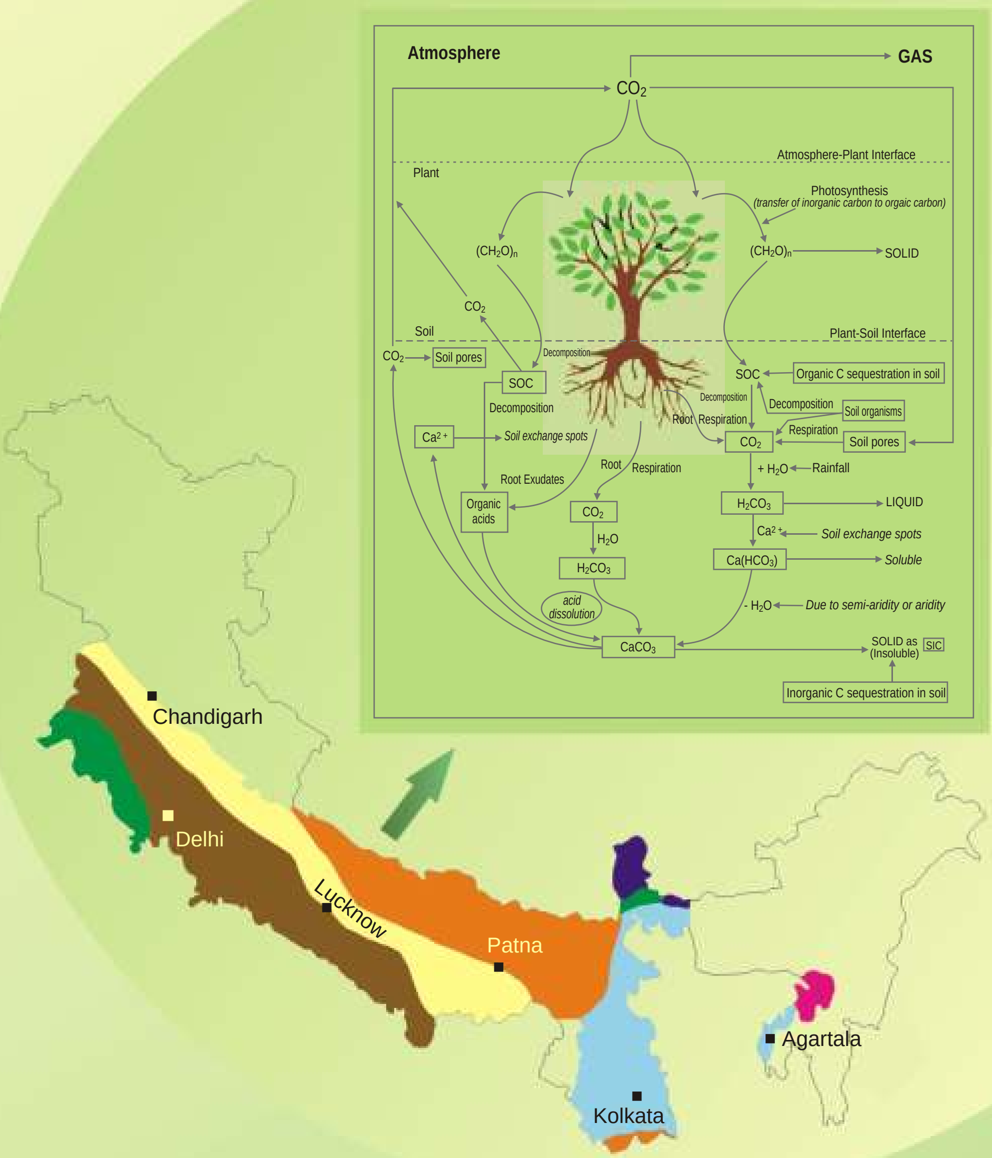
MANAGING SOIL CARBON STOCKS IN THE INDO-GANGETIC PLAINS, INDIA



National Bureau of Soil Survey & Land Use Planning
Rice-Wheat Consortium for the Indo-Gangetic Plains

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The initial support from the Asian Development Bank (ADB) and International Fund for Agricultural Development (IFAD) provided the groundwork for establishment of the RWC in 1994 and formalizing the collaborations between the NARS, IARCs and ARIs. The NARS-driven strategic ecoregional research initiatives with financial support from the DGIS Government of the Netherlands, Department for International Development (DFID), UK, New Zealand, Australia and the US Agency for International Development (USAID) and the World Bank have grown over the years into a dynamic agenda of resource conservation technologies appropriate to different transects of the Indo-Gangetic Plains. The on-going successes in scaling-up resource conservation technologies for enhancing productivity and sustainability of the rice-wheat systems are beginning to create a revolution and favourably benefit large areas and more numbers of farm families.

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Managing Soil Carbon Stocks in the Indo-Gangetic Plains, India

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Introduction

The Indo-Gangetic Alluvial Plains (IGP) of India extends from 21^0 45/ to 31^0 0/ N latitudes and 74^0 15/ to 91^0 30/ E longitudes (Fig. 1) and includes the states of Punjab, Haryana, Delhi, Uttar Pradesh, Bihar, West Bengal, Himachal Pradesh, northern parts of Rajasthan and Tripura. The plains cover a total area of about 43.7 m ha and represent 8 agro-ecoregions (AERs) and 14 agro-ecosubregions (AESRs) (Velayutham et al. 1999) (Table 1).

A closer look at table 1 allows us to divide the entire IGP, India into 7 bioclimatic systems with a general tendency toward increase in rainfall and more Length of Growing Period (LGP) to allow higher cropping intensity without irrigation (Figs. 2 and 3).

The IGP, with about 13% geographical coverage in India, produces nearly 50% of the food grains for 40% of the total population of India. However, recent reports of the land use and soils of the IGP indicate a general decline in soil fertility (Bhandari et al. 2002; Gupta, 2003). Soils which earlier rarely showed any nutrient deficiency symptoms are now deficient in many nutritional elements. Long term soil fertility studies have shown reduction in soil organic matter content as well as in the other

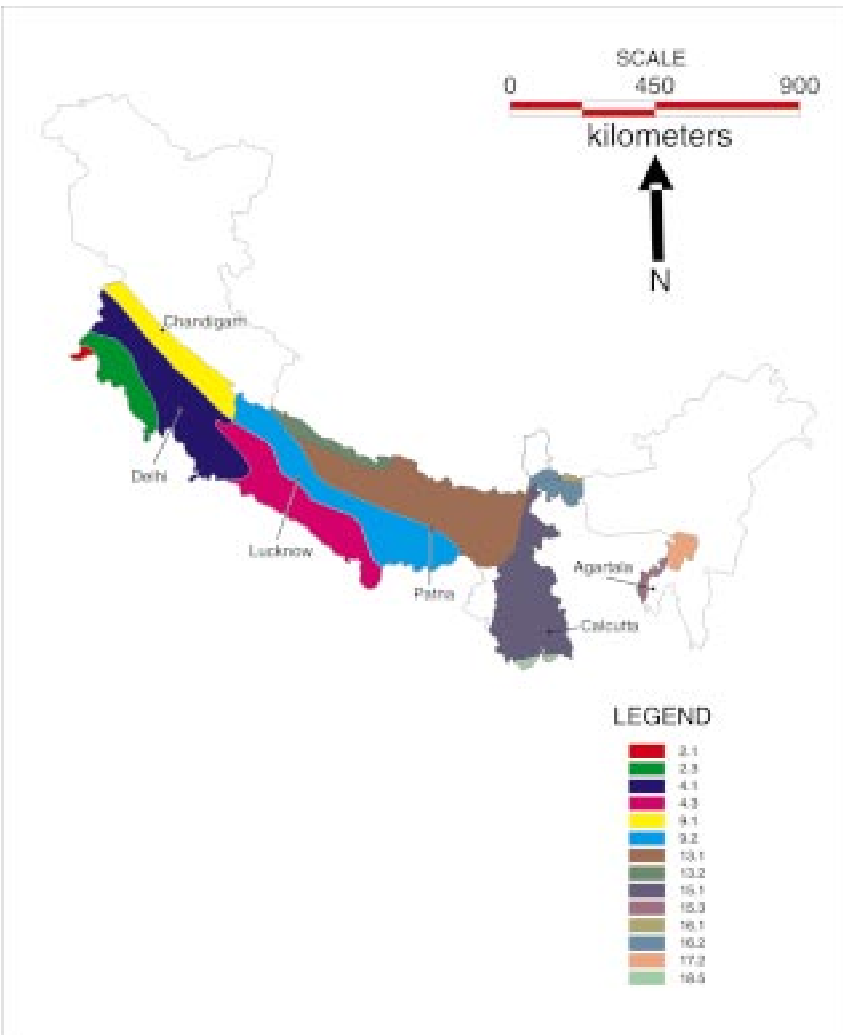


Figure 1. Location map of the IGP, India showing agro-eco-subregions.

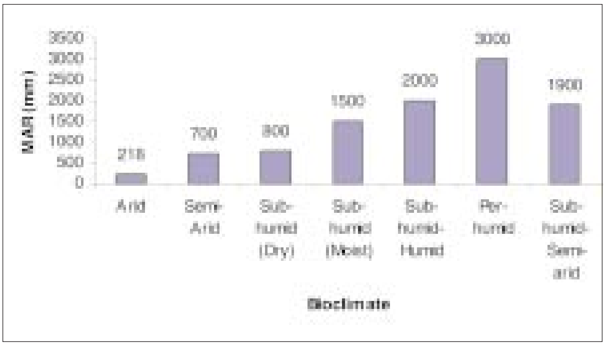


Figure 2. Distribution of mean annual rainfall (MAR) in different bioclimatic systems in IGP, India.

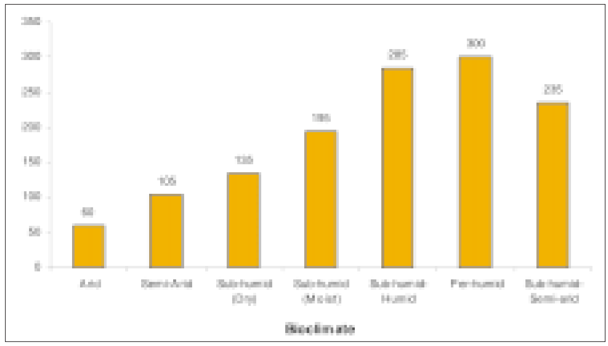


Figure 3. Variation of length of growing period in different bioclimatic systems.

Table 1. Description of Agro-Ecological Regions and Subregions of the Indo-Gangetic Plains, India.

