid and humid bioclimates do not contain calcium carbonate in the soils due to high rainfall¹⁶. The sub-humid bioclimate contains a meagre amount of 0.3 Pg SIC stock constituting only 8% of total SIC reserves of the country. The relative contribution of SOC (89%) and SIC (11%) stocks indicates the effect of more rainfall in building up of high SOC stock in this bioclimate.

The humid to per-humid bioclimatic system covers 34.9 mha area (11% of TGA). In the first 30 cm depth of the soil the SOC stock is estimated as 2.1 Pg, which is 2% of the total SOC stock (Table 7). Many areas of this bioclimate are covered by Arunachal Pradesh, Meghalaya, Mizoram, Manipur and the hilly areas of Tripura (2 ACZs; 12 AESRs; Table 7) where cooler winter months and higher rainfall have helped in higher SOC stock^{6,14,32}. The dominant soils in this bioclimate are non-calcareous, as is reflected by their contribution of a meagre 1% SIC stock of the country. It is interesting to note that ACZ 2 is represented by a few soils which contain CaCO₃. Presence of inorganic carbon in the soils of this bioclimate characterized by high rainfall indicates that this CaCO₃ is non-pedogenic¹⁷. TC in this bioclimate is 2.14 Pg (15% of TC stock of the country), of which 98% is contributed by SOC (Table 7).

The coastal BCS covers an area of 20.403 mha (6.2% of TGA). The SOC stock (1.3 Pg) of this system contributes 13% of the total SOC stock. This system is represented by 10 AESRs and 3 ACZs (Table 7). Total SIC stock of the coastal bioclimate has been estimated as 0.07 Pg, which represents 2% of the total SIC stock. In general, soils in the coastal bioclimate do not contain carbonates. However, there are exceptions like the soils of Kalathur, Thirunallur, Sali and Minicoy^{6,10,33}. Since SIC stock depends on the extent of geographical distribution of soils, the total SIC stock remains, however, low in spite of presence of carbonates in some of the soils.

Prioritizing areas for carbon sequestration in soils

Carbon stock in soil depends largely on the aerial extent of the soils besides other factors such as carbon content, depth and, BD of soils. Even with a relatively small SOC content (0.2–0.3%), the SOC stock of arid and semi-arid systems indicates a high value. This is due to a large area of the dry tracts. Therefore, the carbon stock per unit area (Pg/mha) should ideally be considered to identify the influence of soil and/or management parameters for carbon sequestration in the soils. A threshold value of 0.03 Pg SOC/mha has been found to be effective in finding out a system (agriculture, horticulture, forestry) which sequesters sizeable quality of organic carbon in the soils³⁴.

Criteria such as SOC stock per unit area as well as point data for individual soils indicate that vast areas in the arid (AESR 3, part of ACZ 10), semi-arid and drier parts of the sub-humid BCS (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; Table 7) of the subcontinent are low in SOC and high in SIC stock (0–1.5 m soil depth, Table 6; 0–0.3 m soil depth, Figure 4) and thus should get priority for organic carbon management. The total prioritized area has been worked out as 155.8 mha (arid: 49 mha, semi-arid: 116.4 mha and sub-humid: 34.5 mha; Table 7; Figure 3).

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 loss³⁵. After each change in the land use system, a period of constant management is required to reach a new quasi-equilibrium stage. In this way the SOC is stabilized to another quasi-equilibrium value characteristic of that changed situation in terms of new land-use pattern, vegetation cover and management practice. It has been reported that increase of 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). All these soils are dominated by smectites¹⁷. Presence of smectite also results in improving substrate quality so important for carbon sequestration in the soil. Recent studies have indicated that smectite-rich black soils could sequester 2–3% organic carbon^{32,36}. 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% 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 (Figure 3). Recent studies³⁷ on changes of carbon in the soils of the SAT have shown that over a period of nearly 25 years, SOC stock has increased from 34 to 118%. This has been possible due to adoption of the management intervention³⁷. Thus appropriate management interventions in maintaining the capability of productive soils and also to raise the productivity of less productive soils, are capable of enhancing organic carbon storage capacity of Indian soils. Such management interventions have helped in the dissolution of native SIC (CaCO₃) due to increase in pCO₂ in the soil and contribute partly to the overall pool of SOC following the C transfer model²¹ that works better in the drier parts of the country. This pathway of C transfer from inorganic (atmospheric CO₂) to organic (CH₂O) and organic (CH₂O) to inorganic (CO₂ in soil and then to CaCO₃), 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.

