Changes in levels of carbon in soils over years of two important food production zones of India

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It is realized that the carbon content in soils changes depending on the land use system and time. There is an increasing concern about the decline in soil productivity and the impoverishment of soil organic carbon (SOC) caused by intensive agriculture. The National Bureau of Soil Survey and Land Use Planning, Indian Council of Agricultural Research, through organized research initiatives, sponsored by national and international organizations, has developed datasets SOC and soil inorganic carbon (SIC) for two important crop production zones, viz. the Indo-Gangetic Plains and the black soil region in the semi-arid tropics. The datasets for 1980 and 2005 indicate an overall increase in SOC stock in the Benchmark spots under agriculture, practised for the last 25 years, although the level of SIC has increased indicating an initiation of chemical degradation. This suggests that the agricultural management practices advocated through the national agricultural research system for the last 25 years did not cause any decline in SOC in the major crop-growing zones of the country.

Keywords: Agriculture, carbon, food production zone, soil.

SOILS represent the largest terrestrial stock of C. The first 30 cm of soil holds 1500 Pg C in the world[1] and 9 Pg C in India[2]. Changes in terrestrial C stocks can be of both regional and global significance and may contribute significant amounts of CO_2 emissions and therefore be linked to climate change. Decline in soil organic carbon (SOC) has major implications for the maintenance of soil health.

The major concern over carbon dynamics in soils has triggered many research attempts in India and elsewhere[1–6]. Intensive cultivation during the green and post-green revolution era of Indian agriculture has resulted loss in soil carbon amidst widespread degradation in natural resources and nutrients[7–10]. The Vision 2020 document of the Government of India[11] envisages a production level of rice and wheat as 207 and 173 million tonnes after giving due consideration to biophysical factors restricting crop production. The reports of decline in SOC and the consequent adverse impacts on productivity require research back-up of a sound resource base. This necessitates taking stock of soil carbon at different time intervals. This will provide an essential tool and benchmarks for monitoring the quality of management interventions to sustain the agricultural productivity of the country.

The National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) of Indian Council of Agricultural Research (ICAR), through an organized research initiative sponsored by the National Agricultural Technology Project (NATP) and Global Environment Facility Soil Organic Carbon (GEFSOC), monitored changes in soil carbon between 1980 and 2005 in two important food production zones of India. We present the results of changes in organic and inorganic forms of soil carbon due to agricultural land uses adopted for the last 25 years.

The food production zones studied were the Indo-Gangetic Plains (IGP), India and black and associated red (BSR) soils. A total 13 and 9 benchmark (BM) spots were selected in 1980 in the IGP and BSR respectively[12,13] (Figure 1). Tables 1 and 2 show the agricultural land-use information of these BM spots. However, detailed information is reported elsewhere[12–18]. We sampled soils from these BM spots again during 2005 using Global Positioning System (GPS), for further observation.

The horizon-wise soil samples were collected after examining the profiles following standard methods[19,20]. The soil samples were air-dried and sieved (<2 mm) before analyses. Samples from each horizon were analysed; however, to express data in 0–30, 0–50, 0–100 and 0–150 cm, the weighted mean averages were considered.

The soils were analysed for SOC using the method of Walkley and Black[21]. The inorganic carbon was calculated from the content of $CaCO_3$ equivalent that was determined by acid-base titration method[22]. The bulk density (BD) was determined by a field-moist method using core samples (dia 50 mm) of known volume (100 cubic cm)[23]. The size of carbon stock was calculated following methods described by Batjes[1]. The carbon content was expressed in terms of Tg (1 Tg = 10^{12} g).

Carbon stock in the soil depends largely on the areal extent besides other factors such as carbon content, depth and BD of the soil. Even with a relatively small amount of SOC (0.2–0.3%), the arid and semi-arid tracts showed high SOC stock[2] due to large areal extent of these two bioclimatic systems. To avoid such illusion, here the carbon stock changes have been expressed per unit area (Tables 3 and 4) to interpret the influence of soil and/or a management parameters for sequestration of both organic and inorganic carbon in the soil[2,18]. The SOC tend to attain quasi-equilibrium (QE) values with varying duration of 500–1000 years in a forest system[24,25], 30–50 years in agricultural systems after forest cutting[26], 5–15 years in agricultural systems after forest cutting in red soils of Orissa, India[27], and 20–50 years under different agricultural systems with cotton for 20 years, with cotton and pigeonpea

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Table 1. Description of benchmark spots in the Indo-Gangetic Plains (IGP)