Sl. No.	AER & sub-region number	Description	Location (State and Districts)	Area (000 ha) (%)*
1	2	3	4	5
	2	**Western Plains, Hot Arid Ecoregion, LGP <60 days**		**3112 (7.1)**
1	2.1	Marusthali plains, hot hyper-arid, very low AWC, LGP<60 days	*Punjab* : Southern part Ferozepur *Rajasthan* : Hanumangarh and Ganganagar	358 (0.8)
2	2.3	Kachch Peninsula, hot hyper-arid, low AWC and LGP <60 days	*Punjab*: Muktasar, Bathinda, Central Ferozepur and South Faridkot *Haryana* : Bhiwani, Hisar, West Mahendragarh	2754 (6.3)
	4	**Northern Plains, Hot Semi-Arid Ecoregion, LGP 90-150 days**		**13265 (30.4)**
3	4.1	North Punjab Plain, Ganga-Yamuna Doab, hot semi-arid, medium AWC, LGP 90-120 days	*Punjab*: Amritsar, Kapurthala, Sangrur, Patiala, Moga, Faridkot and Ferozepur *Haryana*: Kurukshetra, Kaithal, Karnal, Jind, Sonepat, Panipat, Rohtak, Faridabad, Gurgaon, Mahendragarh, Rewari *Uttar Pradesh* : Meerut, Ghaziabad, Bulandshahr, Aligarh, Mathura, Etah, Agra, Mainpuri, Firozabad, West Muzafarnagar, South Moradabad and South Etawah	7599 (17.4)
4	4.3	Ganga-Yamuna Doab, Rohilkhand and Avadh Plain, hot moist semi-arid, medium to high AWC, LGP 120-150 days	*Uttar Pradesh :* Budaun, Hardoi, Farrukhabad, Kanpur, Unnao, Varanasi, Etawah, Southern Shahjahanpur, northern parts of Jalaun, Hamirpur, Banda, Mirzapur, Allahabad, Pratapgarh, and Sonbhadra	5666 (13.0)
	9	**Northern Plains, Hot Sub-humid (dry) Ecoregion, LGP 120-180 days**		**9763 (22.3)**

(Continued)

Table 1. *(Continued)*

1	2	3	4	5
5	9.1	Punjab and Rohilkhand Plains, hot/dry moist sub-humid transition, medium AWC and LGP 120-150 days	*Jammu & Kashmir* : Southern parts of Jammu (R.S. Pura) and Kathua *Himachal Pradesh* : Parts of Kangra, Una & Bilaspur *Punjab*: Gurdaspur, Hoshiarpur, Rupnagar, Nawashahar, northern parts of Amritsar, Kapurthala, Jalandhar, Ludhiana and Patiala, Chandigarh and Union Territory *Haryana*: Ambala, Yamuna nagar, northern parts of Kurukshetra & Karnal *Uttar Pradesh* : Saharanpur, Bijnaur, N-E Muzaffar nagar, Northern Muradabad, West Rampur, S-W Nainital	3630 (8.3)
6	9.2	Rohilkhand, Avadh and south Bihar Plains, hot dry sub-humid, medium to high AWC and LGP 150-180 days	*Uttar Pradesh* : Barielly, Pilibhit, Sitapur, Bara Banki, Sultanpur, Azamgarh, Ghazipur, Lucknow, southern parts of Nainital, Lakhimpur kheri, Mau, Faizabad and Balia, Rampur (east), northern parts of Shahjahanpur, Hardoi and Jaunpur, Varanasi (east), Rai Bareli, and Fatehpur *Bihar* : Bhojpur, Rohtas, Aurangabad, Gaya, Jahanabad, Nalanda, patna, Nawada	6133 (14.0)
	13	**Eastern Plains, Hot Sub-humid (moist) Ecoregion, LGP 180-210 days**		**10219 (23.4)**
7	13.1	North Bihar and Avadh Plains, hot dry to moist sub-humid with low to medium AWC and 180-210 days LGP	*Uttar Pradesh* : Bahraich, Gonda, Basti, Gorakhpur, Deoria, northern Faizabad, Azamgarh, Mau and Balia and southern parts of Siddharthanagar and Maharajgang *Bihar* : Paschim and Purba Champaran, Sitamarhi, Gopalganj, Siwan, Saran, Muzaffarpur, Vaishali, Madhubani, Darbhanga, Samastipur, Begusarai, Khagaria, Madhopura, Saharsa, Purnia, Katihar, Bhagalpur, Munger, Godda, Northern Patna, Devghar, Santhal Pargana and Sahibganj	8778 (20.1)
8	13.2	Foothills of Central Himalayas, warm to hot moist, high AWC and LGP 180-210 days	*Uttar Pradesh* : North of Lakhimpur, Bahraich, Gonda, Basti, Gorakhpur and Deoria	1441 (3.3)
	15	**Bengal Plains, Hot Sub-humid to Humid (Inclusions of Per-humid Ecoregion, LGP 210-300 days**		**6641 (15.2)**
9	15.1	Bengal Basin and north Bihar Plains, hot moist sub-humid with medium to high AWC and LGP 210-240 days	*West Bengal* : Kolkata, Haora, Hugli, Medinipur, Bankura, Birbhum, Bardhaman, Murshidabad, Nadia, 24 Parganas (N&S), Maldah, West Dinajpur *Bihar* : East Sahibganj	5861 (13.4)

(Continued)

Table 1. *(Concluded)*

1	2	3	4	5
10	15.3	Teesta, lower Brahmaputra Plain, hot moist humid to per-humid medium AWC and LGP 270-300 days	*West Bengal* : Jalpaiguri and Koch Bihar *Tripura* : Dhalai district (northern part)	780 (1.8)
	16	**Eastern Himalayas, warm per-humid AER, LGP 270-300 days**		**216 (0.5)**
11	16.1	Foot-hills of Eastern Himalayas, warm to hot per-humid, low to medium AWC and LGP 270-300 days	*West Bengal* : Southern parts of Jalpaiguri and Koch Bihar	100 (0.2)
12	16.2	Darjeeling and Sikkim Himalayas, warm to hot per-humid, low to medium AWC and LGP 270-300 days	*West Bengal* : Part of Jalpaiguri district	116 (0.3)
	17	**North-Eastern hills (Purvachal), warm, per-humid AER, LGP >300 days**		**82 (0.2)**
13	17.2	Purvachal (Eastern Range), warm to hot, per-humid, low to medium AWC and LGP >300 days	*Tripura* : West Tripura (Part), South Tripura (Part)	82 (0.2)
	18	**Eastern Coastal Plain, hot sub-humid to semi-arid AER, LGP 240-270 days**		**393 (0.9)**
14	18.5	Gangetic delta, hot moist, sub-humid to humid, medium AWC and LGP 240-270 days.	*West Bengal* : Medinipur, Sagar Islands of South 24 Parganas	393 (0.9)
			Total	43691 (100)

essential nutrients, that had higher levels of nutritional elements in the earlier years (Bhandari et al. 2002; Abrol and Gupta, 1998). The biological activity of soils has gradually declined resulting in reduced efficiency of applied inputs (Abrol and Gupta, 1998). As a consequence parts of the IGP have an aridic environment at present (Eswaran and van den Berg, 1992). The sustainability ratings of some soil series of the IGP for the rice-wheat cropping system indicate many soil constraints including low SOC (soil organic carbon) (Table 2). It is in this context that the soils of the IGP of the Indian subcontinent require focused attention.

Soils under arid and semi-arid climates in IGP cover 16.4 m ha and lack in organic carbon due to high rate of decomposition (Fig. 4). Interestingly, the soils in the arid and semi-arid environments prevailing in some parts of the IGP are abundant in inorganic carbon in the form of calcium carbonate.

The adverse climatic conditions in arid and semi-arid agro-ecoregions induce the precipitation of $CaCO_3$, thereby depriving the soils of Ca^{2+} in soil

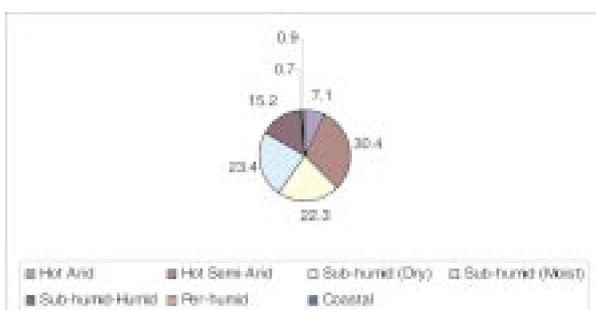


Figure 4. Distribution of bioclimatic systems in IGP, India.

Table 2. Suitability of different soils for rice and wheat in the IGP.

Sr. No.	AESR	Soil Series	Rice	Wheat	Constraints for soil systems	Overall suitability rating for Rice-Wheat system
1	2.1	Masitawali & Nihalkhera	S3sw	S2s	Aridity, frequent deposition of Aeolian sand; seasonal flooding; calcareous substratum	S3sw
2	2.3	Jassi Pauwali & Jodhpur Ramana	S2sw	S3sw	Sandy soils, wind erosion, low nutrient status	S3sw
3	4.1	Fatehpur Phaguwala Zarifa Viran & Ghabdan	S3s S2s N1n	S3s S3 N1n	Highly saline and sodic, imperfect drainage, micronutrient deficiency	S3 S3 N1n
4	4.3	Bijapur Hirapur and Sakit	S2s N1n	S1 N1n	Highly saline and sodic, waterlogging, poor quality groundwater	S2s N1n
5	9.1	Dhoda Jagjitpur Bhanra Berpura	S2sw S3sn S3sw S2s(1)	S1 S3n S3sw S1	Low nutrient holding capacity, highly saline and sodic	S2sw S3sn S3sw S2s(1)
6	9.2	Basiaram & Itwa Simri Akbarpur	S2s(1) S2s(1) N1n	S1 S2w(1) N1n	Salinity & Sodicity, impeded drainage	S2s(1) S2s(1)w(1) N1n
7	13.1	Bahraich	S2s	S2w(1)	Frequent flooding	S2w(1)
8	13.2	Haldi	S2s(1)	S1	Deficient in Zn, Fe & S	S2s(1)
9	15.1	Sasnaga & Konarpara Hangram, Amarpur, Modhupur	S2s(1) S1	S2w(1) S2w(1)	Frequent flooding and waterlogging, salinity, low nutrient status	S2s(1) S2s(1)
10	15.3	Barak Seoraguri	S2s(1) S1	S1s S2w(1)	Frequent flooding and waterlogging, low nutrient status	S2s(1), S2s(1)
11	16.1	Singivita 16.2	S2	S2s(1)	Seasonal flooding	S2s(1)
12	17.2	Khowai and Nayanpur	S1	S2w	Seasonal flooding and waterlogging	
13	18.5	Sagar	S1	S2sw(1)	Salinity, poor drainage	S2sw(1)

S1 = Suitable; S2 = Moderately suitable; S3 = Marginally suitable;

N1 = Currently unsuitable but can be improved (Sys, 1976 & Sys *et al* 1991)

s = Soil related constraints (texture, structure, $CaCO_3$ content, depth and low OC)

w = Wetness related constraints (flooding and drainage)

n = Constraints related to salinity and alkalinity

- = not available

exchange complex with a concomitant development of soil sodicity in the subsoils. The subsoil sodicity impairs the hydraulic conductivity of soils. This self-terminating process (Yaalon, 1983) will lead to the formation of sodic soils with exchangeable sodium percentage (ESP) that decreases with depth. Therefore, the formation of pedogenic (secondary) $CaCO_3$ has been identified as a basic process that initiates the development of sodicity. The process of $CaCO_3$ formation in soils is now considered as a basic and natural process of soil degradation (Pal et al 2000, 2003; Srivastava et. al 2000). In soils of IGP the $CaCO_3$ has been formed during the semi-arid climate prevailing for the last 4000 year B.P. and the rate of formation is proceeding at a very fast rate, i.e., 0.8-0.9 mg per 100 g of soil per year in the first 100 cm of the profile (Pal et al. 2000). Therefore, attempts to increase and stabilize yields in arid and semi-arid regions by extension of irrigation may end up very badly, if adequate care is not taken to prevent the menace of formation of $CaCO_3$. A schematic view of such a long term development of soil degradation process is shown in figures 5 and 6.