Conclusion

Although the unique role of soils as a potential substrate in mitigating the effects of atmospheric CO₂ has been conceived^{31,38}, the present study indicates the sequestration of atmospheric CO₂ in the form of SIC (pedogenic carbonate) and its subsequent important role in enhancing SOC in the drier parts of the country through management interventions. The study also points out the fact that the soil can act as a potential medium for CCS. This tool (thematic maps on soil C stock) may help planners in pri-

oritizing C sequestration programmes in different dry BCS representing various ACZs and AESRs.

1. Anon., Carbon capture and geological storage, 2007; http://www.naturalsciencesbe/pss_css/Public/carbon_capture
2. Goel, M., Carbon capture and storage technology for sustainable energy future. *Curr. Sci.*, 2007, **92**, 1201–1202.
3. Jenny, H. and Raychaudhuri, S. P., Effect of climate and cultivation on nitrogen and organic matter reserves in Indian soils. ICAR, New Delhi, 1960, p. 126.
4. Dadhwal, V. K. and Nayak, S. R. I., A preliminary estimate of biogeochemical cycle of carbon for India. *Curr. Sci.*, 1993, **59**, 9–13.
5. Gupta, R. K. and Rao, D. L. N., Potential of wastelands for sequestering carbon by reforestation. *Curr. Sci.*, 1994, **66**, 378–380.
6. Velayutham, M., Pal, D. K. and Bhattacharyya, T., Organic carbon stock in soils of India. In *Global Climate Change and Tropical Ecosystems* (eds Lal, R., Kimble, J. M. and Stewart, B. A.), Lewis Publishers, FL, USA, 2000, pp. 71–95.
7. Anon., Agro-climatic regional planning (an overview). Planning Commission, Government of India, New Delhi, 1989, p. 144.
8. Bhattacharjee, J. C., Roychaudhuri, C., Landey, R. J. and Pandey, S., Bioclimatic Analysis of India, NBSS&LUP Bull No. 7, Nagpur, 1982, p. 21.
9. Sehgal, J. L., Mandal, D. K., Mandal, C. and Vadivelu, S., Agro-Ecological regions of India, NBSS&LUP, Bull No. 24, Nagpur, 1999, p. 130.
10. Velayutham, M., Mandal, D. K., Mandal, C. and Sehgal, J., Agro-ecological sub-regions of India for development and planning. NBSS&LUP, Nagpur, Publ. 35, 1999, p. 452.
11. Jackson, M. L., *Soil Chemical Analysis*, Prentice Hall of India Pvt Ltd, New Delhi, 1973, p. 498.
12. Bhattacharyya, T., Das, T. A., Dubey, P. N., Baruah, U., Gangopadhyay, S. K. and Dileep Kumar, Soil Survey Report of Morigaon district, Assam (1:50,000 scale). NBSS&LUP, Regional Centre, Jorhat, No. 1995, p. 527.
13. Bhattacharyya, T., Sehgal, J. L. and Sarkar, D., Soils of Tripura for optimising land use: Their kinds, distribution and suitability for major field crops and rubber. NBSS&LUP Publ. 65 (Soils of India Ser. 6), Nagpur, 1996, p. 154.
14. Bhattacharyya, T., Pal, D. K., Velayutham, M., Chandran, P. and Mandal, C., Total carbon stock in Indian soils: Issues, priorities and management. In *Land Resource Management for Food, Employment and Environment Security*, ICLRM, New Delhi, 2000, pp. 1–46.
15. Murthy, R. S. *et al.* (eds), *Benchmark Soils of India*, NBSS&LUP, Nagpur, 1982, p. 374.
16. Lal, S., Deshpande, S. B. and Sehgal, J., *Soil Series of India*, NBSS&LUP, Nagpur, 1994, p. 684.
17. Pal, D. K., Dasog, G. S., Vadivelu, S., Ahuja, R. L. and Bhattacharyya, T., Secondary calcium carbonate in soils of arid and semiarid regions of India. In *Global Climate Change and Pedogenic Carbonates* (eds Lal, R. *et al.*), Lewis Publishers, FL, USA, 2000, pp. 149–185.
18. Eswaran, H., Reich, P. F., Kimble, J. M., Beinroth, F. H., Padmanabhan, E. and Moncharoen, P., In *Global Climate Change and Pedogenic Carbonates* (eds Lal, R. *et al.*), Lewis Publishers, FL, USA, 1999, pp. 15–25.
19. Cerri, C. E. P. *et al.*, Predicted soil organic carbon stocks and changes in the Brazilian Amazon between 2000 and 2030. *Agric. Ecosyst. Environ.*, 2007, **122**, 58–72.