Serial no	Soil series (district/state)	Soil classification: US taxonomy*	Soil classification: WRBSR**	Land use: 1980	Land use: 2005	Locations (latitude and longitude)***: 1980	Locations (latitude and longitude)***: 2005
IGP1	Masitawali (Hanumangarh/ Rajasthan)	Typic Torripsam-ments	Yermic Fluvisols	Cotton/wheat/**** sugarcane/ chickpea	Cotton–wheat/ mustard	Rawatsar village, Hanumangarh Tah. and Dist., Rajasthan (29°15′N; 74°20′E)	Chowk-Bara, Rawat-sar, Hanumangarh, Dist., Rajasthan (29°15′33.3″N; 74°21′30″E)
IGP2	Phaguwala (Sangrur/Punjab)	Calcic Udertic Haplustalfs	Calcic-Sodic Luvisols	Wheat/maize–rice/ sugarcane	Rice–wheat/ mustard	Phaguwala, Sangrur Tah. and Dist. Punjab (30°14′N; 75°59′E)	Phaguwala, Bhawani-garh, Sangrur, Dist. Punjab, (30°15′6.5″N; 75°59°35.7″E)
IGP3	Ghabdan (Patiala/Punjab)	Vertic Haplustalfs	Gleyic Solo-netz	Rice–berseem/ wheat	Rice/wheat/ mustard/ onion/garlic/ cauliflower	Ghabdan (12.5 km from Sangrur), Sangrur Tah. and Dist., Punjab (30°15′N; 75°58′E)	Ghabdan, Sangrur, Tah and Dist., Punjab (30°15′42″N; 75°58′E)
IGP4	Bhanra (Patiala/Punjab)	Typic Ustipsam-ments	Yermi-Protic Arenosol	Groundnut/ pearlmillet/ sesame	Rice–wheat/ mustard/ potato/onion/ garlic	0.5 km right of Ghaggar Canal, Mathas village, Patiala, Dist., Punjab (30°16′N; 76°18′E)	Bhanra, Patiala Tah. and Dist., Punjab (30°15′47″N; 76°18′0.1″E)
IGP5	Zarifa Viran (Karnal/Haryana)	Typic Natrustalfs	Calcic Solo-netz	Barren	Rice–wheat/ mustard	CSSRI Farm/village Gudha, Karnal Tah. and Dist., Haryana (29°25′N; 76°55′E)	Karnal village Tah. and Dist., CSSRI Farm, Haryana (29°42′50.5″N; 76°57′14.3″E)
IGP6	Sakit (Etah/Uttar Pradesh (UP))	Typic Natrustalfs	Haplic Solo-netz	Barren	Rice–wheat	Ramgarhi, Hasanpur Jalesar Tah., Etah Dist., UP (27°29′N; 78°18′E)	Ramgarhi, Jalesar, Etah Dist., UP (27°28′54″N; 78°20′30″E)
IGP7	Dhadde (Kapurthala/ Punjab)	Oxyaquic vertic Haplustalfs	Verti-Gleyic Luvisols	Sugarcane/rice–berseem/ wheat	Rice–wheat (2 yrs)/ sugarcane (2 yrs)	Jagjitpur, Phagwan, Kapurthala Dist., Punjab (31°16′40″N; 75°48′50″E)	Dhadde, Phagwana, Kapurthala, Dist., Punjab (31°16′31.2″N; 75°48′6.2″E)
IGP8	Jagjitpur (Kapurthala/ Punjab)	Oxyaquic vertic Haplustalfs	Verti-Gleyic Luvisols	Rice–wheat	Rice–wheat	Jagjitpur, Phagwan, Kapurthala, Dist., Punjab (31°19′10″N; 75°46′34″E)	Jagjitpur, Phawana, Kapurthala, Dist., Punjab (31°19′10.7″N; 75°48′10.3″E)
IGP9	Fatehpur (Ludhiana/ Punjab)	Typic Haplustepts	Eutri-Haplic Arenosols	Groundnut/ maize/ pearl-millet- wheat	Rice–wheat	PAU Farm, Ludhiana, Ludhiana Dist., Punjab (30°54′N; 75°52′E)	PAU Farm, Ludhiana Dist., Punjab (30°54′17.8″N; 75°47′4.6″E)
IGP10	Haldi (Udham-singhnagar/ UP)	Typic Haplustalfs	Hyposodi-Haplic Luvisols	Maize/soybean–wheat	Maize–wheat	No. H1 Crop Res. Centre, G.B. Pant Univ. of Agric. and Technol., Pant-nagar, Nainital, UP (29°01′20″N; 79°29′20″E)	G.B. Pant Univ. of Agric. and Technol., Pantnagar, Kichha, Udam Singh Nagar Dist., Uttarakhand (29°01′23″N; 79°28′56″E)
IGP11	Hanrgram (Barddhaman/ West Bengal (WB))	Vertic Endoaqualfs	Verti-Endo-Gleyic Luvisols	Rice–wheat	Rice–rice	Shyamsundarpur, Barddhaman, WB (23°14′N; 87°56′E)	Baliuara, Shyamsundarpur, Barddhaman, WB (23°14′39″N; 87°55′56″E)

(Contd.)