Restoration of organic and inorganic carbon balance and its follow-up requires basic information of carbon stock in soils of the IGP. The present study assumes importance since the knowledge on carbon stock will facilitate in deciding appropriate soil and land management techniques.

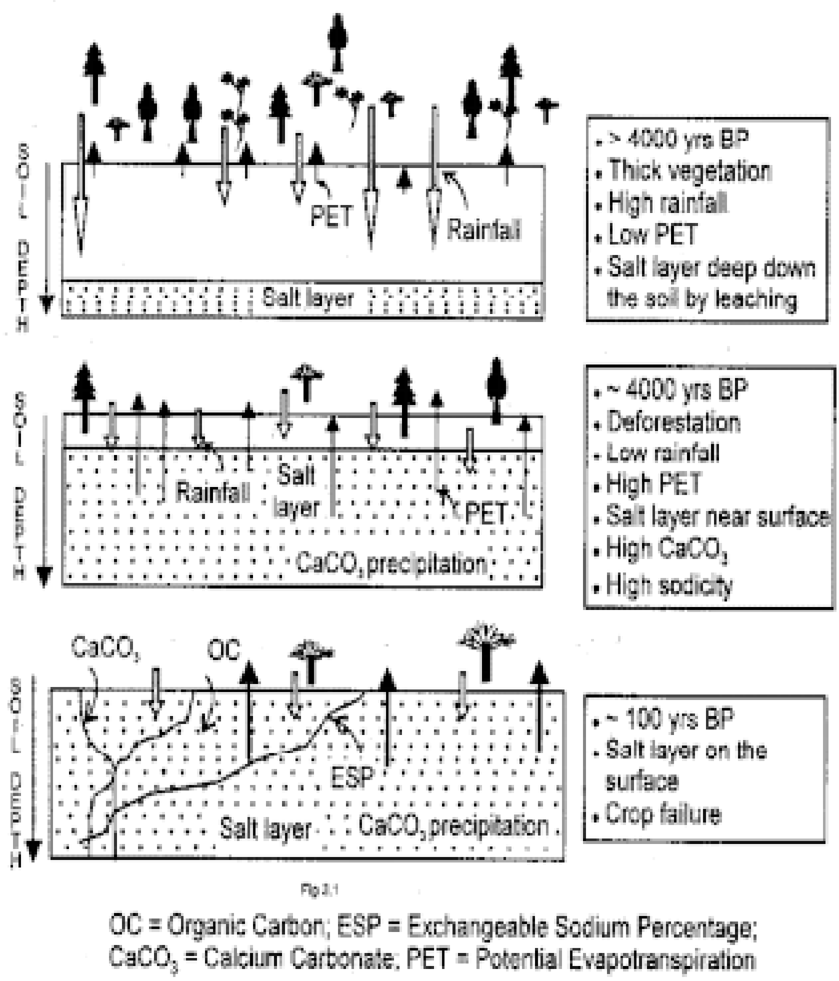


Figure 5. Degradation of soils in IGP *vis-à-vis* cause-effect relationships over geologic time scale (the length and thickness of arrows indicate relative contribution of rainfall and PET).

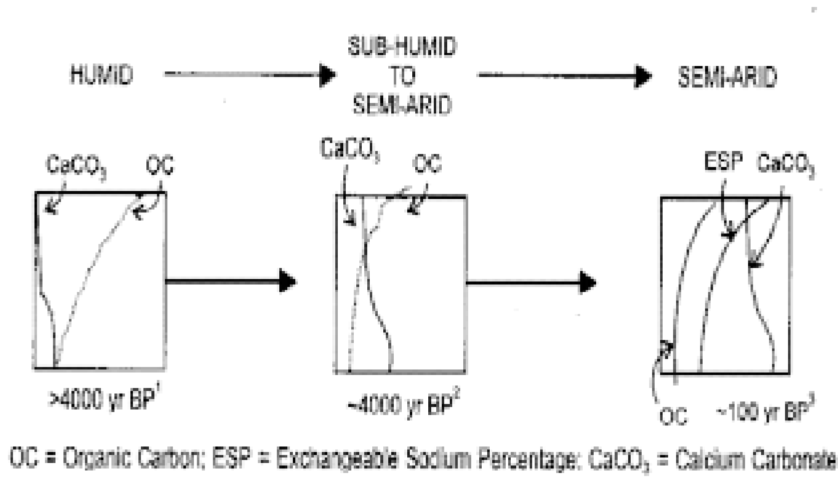


Figure 6. Degree of soil degradation in terms of sodicity, $CaCO_3$ and depletion of OC in soils of IGP as influenced by climate (1: Randhwa, 1945; 2: Srivastava et al. 1994, 1998; 3: known land history with introduction of canal irrigation; Also see Velayutham et al. 2002).

Source of Data to Compute Carbon Stock in Soils

Difference in sampling methods, exact season of collecting soil samples on different types of landscapes, kinds of vegetation, and above all the method of soil analyses in the laboratory determine the quality of organic carbon data of soils. Usually Walkley and Black's method (Jackson, 1973) is an accepted technique to generate SOC data. For inorganic carbon the information on equivalent of calcium carbonate content in soils has been used as the base. The $CaCO_3$ content in soils is determined by standard acid-base titration method (Jackson, 1973). To quantify the degree of expression of effervescence viz., very slight, slight, strong and violent (Soil Survey Division Staff, 1995) the entire field observations of the established soil series of India (Lal et al. 1994) were correlated with their quantitative $CaCO_3$ equivalent value obtained from laboratories.

The necessary information about soil organic and inorganic carbon were obtained from the existing primary database of National Bureau of Soil Survey and Land Use Planning, Nagpur, India (Murthy et al. 1982; Sehgal et al. 1988; Bhattacharyya et al. 1989, 1992, 1994, 1995, 1996; Lal et al. 1994; Pal et al. 2000; Velayutham et al. 2000). The bulk density (BD) data is not available either in soil survey reports or in published literature. For the present study BD values were generated for the soils where they were not available. In a few reports, however, BD values were available and were used to compute the total SOC and SIC (soil inorganic carbon) stocks. BD values were measured by standard method (Black, 1965).

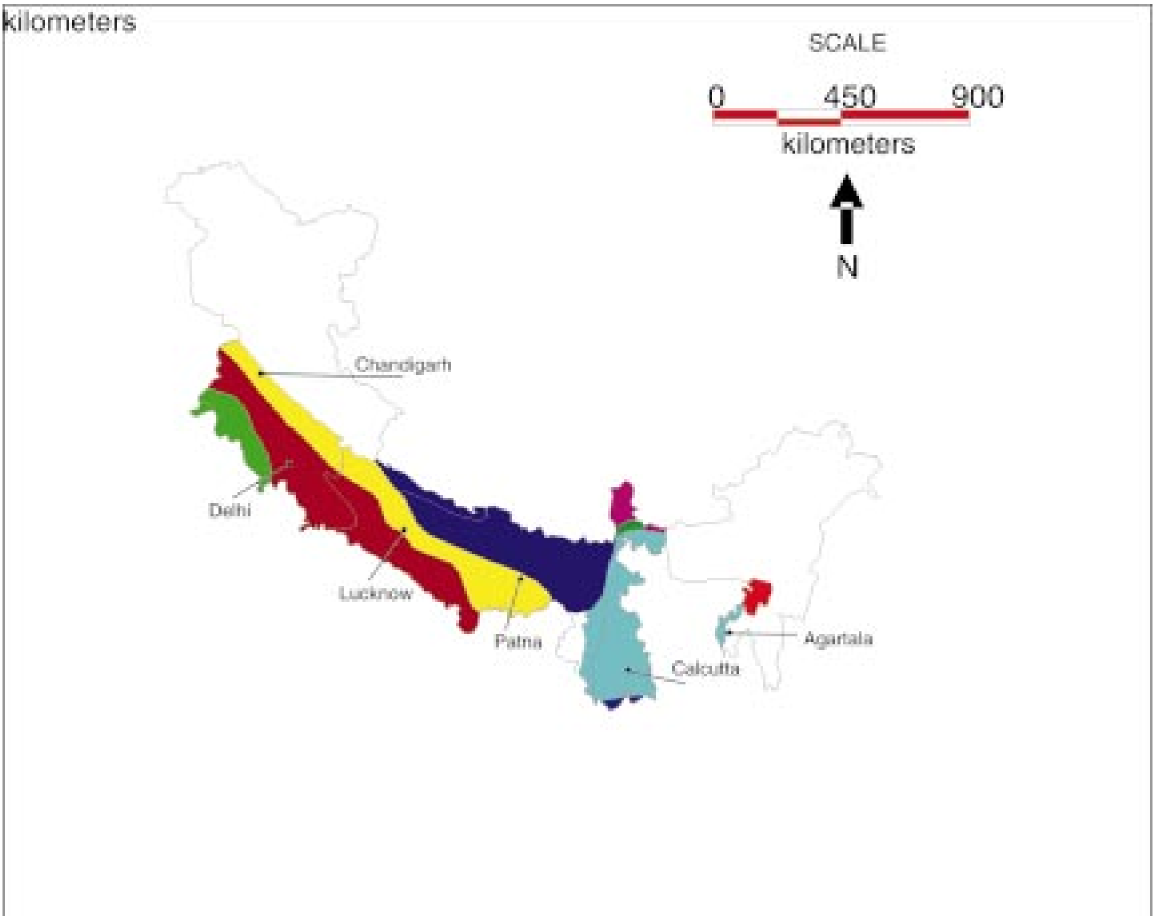
Computation of Soil Carbon Stocks

The total carbon stock in soil is calculated following the methods described by Batjes (1996). The first step (step 1) involves calculation of OC by multiplying OC content (g/g), bulk density (Mg/m^3) and thickness of horizon (m) for individual soil profile with different thickness varying from 0-30, 0-50, 0-100 and 0-150 cm. In the second step (step 2) the total OC content per unit area determined by this process is multiplied by the area (ha) of the soil unit distributed in different agro-ecological subregions (AESRs) of the IGP (Velayutham et al. 1999). Thus total SOC content is calculated in terms of Pg (1 Pg = 10^{15} g). For SIC the calculation was made using 12% C value in $CaCO_3$ using steps 1 and 2.

Soil Organic Carbon Stock in the IGP

Figure 7 indicates SOC stock in different AESRs in the IGP. Although organic carbon content in the soils of warmer areas (arid and semi-arid) is less, the SOC stock is high (Table 3). This is due to more aerial coverage of dry and warmer areas in the IGP.