20. Bhattacharyya, T. *et al.*, Modelled soil organic carbon stocks and changes in the Indo-Gangetic Plains, India from 1980 to 2030. *Agric. Ecosyst. Environ.*, 2007, **122**, 84–94.
21. Bhattacharyya, T., Pal, D. K., Chandran, P., Mandal, C., Ray, S. K., Gupta, R. K. and Gajbhiye, K. S., Managing soil carbon stocks in the Indo-Gangetic Plains, India. Rice–Wheat Consortium for the Indo-Gangetic Plains, New Delhi, 2004, p. 44; <http://www.rwc-cgiar.org> and <http://www.cimmyt.org>.
22. Pal, D. K., Bhattacharyya, T., Ray, S. K., Chandran, P., Srivastava, P., Durge, S. L. and Bhuse, S. R., Significance of soil modifiers (Ca-zeolites and gypsum) in naturally degraded Vertisols of the Peninsular India in redefining the sodic soils. *Geoderma*, 2006, **136**, 210–228.
23. Poonia, S. R. and Niederbudde, E. A., Exchange equilibria of potassium in soils, V. Effect of natural organic matter on K–Ca exchange. *Geoderma*, 1990, **47**, 233–242.
24. Bhattacharyya, T., Pal, D. K. and Deshpande, S. B., Genesis and transformation of minerals in the formation of red (Alfisol) and black (Inceptisols and Vertisols) soils on Deccan basalt in the Western Ghats, India. *J. Soil Sci.*, 1993, **44**, 159–171.
25. Pal, D. K. and Deshpande, S. B., Genesis of clay minerals in a red and black complex soils of southern India. *Clay Res.*, 1987, **6**, 6–13.
26. Pal, D. K. and Deshpande, S. B., Characteristics and genesis of minerals in some benchmark Vertisols of India. *Pedologie*, 1987, **37**, 259–275.
27. Pal, D. K., Deshpande, S. B., Venugopal, K. R. and Kalbande, A. R., Formation of di- and trioctahedral smectite as an evidence for paleoclimatic changes in southern and central Peninsular India. *Geoderma*, 1989, **45**, 175–184.
28. Chandran, P., Ray, S. K., Bhattacharyya, T., Krishnan, P. and Pal, D. K., Clay minerals in two ferruginous soils of southern India. *Clay Res.*, 2000, **19**, 77–84.
29. Soil Survey Staff, *Keys to Soil Taxonomy*, United States Department of Agriculture, Natural Resources Conservation Service, Washington DC, 2003, 9th edn.
30. Elberson, G. W. W., Davies, G. R., Van Recuwijk and Janssen, R. P. T., Quantification of the incorporation of atmospheric CO₂ in calcic horizons. In *Global Climate Change and Pedogenic Carbonates* (eds Lal, R. *et al.*), Lewis Publishers, FL, USA, 2000, pp. 87–95.
31. Schlesinger, W. H., Carbon storage in the caliche of arid soils: A case study of Arizona. *Soil Sci.*, 1982, **133**, 247–255.
32. Bhattacharyya, T., Pal, D. K., Lal, S., Chandran, P. and Ray, S. K., Formation and persistence of Mollisols on zeolitic Deccan basalt of humid tropical India. *Geoderma*, 2006, **136**, 609–620.
33. Vadivelu, S. and Bandyopadhyay, A. K., Characteristics, genesis and classification of soils of Minicoy Island, Lakshadweep. *J. Indian Soc. Soil Sci.*, 1997, **45**, 796–800.
34. Bhattacharyya, T. *et al.*, Carbon sequestration in red and black soils III. Identifying systems through carbon stock and bulk density of soils. *Agropedology*, 2007, **17**, 26–34.
35. Batjes, N. H., Options for increasing carbon sequestration in West African soils: An exploratory study with special focus on Senegal. *Land Degrad. Dev.*, 2001, **12**, 131–142.
36. Dalal, R. C. and Conter, J. U., Soil organic matter dynamics and carbon sequestration. In *Australian Tropical Soils* (eds Lal, R., Kimble, J. M. and Stewart, B. A.), Lewis Publishers, FL, USA, 2000, pp. 283–314.
37. Bhattacharyya, T., Chandran, P., Ray, S. K., Pal, D. K., Venugopalan, M. V., Mandal, C. and Wani, S. P., Changes in levels of carbon in soils over years of two important food production zones of India. *Curr. Sci.*, 2007, **93**, 1854–1863.
38. Batjes, N. H., Management options for reducing CO₂ 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, 1999.

Received 31 December 2007; revised accepted 2 July 2008