Table 1. (*Contd.*)

Serial no	Soil series (district/state)	Soil classification: US taxonomy*	Soil classification: WRBSR**	Land use: 1980	Land use: 2005	Locations (latitude and longitude)***: 1980	Locations (latitude and longitude)***: 2005
IGP12	Madhpur (Barddhaman/WB)	Chromic Vertic Hapludalfs	Verti-Chromic Luvisols	Rice/jute–pulses/oilseeds	Rice–mustard/potato–rice	Madhpur, Barddhaman, WB (23°25′30″N; 88°02′30″E)	Madhpur, Anchal-Nishikgaram, Barddhaman, WB (23°25′14.4″N; 88°02′10″E)
IGP13	Sasanga (Barddhaman/WB)	Chromic Vertic Hapludalfs	Verti-Chromic Luvisols	Rice–wheat	Rice–potato/wheat/mustard–rice	Sasanga, Khandaghosh, Barddhaman, WB (23°17′N; 87°44′E)	Sasanga, Kandaghosh, Barddhaman, WB (23°13′15.5″N; 87°46″56″E)

*Soil taxonomy (Soil Survey Staff, 1975) was updated and revised (Soil Survey Staff, 2003).
**World Reference Base for Soil Resources (1998).
***To reach the exact BM spot, the location of the village was taken as standard, keeping in view the landform as well as the soil (US soil taxonomy), since latitude and longitude for BM spots reported in 1980 were, at places, not precisely mentioned.
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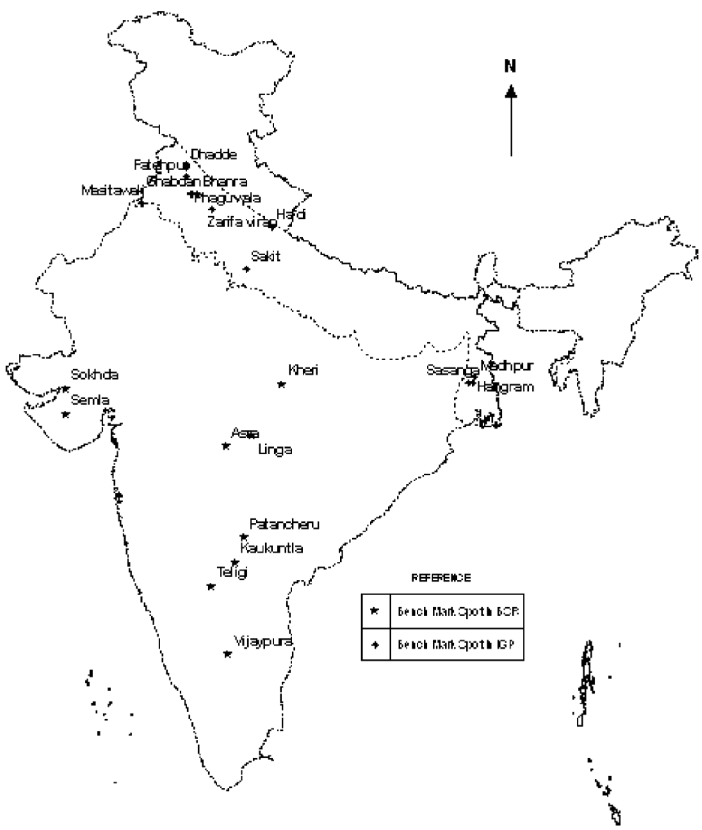

Figure 1. Study area showing benchmark spots in the Indo-Gangetic Plains and black soil region.

for 50 years and horticultural system (citrus) for 30 years[28]. Our observations in two time periods (viz. 1980 and 2005) capture the changes in carbon stock over the last 25 years. Judging by the time required to reach the QE stage for the agricultural system, it may be presumed that the soils under study had reached the QE stage after 25 years.

Table 3 shows the changes in carbon stock of the selected BM spots in the IGP, over two different time periods, namely 1980 and 2005. Although the soil samples were collected at a different periods from 1969 to 1989, 1980 was taken as the base year to report for carbon stock, whereas 2005 was considered as the year of revisit. In the semi-