In an earlier attempt to delineate the sufficient and deficient zones, 1 per cent level of organic



LEGEND

Symbol	AER	Ecosystem	Org C(Pg)
	2	Arid	0.0250
	4	Semi arid	0.4389
	9	Sub-humid (dry)	0.3775
	13	Sub-humid (moist)	0.6494
	15	Sub-humid (Moist)	0.4314
	16	Per-humid (warm)	0.0525
	17	Per-humid (warm)	0·0002
	18	Coastal	0.0309
	Total		2.0055

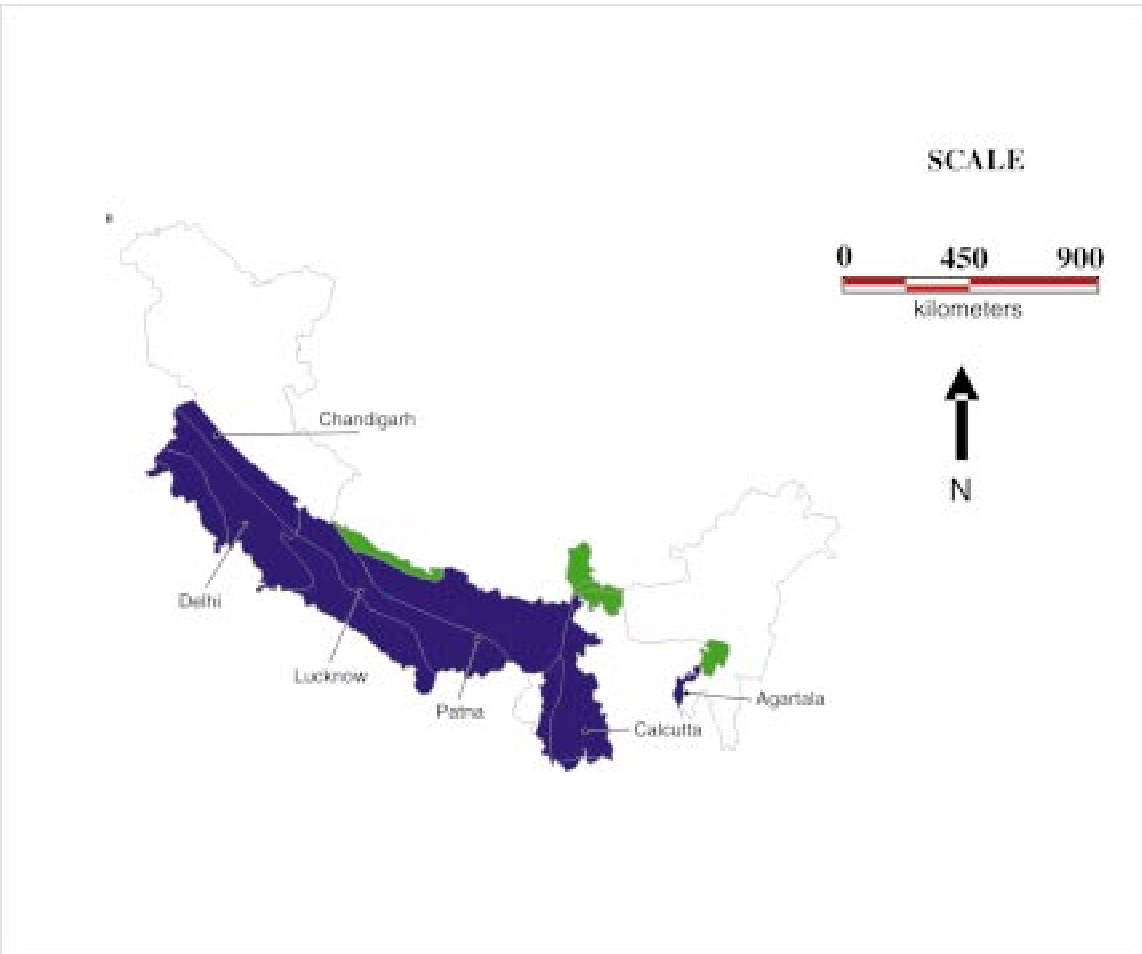
Figure 7. Organic carbon stock (Pg) of first 150 cm depth of soils in AERs of the IGP.

Table 3. Total carbon stock in soils of the IGP, India.

AESR No.	AESRs/Characteristics	Carbon	Depth range (cm)	Carbon stock (Pg)		
			0-30	0-50	0-100	0-150
2.1	Marusthali plains, hot hyper-arid very low AWC, LGP<60 days	SOC	0.0008	0.0022	0.0039	0.0074
		SIC	0.0168	0.0164	0.0360	0.0581
		TC	0.0176	0.0186	0.0399	0.0655
2.3	Kachch Peninsula, hot hyper-arid, low AWC and LGP <60 days	SOC	0.0214	0.0310	0.0413	0.0157
		SIC	0.0029	0.0060	0.3341	0.5802
		TC	0.0243	0.0370	0.3754	0.5959
4.1	North Punjab Plain, Ganga-Yamuna Doab, hot semi-arid, medium AWC, LGP 90-120 days	SOC	0.0609	0.1056	0.1770	0.2307
		SIC	0.1103	0.1769	0.3636	0.9422
		TC	0.1712	0.2825	0.5406	1.1729
4.3	Ganga-Yamuna Doab, Rohilkhand and Avadh Plain, hot moist semi-arid, medium to high AWC, LGP 120-150 days	SOC	0.0517	0.0773	0.1535	0.2032
		SIC	0.0000	0.0285	0.1523	0.8566
		TC	0.0517	0.1058	0.3058	1.0598
9.1	Punjab and Rohilkhand Plains, hot/dry moist subhumid transition, medium AWC and LGP 120-150 days	SOC	0.0786	0.0497	0.0997	0.1376
		SIC	0.0020	0.0046	0.0065	0.0098
		TC	0.0806	0.0543	0.0162	0.1474
9.2	Rohilkhand, Avadh and south Bihar Plains, hot dry subhumid, medium to high AWC and LGP 150-180 days	SOC	0.0639	0.0961	0.1472	0.2391
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.0639	0.0961	0.1472	0.2391
13.1	North Bihar and Avadh Plains, hot dry to moist subhumid with low to medium AWC and 180-210 days LGP	SOC	0.0649	0.1370	0.2265	0.3440
		SIC	0.0000	0.4925	1.0187	2.0733
		TC	0.0649	0.6295	1.2452	2.4173
13.2	Foothills of Central Himalayas, warm to hot moist, high AWC and LGP 180-210 days	SOC	0.1024	0.1391	0.2503	0.3054
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.1024	0.1391	0.2503	0.3054
15.1	Bengal Basin and north Bihar Plains, hot moist subhumid with medium to high AWC and LGP 210-240 days	SOC	0.0985	0.1530	0.2474	0.2407
		SIC	0.0050	0.0251	0.0488	0.0598
		TC	0.1035	0.1781	0.2962	0.3005
15.3	Teesta, lower Brahmaputra Plain, hot moist humid to perhumid medium AWC and LGP 270-300 days	SOC	0.0542	0.0698	0.1511	0.1908
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.0542	0.0698	0.1511	0.1908
16.1	Foot-hills of Eastern Himalayas, warm to hot perhumid, low to medium AWC and LGP 270-300 days	SOC	0.0096	0.0136	0.0208	0.0279
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.0096	0.0136	0.0208	0.0279
16.2	Darjeeling and Sikkim Himalayas, warm to hot perhumid, low to medium AWC and LGP 270-300 days	SOC	0.0087	0.0091	0.0176	0.0246
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.0087	0.0091	0.0176	0.0246
17.2	Purvachal (Eastern Range), warm to hot, perhumid, low to medium AWC and LGP >300 days	SOC	0.0005	0.0008	0.0016	0.0020
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.0005	0.0008	0.0016	0.0020
18.5	Gangetic delta, hot moist, subhumid to humid, medium AWC and LGP 240-270 days	SOC	0.0122	0.0147	0.0221	0.0309
		SIC	0.0000	0.0000	0.0000	0.0000
		TC	0.0122	0.0147	0.0221	0.0309
	Total	SOC	0.6283	0.8990	1.5600	2.0000
		SIC	0.1317	0.7500	1.9600	4.5800
		TC	0.7600	1.6490	3.5200	6.5800

carbon was considered as the tentative boundary between sufficient and deficient zones (Velayutham et al. 2000) considering OC equilibrium value at 1-2 per cent (Saikh et al. 1998). In an effort to identify systems for carbon sequestration in semi-arid tropics of India, it was reported that forest and horticultural (citrus) systems reach a quasi-equilibrium value of nearly 0.9-1.0 per cent SOC in shrink-swell soils (Naitam and Bhattacharyya, 2004). This observation further supports 1 per cent value of SOC as a limit of sufficient or deficient zones of organic carbon.

On the basis of 1 per cent SOC, it has been observed that 5 AERs (13.2, 15.3, 16.1, 16.2 and 17.2) comprising only 6 per cent area of the IGP falls in sufficient zone of organic carbon and the remaining 9 AERs comprising 94 per cent area of



Symbol	OC content(%) 0-30cm	AESRs		
		Nos.	Area ('000ha)	%
(green)	Sufficient Zones >1.0	13.2,15.3,16.1, 16.2,17.2	2519	6
(blue)	Deficient Zones <1.0	2.1,2.3,4.1,4.3,9.1, 9.2,13.1,15.1,18.5	41172	94

Figure 8. Map showing sufficient and deficient zones of organic carbon in the IGP.

the IGP are under deficient zone (Fig. 8). Soils under all categories of humid climate do not, however, fall under sufficient zone of SOC except in about 6% of the area. The remaining areas under humid climate are deficient in SOC due to intensive agricultural practices (Abrol and Gupta, 1998). However, when point data on OC content were compared it was found that the cooler humid tracts of the IGP (AESR 13.2 and the AESRs 15.3, 16.1 and 16.2) have sufficient OC in the first 30 cm of soil depth (Table 6 – described later). Similar observations were earlier made in soils of Madhya Pradesh and Tripura (Bhattacharyya et al. 1996; Bhattacharyya & Pal, 1998; Bhattacharyya et al. 2000a) and in other parts of India (Velayutham et al. 2000).

Distribution of Soil Inorganic Carbon Stock in the IGP

The presence of free carbonates in soils and parent materials is confirmed by the effervescence with dilute hydrochloric acid (1:4) in the field. The amount and expression of effervescence is affected by size distribution and mineralogy as well as by the amount of carbonates in the soil (Soil Survey Staff, 1995). Till date, there is no report about the quantitative expression of carbonates of soils in terms of their mapping. To quantify the degree of expression of effervescence viz., very slight, slight, strong and violent, the entire field observations of the already established soil series of India (Murthy et al. 1982; Lal et al. 1994; Sehgal et al. 1988) were correlated with their quantitative $CaCO_3$ equivalent values obtained from laboratories.