Table 2. Description of benchmark spots in the black soil regions

Serial no.	Soil series (district/State)	Soil classification: US taxonomy (taxonomy updated)*	Soil classification: WRBSR**	Land use: 1980	Land use: 2005	Location (latitude and longitude)***: 1980	Location (latitude and longitude)***: 2005
BSR1–P27	Kheri (Jabalpur/ Madhya Pradesh (MP))	Typic Haplusterts	Haplic Vertisols	Rice–wheat/**** chickpea	Rice–wheat	JNKVV Res. Farm (previously), Kheri village, Jabalpur Tah. and Dist., MP (23°10′N; 79°57′E)	Presently the land belongs to NRCWS Res. Farm, Jabalpur Tah. and Dist., MP (23°10′53″N; 79°51′19″E)
BSR2–P3	Linga (Nagpur/ Maharashtra)	Typic Haplusterts	Haplic Vertisols	Citrus	Citrus	Regional Fruit Research Station Farm, Wandli, Katol, Nagpur Tah. and Dist., Maharashtra (21°06′N; 79°03′E)	Regional Fruit Research Station, Wandli Katol, Nagpur Dist., Maharashtra (21°15′18″N; 78°36′40″E)
BSR3–P10	Asra (Amravati/ Maharashtra)	Typic Haplusterts	Haplic Vertisols	Sorghum/ peanut–chickpea/ wheat	Cotton/ greengram +pigeonpea	Asra village, Bahtkuli Tah., Amravati Dist., Maharashtra (21°08′20″N; 77°30′0″E)	Asra, village, Bahtkuli, Amravati Dist., Maharashtra (20°52′42″N; 77°29′12″E)
BSR4–P29	Semla (Rajkot/ Gujarat)	Typic Haplusterts	Haplosodic Vertisols	Cotton/sorghum/ wheat/soybean/ chickpea	Cotton/peanut – wheat	Semla, Gondal Tah., Rajkot Dist., Gujarat (22°03′N; 70°48′E)	Semla, Gondal, Tah., Rajkot Dist., Gujarat (22°01′59″N; 70°48′22″E)
BSR5–P43	Teligi (Bellary/ Karnataka)	Sodic Haplusterts	Endosodic Vertisols	Jowar, cotton	Rice–rice	Siruguppa Farm, Bellary Dist., Karnataka (15°38′N; 76°54′E)	Research Farm, UAS Dharwad, Siruguppa, Bellary Dist., Karna-taka (15°37′4″N; 76°54′35″E)
BSR6–P31	Sokhda (Rajkot/ Gujarat)	Sodic Haplusterts	Sodic Vertisols	Cotton–wheat/ sugarcane/ peanut	Cotton–pearl-millet/sesame	Sokhda, Morbi Tah., Rajkot, Dist., Gujarat (23°03′N; 70°48′E)	Sokhda, Morbi Tah., Rajkot Dist., Gujarat (23°02′19″N; 70°47′30″E)
BSR7–P17	Vijaypura (Bangalore/ Karnataka)	Typic Rhodustalfs	Rhodic Luvisols	Pigeonpea/ beans/sorghum/ peanut	Finger millet/ pigeonpea/ redgram/ peanut	Plot No. 16, GKVK Farm, UAS Banga-lore, Kodihalli vil-lage, Bangalore Tah. and Dist., Karnataka (13°24′N; 77°35′E)	Plot No. 16, GKVK Farm, UAS Bangalore, Karnataka (13°05′02″N; 77°34′25″E)
BSR8–P34	Kaukuntla (Mehboobnagar/ Andhra Pradesh (AP))	Vertic Haplustalfs	Vertic Luvisols	Sorghum/finger millet/peanut–pigeonpea/ castor	Castor, pigeonpea	Kaukuntla, Mahboob-nagar Tah. and Dist., AP (16°31′20″N; 75°51′50″E)	Kaukuntla, village Atmakur, Mehboobnagar Dist., AP (16°31′42″N; 77°51′19″E)
BSR9–P41	Patancheru (Medak/AP)	Typic Rhodustalfs	Rhodic Luvisols	Sorghum + pulses (1978–93)	Fallow (since 1993)	ICRISAT Res. Farm, Patancheru village, Medak Dist., AP (17°35′N; 78°50′E)	ICRISAT Research Farm, Patancheru, Sangareddy, Medak Dist., AP (17°28′36″N; 78°16′54″E)

*Soil taxonomy (Soil Survey Staff, 1975) was updated and revised (Soil Survey Staff, 2003).
**World Reference Base for Soil Resources (1998); /, Either, or.
***To reach the exact BM spot, the location of the village was taken as standard, keeping in view the landform as well as the soil (US soil taxonomy), since latitude and longitude for BM spots reported in 1980 were, at places, not precisely mentioned.
****Means, either, or.

arid bioclimatic system of the IGP, the SOC stock has increased from 30% to 395% since 1980. The soil inorganic carbon (SIC) stock has increased only in Phaguwala. In Fatehpur and Dhadde soils, $CaCO_3$ (SIC) was not detected during 1980s but in 2005 both field and laboratory examination indicated the presence of $CaCO_3$ in these sites

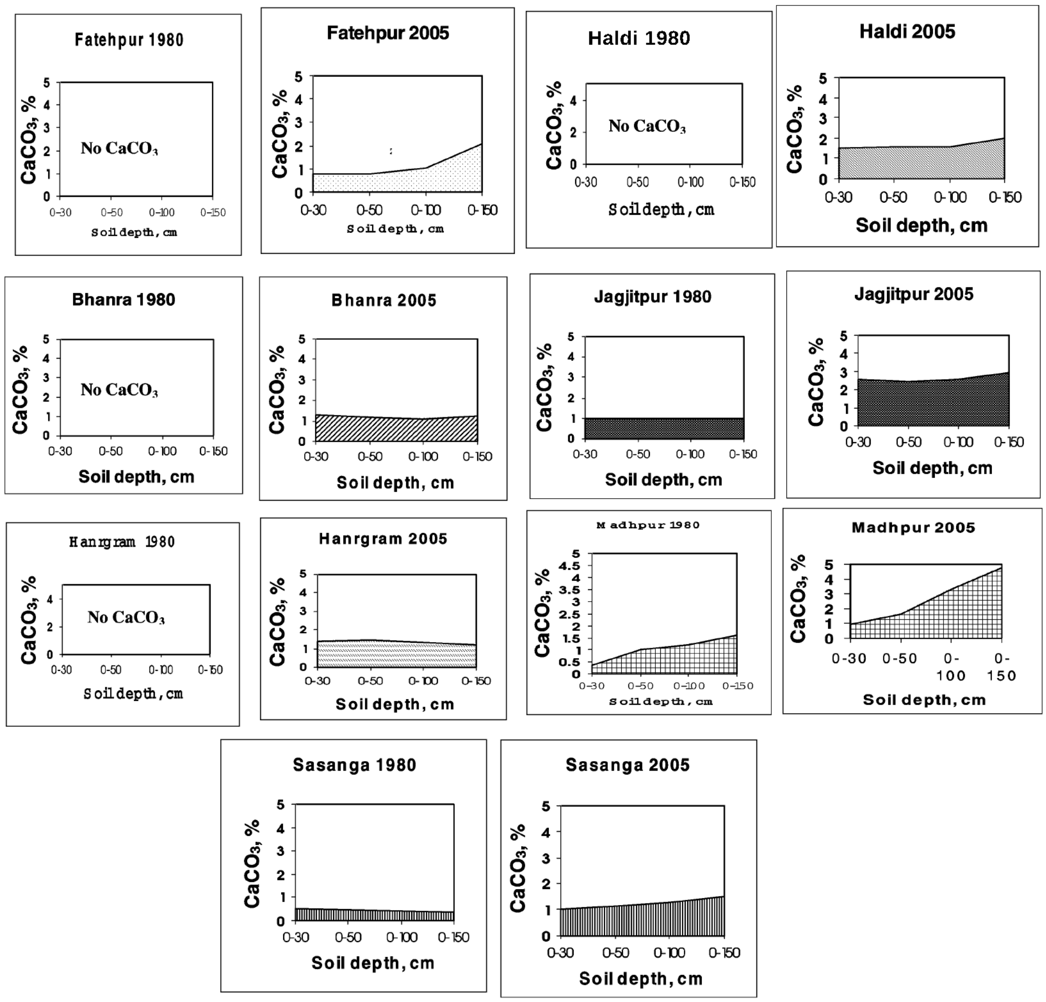

Figure 2. Changes in $CaCO_3$ content (1980–2005) in soils of a few benchmark spots under semi-arid, sub-humid and humid bio-climatic systems of the IGP.

(Figures 2 and 3). Hence the increase in SIC stock in these two sites was considered as 100%. In Ghabdan, Sakit and Zarifa Viran soils (Table 3), increase in SOC was accompanied by a decrease in the SIC stock. This was caused by reclamation through the application of gypsum and effects of cropping for more than 10 years[29] (Table 3).

In the sub-humid bioclimatic system, SOC stock increased substantially in general. However, this was not observed in Haldi soils (Table 3). The SIC stock increased to a great extent in the Jagjitpur site. In Bhanra and Haldi soils, $CaCO_3$ was not detected in the first 150 cm during 1980s, but it has formed during the last 25 years. Thus the increase in SIC stock for 2005 was considered as 100% (Table 3). In the humid bioclimatic system the SOC stock increased by 25% to 61% and the SIC stock nearly by 100 to 400%. In Hanrgram soils, $CaCO_3$ was not detected during 1980s. In general, in all BM spots of the IGP (except Haldi), increase in SOC stock was higher in the relatively dry tract (semi-arid and sub-humid dry) of the IGP. Interestingly, the increase in SIC stock is more pronounced in the wetter part of the IGP, due possibly to the presence of carbonates and bicarbonates in the tubewell water used for irrigation in the dry season.

Table 4 indicates carbon stock changes in the soils of selected BM spots in the BSR. Figure 2 shows the changes in $CaCO_3$ over time. All the soils show gradual increase in $CaCO_3$ with depth, except the Semla soils. The Kheri soils show an interesting trend. The first 50 cm depth of these soils, which was non-calcareous during 1980, is now calcareous. This suggests that although intensive agriculture increases the SOC, simultaneously it causes an increase in $CaCO_3$ in soils. It is known that the formation of $CaCO_3$ causes concomitant development of sodicity in the sub-surface horizons even though the surface soils remain non-calcareous, non-sodic and relatively porous. However, the formation and retention of

Table 3. Changes in carbon stock over years in the selected benchmark spots of the IGP (0–150 cm)

Bioclimatic systems	Soil series	SOC stock (Tg/lakh ha)		SOC change over 1980 (%)	SIC stock (Tg/lakh ha)		SIC change over 1980 (%)
		1980	2005		1980	2005	
Semi-arid	Phaguwala	3.36	5.48	63	13.10	26.14	99
	Ghabdan	2.63	7.04	167	18.95	7.71	–59
	Zarifa Viran	4.13	5.38	30	22.36	16.98	–24
	Fatehpur	1.11	5.50	395	0	58.13	100
	Sakit	4.05	8.55	111	51.03	5.37	–89
	Dhadde	4.47	5.84	31	0	10.15	100
Sub-humid	Bhanra	1.81	5.34	197	0	0.58	100
	Jagjitpur	2.52	8.76	248	2.52	8.86	251
	Haldi	8.55	6.28	–26	0	2.84	100
Humid	Hanrgram	6.93	11.02	59	0	3.68	100
	Madhpur	3.99	4.97	25	4.03	15.98	296
	Sasanga	5.25	8.42	61	0.88	4.45	405