The values for different degrees of effervescence were ascertained as follows:

Very slight effervescence	: <2.5% $CaCO_3$
Slight effervescence	: 2.5 – 5.0% $CaCO_3$
Strong effervescence	: 5.0 – 13.0% $CaCO_3$
Violent effervescence	: >13.0% $CaCO_3$

These values were used to draw the $CaCO_3$ map of the IGP (Fig. 9). The $CaCO_3$ distribution map shows that the area of the AESRs 9.1 and 15.1 falls under very low (VL) $CaCO_3$, AESR 13.2 corresponds to low (L), the AESRs 2.1, 4.1, and 4.3 fall under medium (M) and AESR 2.3 as high $CaCO_3$ (H) zones. The area estimates suggest that very low, low, medium and high $CaCO_3$ content correspond to very slight, slight, strong and violent effervescence observed in the field cover 21.7, 3.3, 31.2, and 6.3%, respectively. The remaining areas constituting 37.5% area of the IGP do not contain any $CaCO_3$ in the first 150 cm soil depth (Fig. 9).

Total Soil Carbon Stock in the IGP

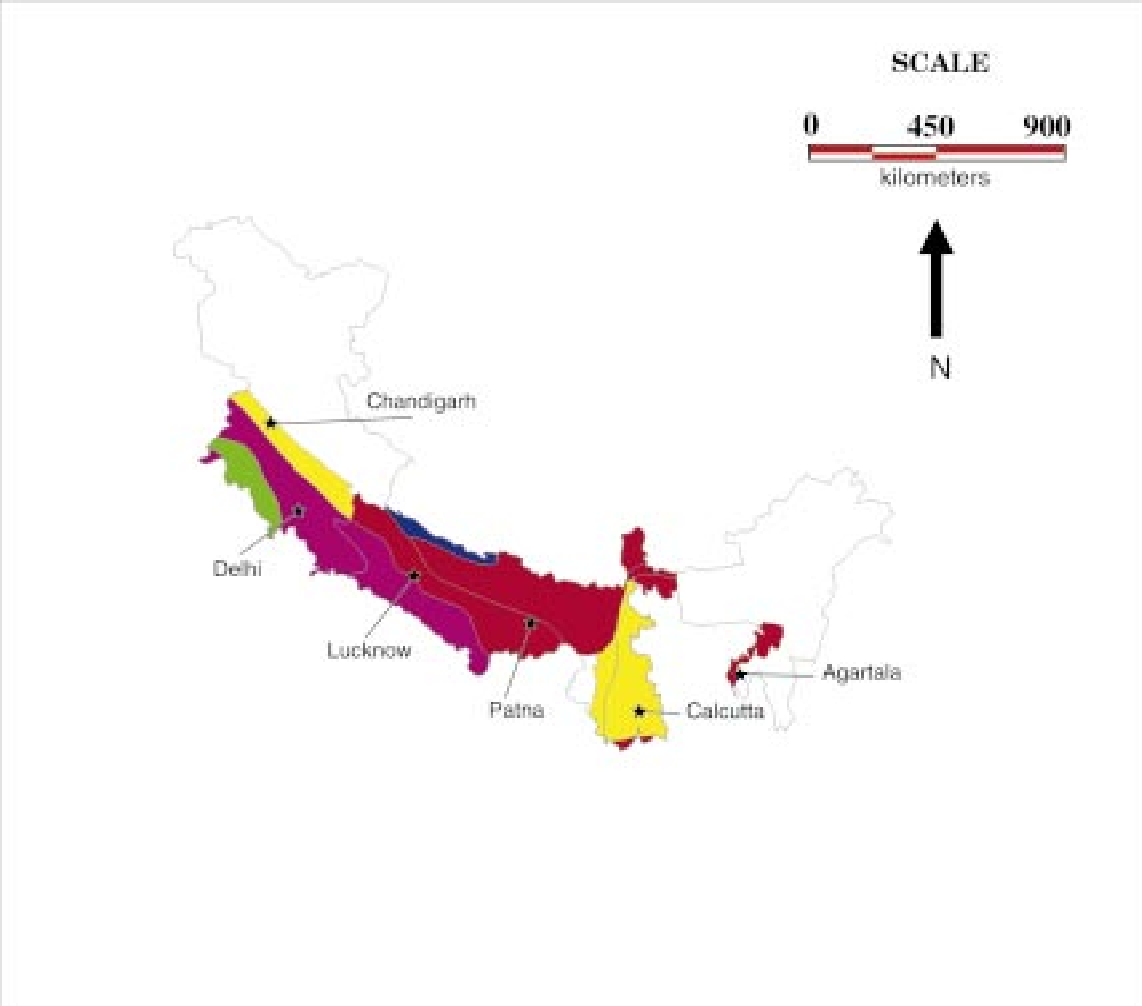
The total carbon stock (TC) in different agro-ecological regions (Sehgal et al. 1992) of the IGP (Figs. 10 & 11) indicates that the AERs 4 and 13 (hot semi-arid and hot subhumid moist) have the highest carbon stock followed by AERs 2, 9 and 15 (hot arid, hot sub-humid, dry and hot sub-humid, moist to humid) (Fig. 11). The contribution of SOC stock in the overall total carbon stock decreases with depth and SIC stock increases, indicating an inverse relation between these two forms of carbon (Fig. 10).

The SOC, SIC & TC stocks of each AESR at 30, 50, 100 and 150 cm depth of soils are shown in Table 3.

Figure 7 shows the spatial distribution of total carbon stock in different AERs in the IGP. The AERs 4 and 13 have the highest carbon stock followed by AERs 2, 9 and 15. Due to their low aereal extent other AERs have poor TC stock. It is observed that the contribution of OC stock over the TC stock in the IGP decreases from 83% at 30 cm depth to 30% at 150 cm depth whereas SIC increases at the corresponding soil depth.

Low and High Organic Carbon in Soils of the IGP

The poor base soils under humid tropical climate with relatively high annual rainfall (*Dystrustepts* / *Haplustepts* and Ultisols) with similar pH and CEC



Symbol	$CaCO_3$ Content	AESR Unit	Area	%
	High (H)	2.3	2754	6
	Medium (M)	2.1,4.1,4.3.	13623	32
	Low (L)	13.2	1441	3
	Very low (VL))	9.1,15.1	9491	22
	NIL	19.2,13.1,15.3,16.1 16.2, 17.2,18.5	16382	37

Figure 9. Map showing different degrees of $CaCO_3$ content in the soils of the IGP.

can differ in terms of content of OC due to cool or warm winter months (Bhattacharyya and Pal 1998; Bhattacharyya et al. 1992, 2000a; Velayutham et al. 2000). The mere presence of cool winter in many parts of the IGP covering northern states of Punjab and Haryana, does not, however, allow a higher SOC build up except in the cooler *Terai* areas (AESR 13.2) with Mollisols (Tables 4 and 5). Higher accumulation of OC in soils is related to vegetative cover supported by high rainfall. Such a

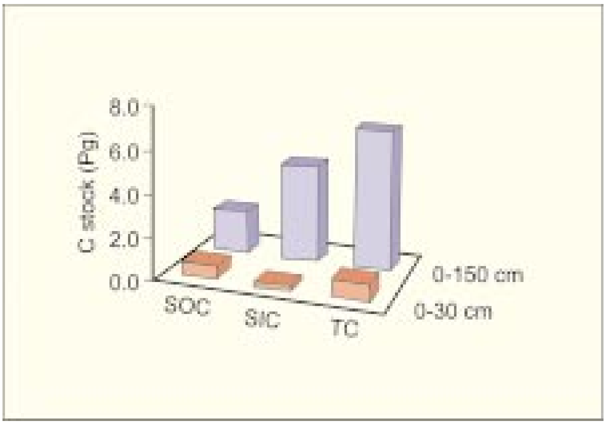


Figure 10. SOC, SIC, and TC stock in the IGP.

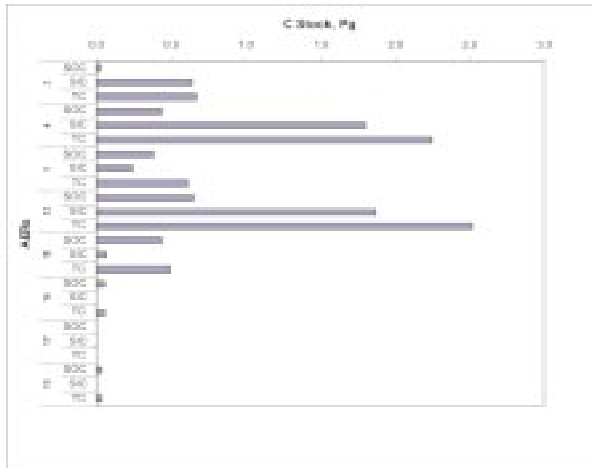


Figure 11. AER wise distribution of SOC, SIC and TC in the IGP in first 150 cm of soils.

situation is common in the eastern parts of the IGP under humid to per-humid agro-ecoregion (Table 1). When point data on OC content were compared, it was found that the cooler humid (AESR 13.2) and humid to per-humid (AESRs 15.3, 16.1 and 16.2) areas have sufficient OC in the first 30 cm of soil depth (Table 6). Similar observations were earlier made in the soils of Madhya Pradesh and Tripura (Bhattacharyya et al. 1996; Bhattacharyya and Pal, 1998) and in other parts of India (Jenny & Raychaudhuri, 1960; Velayutham et al. 2000; Bhattacharyya et al. 2000a). The combined influence of rainfall, temperature and other substrate (soil) quality determines the amount of OC accumulated in soils to qualify them as Mollisols, or other orders like Alfisols, Aridisols, Entisols and Umbric intergrades of Inceptisols commonly observed in the IGP (Fig. 12). This indicates that the most conducive condition favouring accumulation of OC in soils of the IGP should be humid to per-humid climate punctuated with a cool winter for 2-3 months.

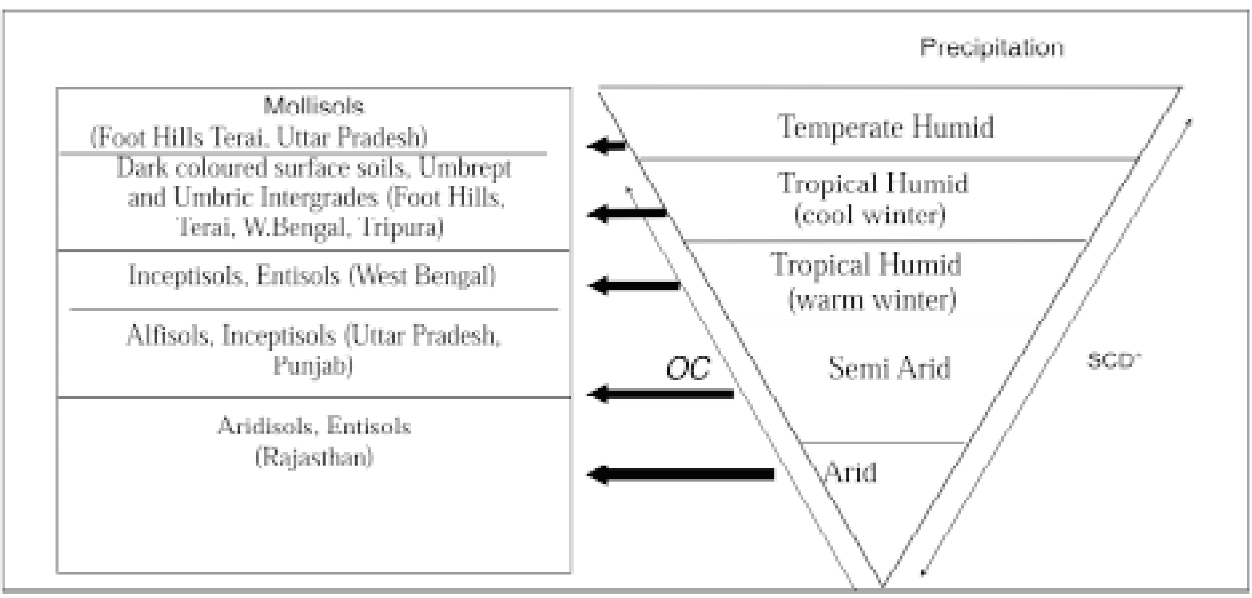


Figure 12. Accumulation of OC in soils of the IGP as influenced by rainfall, temperature and substrate quality. Bhattacharyya et al. (1999). *SCD = Surface Charge Density.