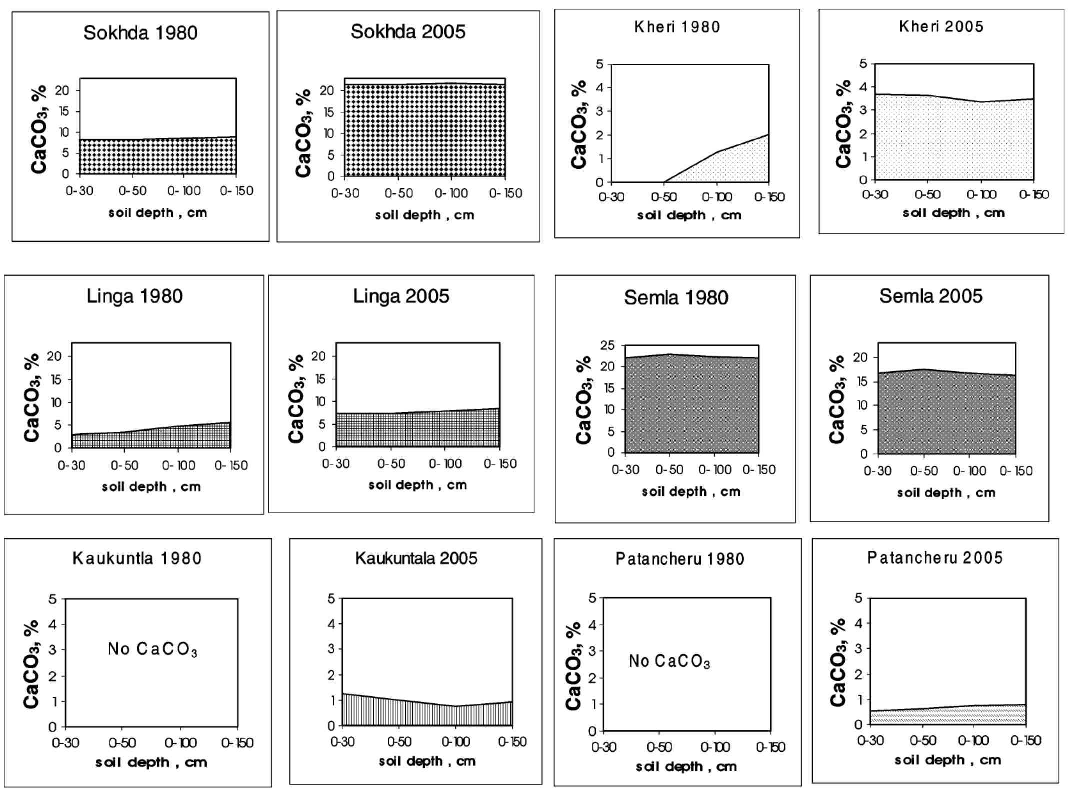

Figure 3. Changes in $CaCO_3$ content (1980–2005) in soils of a few benchmark spots under arid, semi-arid and sub-humid bioclimatic systems of the BSR.

$CaCO_3$ even in the surface horizons impair the productivity of the soils[30–32].

It has been reported earlier that increase in SOC helps in dissolving the native $CaCO_3$ reserves due to increase in pCO_2 in the soil and to contribute partly to the overall pool of SOC following the C-transfer pathway that works better in the drier part of the IGP[4]. In soils of dry bioclimate, exchangeable sodium percentage (ESP) and $CaCO_3$ content increase with pedon depth[5]. This depth function suggests that due to the formation of $CaCO_3$, sodicity develops initially in the subsoil regions. This subsoil sodicity impairs the drainage of soils[5] and with the passage of time, the entire soil profile becomes sodic. The $CaCO_3$ formed in these soils gets dissolved through the cations of

Table 4. Changes in carbon stock over years in the selected benchmark spots of the BSR (0–150 cm)

Bioclimatic systems	Soil series	SOC stock (Tg/lakh ha) 1980	SOC stock (Tg/lakh ha) 2005	SOC change over 1980 (%)	SIC stock (Tg/lakh ha) 1980	SIC stock (Tg/lakh ha) 2005	SIC change over 1980 (%)
Arid	Sokhda	11.19	9.20	–18	23.63	60.92	158
Semi-arid	Asra	6.29	13.59	116	2.00	2.00	0
	Teligi	7.41	15.20	105	21.01	29.60	41
	Semla	15.78	13.28	–16	73.82	46.11	–37
	Vijaypura	7.70	7.70	0	0	0	0
	Kaukantla	4.71	10.25	118	0	12.52	100
	Patancheru	8.39	16.72	101	0	11.78	100
Sub-humid	Kheri	5.62	10.51	87	8.32	9.71	17
	Linga	9.66	12.92	34	15.41	21.66	40

Table 5. Agricultural management practices in the BM spots of the IGP (during 2005)

Soil series (Sl. no.)	Production system	Management practice
Masitawali IGP 1	Cotton–wheat/mustard/onion/garlic/fodder berseem or guar followed by rabi season crops under irrigation	Cotton and wheat (180 : 90 : 0)*, mustard (180 : 45 : 0) $ZnSO_4$ (18 kg/ha) once in 2–3 yrs, cowdung 15–20 t/ha
Phaguwala IGP 2	Rice–wheat/mustard/potato/fodder, berseen, sugarcane onion, garlic all under irrigation	Rice (375 : 0 : 0), wheat (375 : 250 : 0) $ZnSO_4$ (20 kg/ha), amendment as gypsum (50 t/ha) in kharif once in 3 yrs
Ghabdan IGP 3	Rice–wheat/mustard/wheat–mustard intercropping, sugarcane onion, garlic, all under irrigation	Rice (375 : 0 : 0), wheat (190 : 0 : 0) $ZnSO_4$ (37 kg/ha), amendments as gypsum (5–12 t/ha) once in 2–3 years, cowdung (50–65 t/ha) Inclusion of fodder berseem
Bhanra IGP 4	Rice–wheat/mustard guar/bajra–wheat/potato, cotton, all under irrigation	Rice–wheat (375 : 0 : 0) $ZnSO_4$ (50 kg/ha), cowdung (65–75 t/ha) every 3 yrs; inclusion of fodder berseem in the rotation
Zarifa Viran IGP 5	Rice–wheat/mustard	Rice–wheat (120 : 60 : 60) Amendments (4–5 t/ha)
Sakit IGP 6	Rice–wheat for about 12 years, previously it was barren	Rice–wheat (300 : 140 : 0), $ZnSO_4$ (6–8 kg/ha), cowdung (50–65 t/ha), amendments as gypsum (250 kg/ha)
Dhadde IGP 7	Rice–wheat/mustard sugarcane	Rice (500 : 125 : 0), wheat (375 : 125 : 0), sugarcane (375 : 125 : 0), mustard (125 : 65 : 0), cowdung (5–6 t/ha)
Jagjitpur IGP 8	Rice–wheat/mustard maize–wheat/mustard, sugarcane–berseem	Rice–wheat (375 : 125 : 0) under canal irrigation as well as groundwater, cowdung (5–6 t/ha)
Fatehpur IGP 9	Rice–wheat since four decades. previous barren/mustard/sunflower	Rice–wheat (300 : 125 : 0) $ZnSO_4$ (10 kg/ha)
Haldi IGP 10	Rice/maize/soybean–wheat	Rice (375 : 150 : 100), maize–wheat (300 : 150 : 100), $ZnSO_4$ (65 kg/ha for rice/wheat)
Hanrgram IGP 11	Rice–rice	Kharif rice (90 : 60 : 60), Micronutrient mixture 12–14 kg/ha 'Gromor' (14 : 35 : 14) 600 kg ha, Micronutrient mixture 12–14 kg/ha Boro rice (130 : 140 : 75), Micronutrient mixture 12–14 kg/ha 'Gromor' (10 : 26 : 26) 120 kg/ha, Micronutrient mixture 12–14 kg/ha Cowdung (19–20 t/ha) depending upon availability
Madhpur IGP 12	Rice–mustard/potato–rice Rice–wheat	Kharif rice (100 : 65 : 65), Boro rice (130 : 130 : 100), potato (450 : 0 : 0; 10 : 26 : 26 as 'Gromor' about 150 kg/ha), mustard (250 : 480 : 0; 10 : 26 : 26 as 'Gromor' 300 kg/ha), wheat (65 : 0 : 0; 'Gromor' 10 : 26 : 26 about 130 kg/ha), FYM (cowdung + ash + kitchen waste + straw), 1.4 t/ha for rice-mustard–rice and 1.0 t/ha for rice–wheat
Sasanga IGP 13	Rice–mustard/potato–rice Rice–wheat	Rice (200 : 200 : 130), mustard (140 : 320 : 0), potato (250 : 650 : 350), micronutrients 'agromin' (13 kg/ha), FYM (cowdung + ash + kitchen waste + rice straw and stubble; 1.0 t/ha)

*N : P_2O_5 : K_2O per hectare.

Table 6. Agricultural management practices in the BM spots of the BSR (during 2005)

Soil series (Sl. no.)	Production system	Management practices
Kheri (BSR1-P27)	Soybean–wheat production double-cropping system under irrigation	Integrated nutrient management, NPK based on STCR approach.
Linga (BSR2-P3)	Soybean–wheat/chickpea double-cropping using well-water for irrigation; 2–4 months of fallow	Inclusion of legumes in rotation-cover cropping. Use of biofertilizers recommended: NPK (20 : 40 : 40 for soybean/chickpea) and 80 : 40 : 40 (N : P_2O_5 : K_2O) for wheat; FYM application once in 3 yrs.
Asra (BSR3-P10)	Rainfed mustard/intercropping system. Cotton/ pigeonpea + green gram or sorghum chickpea during monsoon season. Fallow period 3–6 months. Chickpea on residual moisture after sorghum.	Inclusion of legumes in rotation or as intercrop. Stubble incorporation cultivation using ridge/furrow technique.
Semla (BSR4-P29)	Cotton–groundnut rainfed system, wheat after groundnut subject to availability of water	Mixing top soil silt murrum/silt from river bed. FYM application @5 t/ha alternate year. Inclusion of legumes. Recommended NPK application.
Teligi (BSR5-P43)	Monocropping of rice; lowland rice; 7–8 months fallow	Improved seeds; 150 kg N/ha, 75 kg P_2O_5/ha/yr, 75 kg K_2O/ha/yr, no FYM; stubble incorporated; rice transplanted
Sokhda (BSR6-P31)	Cotton–pearlmillet/sesame – a two-year single monsoon season cropping with 4–5 months of fallow	Ridge-furrow cultivation. *In situ* green manuring in cotton with green gram; moisture conservation using organic mulches.
Vijaypura (BSR7-P17)	Rainfed groundnut–finger millet (3 yr rotation period), cropped during kharif with 8–9 month fallow (winter and summer)	Improved seeds; optimum plant stand; FYM @10 t/ha for finger millet; chemical fertilizers – 25 : 50 : 25 for groundnut, 25 : 40 : 25 for finger millet; need-based application of insecticides, conservation measure – land levelling.
Kaukuntla (BSR8-P34)	Rainfed castor + pigeonpea strip cropping – single monsoon season crop with 5 months of fallow period. Occasionally green gram–chickpea double-cropping is practised	Inclusion of legumes in the system; continuous application of FYM in the past and compulsory inclusion of legume (pigeonpea or chickpea) in the system.
Patancheru (BSR9-P41)	Fallow land under continuous native grassland	Undisturbed land with year-round grass cover.