Table 4. Carbon stock in various soil orders of the IGP, India. *(values in Pg)*

Soil orders	Carbon	Soil depth range in cm			
		0-30	0-50	0-100	0-150
1. Entisols	SOC	0.080	0.130	0.250	0.274
	SIC	0.010	0.270	0.610	1.050
	TC	0.090	0.400	0.860	1.324
2. Inceptisols	SOC	0.330	0.480	0.790	1.152
	SIC	0.030	0.310	0.660	1.444
	TC	0.360	0.790	1.450	2.596
3. Alfisols	SOC	0.100	0.150	0.250	0.284
	SIC	0.080	0.160	0.340	1.372
	TC	0.180	0.310	0.590	1.656
4. Mollisols	SOC	0.120	0.150	0.250	0.269
	SIC	0.000	0.000	0.000	0.115
	TC	0.120	0.150	0.250	0.385
5. Aridisols	SOC	0.001	0.02	0.023	0.021
	SIC	0.008	0.014	0.348	0.610
	TC	0.009	0.03	0.371	0.631
TOTAL	SOC	0.630	0.910	1.560	2.000
	SIC	0.130	0.750	1.960	4.587
	TC	0.760	1.660	3.520	6.587

Table 5. Carbon stock in Mollisols of the IGP, India. *(values in Pg)*

Subgroups	Carbon	Soil depth range in cm			
		0-30	0-50	0-100	0-150
Aquic Hapludolls	SOC	0.0980	0.1211	0.2083	0.2201
	SIC	Nil	Nil	Nil	0.1155
	TC	0.0980	0.1211	0.2083	0.3356
Typic Hapludolls	SOC	0.0183	0.0260	0.0420	0.0492
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0183	0.0260	0.0420	0.0492
Total	SOC	0.1163	0.1471	0.2503	0.2693
	SIC	0.0000	0.0000	0.0000	0.1155
	TC	0.1163	0.1471	0.2503	0.3848

Carbon Stock in Soil Orders

Out of the 12 soil orders in Soil Taxonomy (Soil Survey Staff, 1999) 5 orders were identified in the IGP (Table 4) and the SOC stocks in 5 soil orders were estimated and may have relevance in comparing it in soils occurring elsewhere and can also serve as an international reference.

Entisols: This soil order is commonly found in almost all parts of the IGP encompassing different climatic areas. These soils occupy 8.3 m ha area covering 19 per cent of the IGP. These are commonly observed in young geomorphic surfaces, deserts and in coasts. A few Entisols commonly occur in lower topographic situation in a hydromorphic

Table 6. Organic carbon and calcium carbonate content of some representative soils from various agro-eco subregions (AESRs) of the IGP, India.

Horizon	Depth (cm)	pH (water)	CEC {cmol(+)kg^{-1}}	Organic carbon (Percent)	Calcium carbonate equiv. (Percent)
AESR 2.1 (MAT 27°C; MAP 218mm; LGP < 60 days) *Typic Camborthids* (Rajasthan)					
A	0-20	8.5	6.0	0.01	1.4
Bw1	20-53	8.5	6.1	0.01	6.4
Bw2	53-110	8.6	8.1	0.01	10.2
Ck1	110-144	8.6	7.0	0.01	11.0
Ck2	144-168	8.4	8.5	0.08	11.3
Ck3	168-180	8.5	10.2	0.01	3.9
AESR 4.1 (MAT 25°C; MAP 700mm; LGP 90-120 days) *Typic Natrustalfs* (Haryana)					
A1	0-5	10.4	10.2	0.30	0.5
A2	5-24	10.3	12.8	0.30	0.9
Btn1	24-56	9.8	14.8	0.20	1.4
Btn2	56-85	9.8	14.6	0.20	3.3
BCkn	85-118	9.6	11.2	0.10	12.4
Ckn	118-140	9.2	9.8	0.10	20.5
AESR 9.1(MAT 25°C; MAP 800mm; LGP 120-150 days) *Typic Haplustepts* (Punjab)					
A1	0-15	9.3	10.3	0.42	1.0
A2	15-28	10.1	11.1	0.21	1.0
Bw1	28-60	10.5	9.2	0.07	1.0
Bw2	60-72	10.5	11.7	0.08	1.0
Bw3	72-98	10.2	12.5	0.07	1.0
Bw4	98-135	10.0	14.0	0.08	1.0
AESR 13.2(MAT 22°C; MAP 1500mm; LGP 180-210 days) *Aquic Hapludolls* (Uttar Pradesh)					
Ap	0-15	7.1	26.9	2.1	0.0
A1	15-38	8.0	24.3	1.4	0.0
Bg1	38-53	8.3	21.5	1.1	1.2
Bg2	53-66	8.3	13.9	0.7	2.7
Cg1	66-94	8.4	10.0	0.5	2.5
Cg2	94-135	8.4	8.9	0.4	2.6
AESR 15.1(MAT 26°C; MAP 1500 mm; IGP 210-240 days) *Typic Endoaqualfs* (West Bengal)					
Ap	0-14	6.4	13.7	0.48	0.5
BA	14-38	6.9	15.0	0.20	0.9
Bt1	38-98	7.2	22.5	0.19	1.4
Bt2	98-150	7.5	25.6	0.10	2.3
AESR 15.3 (MAT 25°C; MAP 2000-3200; LGP 270-300 days) *Typic Dystrudepts* (Assam)					
Ap	0-25	4.5	13.6	1.84	Nil
B1	25-75	4.5	12.8	1.60	Nil
B2	75-150	4.6	14.4	0.86	Nil

(Continued)

Table 6. Continued

Horizon	Depth (cm)	pH (water)	CEC {cmol(+)kg^{-1}}	Organic carbon (Percent)	Calcium carbonate equiv. (Percent)
AESR 16.1 (MAT 23°C; MAP 2600-3000 mm; LGP 270-300 days) *Humic Dystrudepts* (West Bengal)					
Ap	0-25	5.0	6.5	1.4	Nil
Bw1	25-75	5.6	6.2	0.7	Nil
Bw2	75-150	5.7	7.5	0.6	Nil
AESR 16.2 (MAT 14°C; MAP >2500 mm; LGP 270-300 days) *Humic Dystrudepts* (West Bengal)					
Ap	0-25	4.6	9.3	3.2	Nil
Bw1	25-75	4.6	7.2	1.3	Nil
Bw2	75-150	4.7	8.4	1.3	Nil
AESR 17.2 (MAT ~22°C; MAP >3000 mm; LGP > 300 days) *Typic Epiaquept* (Tripura))					
Ap	0-13	5.5	7.8	1.3	Nil
Bg1	13-24	5.4	8.4	1.1	Nil
Bg2	24-43	5.3	8.9	0.4	Nil
Bg3	43-65	5.0	14.6	0.6	Nil
Bg4	65-115	5.2	15.6	0.5	Nil
AESR 18.5 (MAT ~26.7°C; MAP 1900 mm; LGP 240 - 270 days) *Typic Haplaquept* (West Bengal))					
Ap	0-25	6.6	22.0	0.7	Nil
Bw1	25-75	7.5	25.7	0.2	Nil
Bw2	75-150	7.8	26.1	0.2	Nil
Bg3	43-65	5.0	14.6	0.6	Nil
Bg4	65-115	5.2	15.6	0.5	Nil

MAT – Mean Annual Temperature; MAP – Mean Annual Precipitation; LGP – Length of Growing Period

(*aquic* moisture regime) environment. In the IGP, Entisols dominated by sands (*Psamments*) are common in Rajasthan whereas Entisols developed by fluvial deposits (*Fluvents*) and with aquic moisture regimes (*Fluvaquents*) are common in Punjab, Uttar Pradesh and West Bengal.

The SOC stock of Entisols ranges between 0.08 and 0.27 Pg in the upper 30 cm to 150 cm depth, respectively (Table 4). Within various subgroups of Entisols, *Typic Ustifluvents* have higher SOC stock than other subgroups (Table 7).

The SIC stock increases down the depth (Table 7). In *Typic Ustipsamments* $CaCO_3$ is not present. In *Typic Fluvaquents* $CaCO_3$ is not found in the first 30 cm whereas it is present in the lower horizons. Total SIC stock in these soils is 1.05 Pg (Table 7).

The total carbon (TC) stock in Entisols is 1.32 Pg in the first 150 cm soil depth which is approximately 20 percent of the TC stock in the IGP (Tables 4 and 7).

Inceptisols: Most of the IGP soils are grouped into the Inceptisols. In the IGP, the Inceptisols occupy 23.0 m ha area and cover 53 per cent area. At subgroup levels various characteristics ranging from moisture regime to fluvial characteristics are observed. Inceptisols occur mostly in the plains of Punjab, Uttar Pradesh, and West Bengal. A few Inceptisols also occur in the lower topographic situation in a hydromorphic (*aquic* moisture regime) environment in West Bengal and Tripura. These are mostly utilized for paddy cultivation.

The SOC stock of Inceptisols ranges from 0.33 to 1.08 Pg in the first 30 cm and 150 cm depth of soils, respectively (Table 4). Among the various subgroups of Inceptisols, *Typic Haplustepts* have

Table 7. Carbon stock in Entisols of the IGP, India. *(values in Pg)*

Subgroups	Carbon	Soil depth range in cm			
		0-30	0-50	0-100	0-150
Typic Torripsamments	SOC	0.0007	0.0011	0.0016	0.0021
	SIC	0.0049	0.0084	0.0180	0.0286
	TC	0.0056	0.0095	0.0196	0.0307
Typic Ustipsamments	SOC	0.0025	0.0037	0.0073	0.0098
	SIC	0.0000	0.000	0.000	0.000
	TC	0.0025	0.0037	0.0073	0.0098
Typic Ustifluvents	SOC	0.0610	0.0999	0.1941	0.2097
	SIC	0.0029	0.2590	0.5815	0.9946
	TC	0.0639	0.3589	0.7756	1.2043
Typic Fluvaquents	SOC	0.0179	0.0266	0.0433	0.0524
	SIC	0.0000	0.0015	0.0104	0.0261
	TC	0.0179	0.0281	0.0537	0.0785
Total	SOC	0.0821	0.1313	0.2463	0.2740
	SIC	0.0078	0.2689	0.6099	1.0493
	TC	0.0899	0.4002	0.8562	1.3233

the maximum content of SOC in the first 150 cm depth of soils followed by *Aquic Haplustepts*, *Fluventic Haplustepts*, *Udic Haplustepts*, *Vertic Endoaquepts*, *Typic Endoaquepts*, *Aeric Endoaquepts*, *Typic Haplustepts* and *Humic Dystrudepts* (Table 8).

Like Entisols, SIC stock of Inceptisols also decrease down the depth. It is interesting to observe that out of 10 subgroups of Inceptisols 6 subgroups do not have any inorganic carbon reserves. Maximum $CaCO_3$ has been found to be formed in the *Fluventic Haplustepts.* The SIC stock for other three subgroups namely *Typic Haplustepts*, *Aeric Endoaquepts*, and *Udic Haplustepts* are also substantial in the first 150 cm depth of soils. The SIC stock of the Inceptisols in the first 30, 50, 100 and 150 cm depth of soils is shown in Table 8.

The total C stock in the Inceptisols is 2.52 Pg in the first 150 cm which is 38 per cent of the total C stock of the soils of IGP (Tables 4 and 8).

Alfisols: Alfisols in the IGP with sodicity occur in Punjab, Uttar Pradesh and Haryana. At places in Punjab and Bihar these are found in lower topographic situation in hydromorphic (*aquic* moisture regimes) situation. These Alfisols occupy about 8.1 m ha covering 18.5 per cent area in the IGP.

The soil subgroups namely *Typic Natrustalfs* followed by *Typic Endoaqualfs*, *Aeric Endoaqualfs*, and *Aquic Natrustalfs* contain maximum amount of SOC stock in the IGP. Out of a total OC stock of 0.282 Pg, 46 percent SOC is stored in *Typic Natrustalfs* (Table 9).

The SIC stock in Alfisols increases with depth. Out of 4 subgroups of Alfisols, only one soil subgroup viz., *Aeric Endoaqualfs* do not contain $CaCO_3$. The $CaCO_3$ content is maximum in *Typic Natrustalfs* which contributes about 75 per cent of the total SIC stock of Alfisols (Table 9) in the first 150 cm of soils.

The total carbon stock in the Alfisols ranges from 0.1823 to 1.6536 Pg in the first 30 to 150 cm depth of soils, respectively. The highest content of

Table 8. Carbon stock in Inceptisols of the IGP, India. *(values in Pg)*

Subgroups	Carbon	Soil depth range in cm			
		0-30	0-50	0-100	0-150
Aquic Haplustepts	SOC	0.0199	0.0277	0.0466	0.0592
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0199	0.0277	0.0466	0.0592
Fluventic Haplustepts	SOC	0.0380	0.0598	0.1086	0.2036
	SIC	0.0000	0.2212	0.3686	0.7584
	TC	0.0380	0.2810	0.4772	0.9620
Udic Haplustepts	SOC	0.0314	0.0500	0.0957	0.1441
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0314	0.0500	0.0957	0.1441
Vertic Endoaquepts	SOC	0.0341	0.0503	0.0669	0.0827
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0341	0.0503	0.0669	0.0827
Typic Endoaquepts	SOC	0.0297	0.0280	0.0621	0.0822
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0297	0.0280	0.0621	0.0822
Aeric Endoaquepts	SOC	0.0214	0.0297	0.0547	0.0714
	SIC	0.0000	0.0286	0.1142	0.2570
	TC	0.0214	0.0583	0.1689	0.3284
Typic Haplustepts	SOC	0.1479	0.2247	0.3351	0.4845
	SIC	0.0307	0.0561	0.1801	0.4283
	TC	0.1786	0.2808	0.5152	0.9128
Humic Dystrudepts	SOC	0.0096	0.0136	0.0208	0.0278
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0096	0.0136	0.0208	0.0278
Total	SOC	0.3320	0.4798	0.7905	1.1520
	SIC	0.0307	0.3059	0.6629	1.4437
	TC	0.3630	0.7857	1.4534	2.5292

total carbon at 150 cm of Alfisols corresponds to about 29 per cent of the total carbon stock of the IGP (Tables 4 and 9).

Mollisols: Mollisols contain more than 1 per cent OC in the surface layers (Bhattacharyya and Pal, 1998; Velayutham et al. 2000). These soils occur in a very limited area in the terai and sub-Himalayan regions of the country (Deshpande et al. 1971) and occupy 1.4 m ha covering 3.5 per cent area of the IGP, India.

Only two subgroups of Mollisols are identified in the IGP (Table 6). The soil subgroup viz., *Aquic Hapludolls* are observed to contain 0.22 Pg whereas *Typic Hapludolls* contain 0.05 Pg of SOC in the first 150 cm depth (Table 5).

The Mollisols in the IGP generally do not contain $CaCO_3$. However, a little amount of $CaCO_3$ is observed in one of their subgroups below 100 cm (Table 5).

Table 9. Carbon stock in Alfisols of the IGP, India. *(values in Pg)*

Subgroups	Carbon	Soil depth range in cm			
		0-30	0-50	0-100	0-150
Typic Natrustalfs	SOC	0.0547	0.0827	0.1293	0.1317
	SIC	0.0159	0.0345	0.2154	1.0289
	TC	0.0706	0.1172	0.3447	1.1594
Aquic Natrustalfs	SOC	0.0112	0.0187	0.0331	0.0442
	SIC	0.0666	0.1084	0.1039	0.3094
	TC	0.0778	0.1271	0.1370	0.3536
Aeric Endoaqualfs	SOC	0.0165	0.0258	0.0418	0.0580
	SIC	0.0000	0.0000	0.0000	0.0000
	TC	0.0165	0.0258	0.0418	0.0580
Typic Endoaqualfs	SOC	0.0153	0.0228	0.0422	0.0501
	SIC	0.0021	0.0147	0.0257	0.0337
	TC	0.0174	0.0375	0.0679	0.0838
Total	SOC	0.0977	0.1500	0.2464	0.2840
	SIC	0.0846	0.1576	0.3450	1.3720
	TC	0.1823	0.3076	0.5914	1.6536

The total carbon stock ranges from 0.1163 to 0.3848 Pg in the first 30 to 150 cm depth of soils, respectively. The total carbon stock in Mollisols has a share of 8.1 per cent of the total carbon stock of the IGP (Tables 4 and 5).

Aridisols: In the IGP, a small part in the state of Rajasthan is represented by Aridisols. These soils contain appreciably higher amount of $CaCO_3$. These soils occupy 2.754 m ha covering about 6 per cent area of the IGP.

In Aridisols, the SOC stock is relatively less. The two soil subgroups, *Typic Camborthids* and *Typic Calciorthids*, contain 0.0053 and 0.0157 Pg SOC respectively, in the first 150 cm soil depth (Table 10). The SIC stock ranges from 0.0076 to 0.6096 Pg in first 30 to 150 cm of soils, respectively. The total carbon stock ranges from 0.0088 to 0.6306 Pg in similar depth ranges and account for 1 per cent to 9.6 per cent of the total carbon stock of the IGP (Tables 4 and 10).

SOC and SIC Stock in the IGP, India and World

Table 11 shows the SOC and SIC stock of the IGP, India, tropical regions and the world. It is interesting to note that SOC stock of the IGP constitutes 6.45% of the total SOC stock of India, 0.30% of the tropical regions and 0.09% of the world in the first 30 cm depth of soils. The corresponding values for SIC are 3.20% for India, 0.17% for tropical regions and 0.06% for world, respectively. Figure 13 shows the relative proportion of SOC and SIC in the IGP. Figure 14 indicates that IGP has only 3% SOC stock of the country. The impoverishment of SOC in the IGP as compared to tropical regions and world in general and to India in particular is thus apparent.

Table 10. Carbon stock in Aridisols of the IGP, India. *(values in Pg)*

Subgroups	Carbon	Soil depth range in cm			
		0-30	0-50	0-100	0-150
Typic Camborthids	SOC	0.0001	0.0010	0.0023	0.0053
	SIC	0.0048	0.0080	0.0181	0.0295
	TC	0.0049	0.0090	0.0204	0.0348
Typic Calciorthids	SOC	0.0011	0.0174	0.0206	0.0157
	SIC	0.0028	0.0060	0.3296	0.5801
	TC	0.0039	0.0234	0.3502	0.5958
Total	SOC	0.0012	0.0184	0.0229	0.0210
	SIC	0.0076	0.0140	0.3477	0.6096
	TC	0.0088	0.0324	0.3706	0.6306

Table 11. Total carbon stock in IGP, India and other regions.

Region IGP, India	Soil depth range (cm)		
	0-30	0-100	0-150
	<——Pg——>		
SOC	0.63 (6.45/0.30/0.09)*	1.56 (6.23/0.39/0.10)*	2.00 (6.67/0.32/0.08)*
SIC	0.13 (3.20/0.17/0.06)*	1.96 (8.76/0.93/0.27)*	4.58 (—/—/—)*
Total	0.76 (5.50/0.27/0.0.08)*	3.52 (7.42/0.58/0.16)*	6.58 (10.28/—/—)*
India[1]			
SOC	9.77	25.04	29.97
SIC	4.06	22.37	34.03
Total	13.83	47.41	64.00
Tropical Regions[2]			
SOC	207	395	628
SIC	76	211	—
Total	283	604	
World[2]			
SOC	704	1505	2416
SIC	234	722	—
Total	938	2227	—

* Values in parentheses indicate % of stock in India, Tropical Regions and the world respectively,

\- = figures not available

[1] Bhattacharyya *et al* (2001)

[2] Batjes (1996)

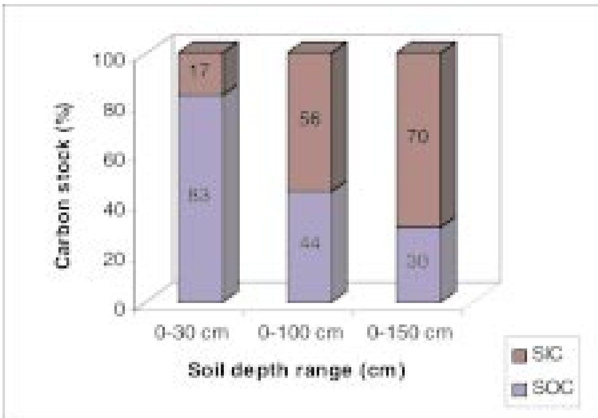


Figure 13. Relative proportion of SOC and SIC stock in IGP in different soil depth range.

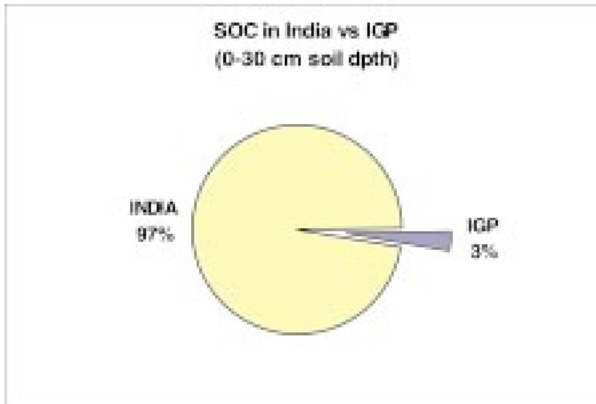


Figure 14. Relative share of SOC stock of the IGP over that of India.