acidic root exudates and carbonic acid (H_2CO_3) formed due to evolved carbon dioxide from root respiration in aqueous solution. As a result, calcium bicarbonate ($Ca(HCO_3)_2$) is formed. The soluble $Ca(HCO_3)_2$ thus helps in restoring the soluble and exchangeable Ca levels in the soils. The ESP decreases and soil structure is improved, which in effect, improves soil drainage. The CO_2 evolved goes back to atmosphere and thus makes the C-cycle complete. This pathway of C-transfer from inorganic (atmospheric CO_2) to organic (CH_2O) and organic (CH_2O) to inorganic (CO_2 in soil and then to $CaCO_3$), which indirectly helps in better vegetative growth (organic) in improved soil environment (good structure, better drainage) is largely active in the soil systems of the IGP and BSR[4]. Sites like Bhanra, Haldi and Hanrgram in the wetter part, and Fatehpur and Dhadde in the drier part of the IGP, show how the non-calcareous soils are gradually becoming calcareous (Figures 2 and 3). Intensive agriculture demands huge amount of irrigation along with other inputs. The irrigation water containing HCO_3^- and CO_3^{--} ions gradually accumulates and forms calcium carbonate in these soils[30,33]. Except two BM spots in the BSR (Sokhda in the arid and Semla in the semi-arid), the soils showed increase in both SOC and SIC stocks over the last 25 years. For Vijaypura (red) soils, carbon stocks did not change. In the Sokhda soils (arid bioclimatic system), the SIC stock increased by 158%.

Out of the two important food-growing regions, the IGP has contributed largely to high levels of crop production compared to the BSR. It is observed that during the post-green revolution era, the cropping intensity in the dominant states of the IGP (Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal) increased from 137% (1976–77) to 158% (1999–2000). During the same period, the states in the BSR (Andhra Pradesh, Madhya Pradesh, Karnataka, Gujarat and Maharashtra) remained less intensively cultivated[34,35], with an increase in cropping intensity from 111% to 123%. Despite the difference in cropping intensity, SOC stock of both the soils has increased from 1980 to 2005. However, the increase was more in the IGP than the BSR. This is due to the turnover of more biomass to the soils (both as above-ground and below-ground biomass) as evidenced from the increased SOC in fertilized (NPK) areas of a long-term experiment (30 years) of the IGP[36]. In addition, the exercise through the GEFSOC Modelling System[37,38] also projected an increase in SOC stock using the long-term experimental datasets from the selected BM spots of the IGP[39,40]. SOC stocks in the BSR indicated an increase, more in double-cropped areas, viz. Kaukuntla, Kheri and Teligi soils and also in areas where green manuring was practised (Asra soils). It, therefore, confirmed that the prevailing agricultural land uses helped in sequestering more organic carbon in soils. The mechanisms involved in preferential accumulation of organic matter in Teligi wetland soils under paddy may be ascribed mainly to anaerobiosis and the associated chemical and biochemical changes that take place in submerged soils[41]. It has recently been reported that the SIC : N ratio is relatively narrow in Teligi soils under lowland rice double-crop system. It indicates that the pedoenvironment in rice soils keeps the deteriorating effect of $CaCO_3$ formation and concomitant sodicity at bay[5].

Pedogenic $CaCO_3$ formation has been linked with the development of soil sodicity. This sodicity causes chemical soil degradation, indicating poor content of SOC. Despite this, the present study shows that intensive agriculture in the IGP and BSR has increased the SOC stock. In spite of the formation of $CaCO_3$ in the soils, the SOC increase suggests that the prevailing agricultural land uses have been able to enhance or maintain the level of organic carbon in the soils of these two food-production zones of the country. Adoption of the management intervention recommended by the National Agricultural Research System (Tables 5 and 6) for agricultural land use, during the post-green revolution, helped maintain the health of soils in the IGP and BSR areas, without causing decline in SOC since 1980.

Despite the fact that the increase in SIC stock is a bane[5,26], the increase in SOC has always been possible due to the adoption of suggested management interventions, even in arid and semi-arid environment. However, the rise in SIC warrants a fine-tuning of the existing management interventions. Until then, the status of SIC will remain a warning signal for potential soil degradation.

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