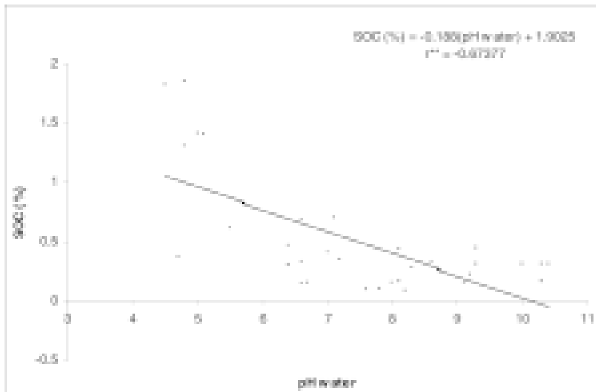


Figure 15. Correlation between pH water and SOC in IGP, India (0-30 cm soil depth).

Correlation of Carbon Content with Soils, Climate and Crops in IGP, India

Correlation of Soil Carbon Content (SOC) with selected soil parameters

Correlation between SOC and pH: The soils of IGP contain variable amounts of SOC depending on rainfall or aridity which results in higher degree of decomposition and absence of luxuriant vegetation. All these factors indirectly influence the soil reaction (pH). Increase in aridity increases the pH due to precipitation of $CaCO_3$ and this increases the ESP. Therefore it is expected that an increase in rainfall or decrease in aridity retards the formation of $CaCO_3$ and also decreases soil pH. Therefore, one can expect an increase in SOC with the decrease of soil pH (Bhattacharyya et al. 2003).

The relation between pH (water) and SOC is inverse in the soils of IGP (Fig 15). A highly significant negative correlation between SOC and pH (r = 0.67) was observed.

Correlation between SIC and pH: The soils of IGP have both pedogenic and non-pedogenic calcium carbonate (Pal et al. 2000). The formation of pedogenic calcium carbonate can be attributed solely to ranges from and to semi-arid climate. This leads to precipitation of $CaCo_3$ and increase in the ESP and SAR. Therefore, the formation of calcium carbonate is also a basic process for the development of sodicity (Pal et al. 2000) to increase soil pH. It is expected that the soils (especially those under drier tracts) of IGP, India may have a positive correlation between SIC and pH. The data observed follow a trend similar to that shown in figure 16, which indicate a highly significant correlation (r = 0.496).

Correlation between SOC and Clay: The significance of nature and content of clay as substrate has been stressed as the most important factor influencing organic carbon dynamics (Arrouays et al. 1995). Soils containing minerals with higher surface area are the most suitable substrate for sequestering organic carbon (Bhattacharyya and Pal 2003a).

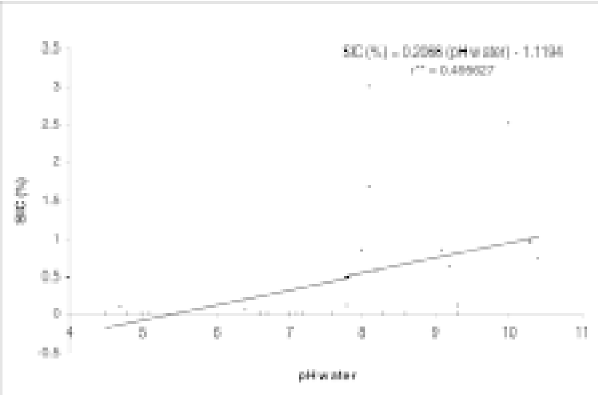


Figure 16. Correlation between pH water and SIC in IGP, India (0-150 cm soil depth).

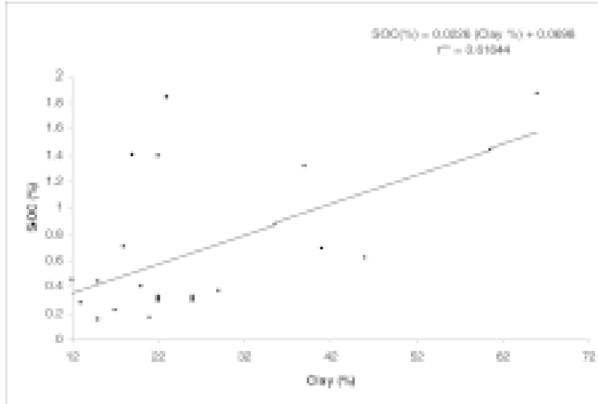


Figure 17. Correlation between SOC and Clay in IGP, India (0-30 cm soil depth).

Since the finer colloids have more surface area a positive correlation between clay particles and organic carbon is expected. The data generated through this study also supports this connotation as shown in figure 17. A highly significant correlation between SOC and clay (r = 0.616) is observed in the soils of the study area. An earlier study on black soils also indicated a similar correlation between substrate and SOC (Bhattacharyya et al. 2003).

Relation between SIC and Clay

It has been reported that clay and organic matter remain as a complex form known as clay-humus complexes. SIC present, mostly in the form of calcium carbonate, also has a cementing effect in binding inorganic colloids; mainly in binding the clay-fractions. It has been reported that the amount of finer particles dominated by shrink-swell minerals and sodium in exchange complex may control the water movement in an Ultisol profile (Bhattacharyya et al. 2003). Therefore, in an arid climate the high ESP in the clay exchange site increases the precipitation of carbonates and hence a positive correlation between clay and SIC is expected. This model of understanding, however, does not hold good for the soils of IGP. The probable reason could be that many areas in IGP, India experience more rainfall as compared to the areas under Vertisols. Figure 18 shows the relation between SIC and Clay in IGP, India.

Relation between SOC and BD

Bulk density (BD) indicates the weight of all the organic and inorganic materials of a given volume of soil. Higher SOC shows lower BD. High clay content and introduction of a farm machinery causes compaction of subsurface layer, which increases BD. Bulk density also varies with the content of coarser fragments in soils. There is a growing concept that BD might change due to change in land use pattern. In a study of Zagrous Mountains of Iran, Hajabassi et al. (1997) reported an increase in BD. Figure 19 shows the negative correlation

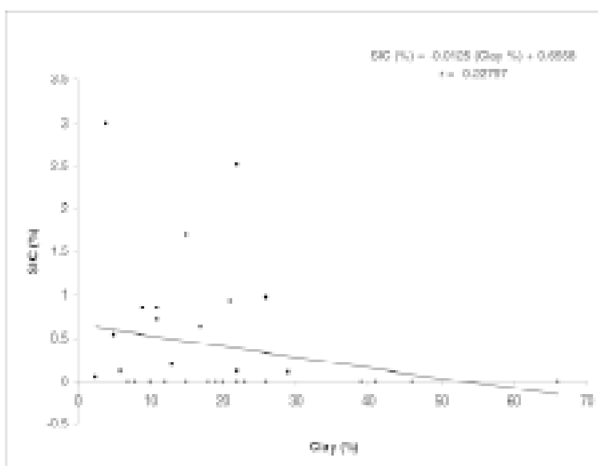


Figure 18. Correlation between SIC and Clay in IGP, India.

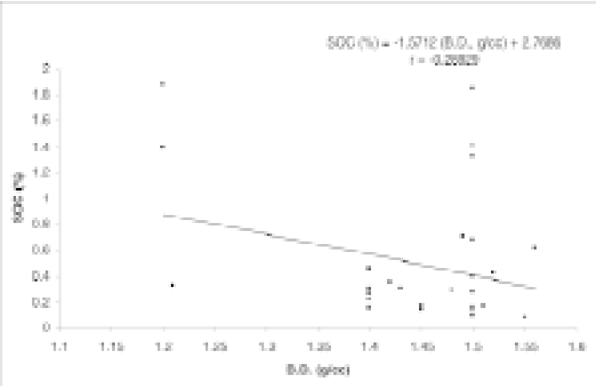


Figure 19. Correlation between SOC and BD in IGP, India.

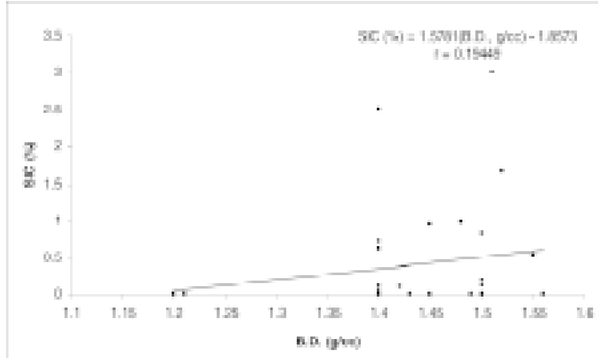


Figure 20. Correlation between SIC and BD in IGP, India.

between SOC content and BD in first 30 cm depth soils.

Relation between SIC and BD

Since SIC is contributed by $CaCO_3$ the increase in content of SIC increases BD value as shown in figure 20. Similar observations were earlier made by Bhattacharyya et al (2003) while studying the black soils of the central and southern India.

Relation between SOC and CEC

It is well-known that the interaction between organic carbon and soil colloids and the building up of SOC is a function of quality of substrate (Tate and Theng, 1980; Bhattacharyya and Ghosh, 1994, 1995; Feller and Bear, 1997; Parfitt et al. 2002). Because of higher surface area and surface charge mostly the clay components act as the substrate of the soils to store SOC. The cation exchange capacity (CEC) may therefore be considered as an indirect measurement of the quality of soil substrate.

It is therefore expected that SOC and CEC should show a positive correlation. Figure 21 supports this as indicated by highly significant correlation (r = 0.514).

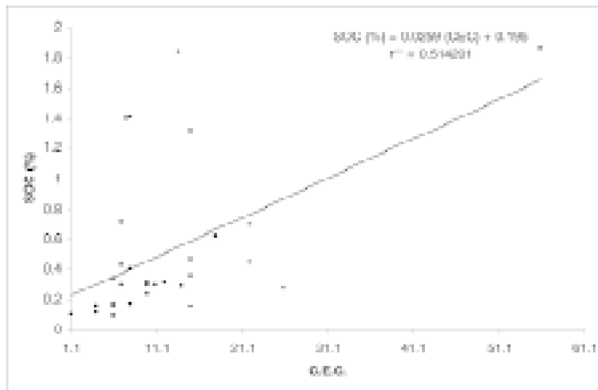


Figure 21. Correlation between SOC and CEC in IGP, India.

Relation between SIC and CEC

$CaCO_3$, the contributing factor for SIC, may block exchange spots as a cementing agent and reduce CEC. However, the trend of relation between SIC and CEC does not support this. It indicates that the $CaCO_3$ present in soils of IGP perhaps do not positively influence CEC as shown in figure 22.

Correlation between Carbon and Climate in IGP, India

Relation between SOC and SIC vs. MAR and MAT: Many factors influence SOC and SIC accumulation in soils. Rainfall and temperature have been reported to be major climate factors which help in building SOC (Jenny and Raychaudhari, 1960; Velayutham et al. 2000).

The correlation trend between SOC and SIC vs MAR is just opposite. SOC increases if rainfall increases in IGP, India (Fig. 23) while SIC increases with decreasing rainfall (Fig. 24).

Similarly, the trend of correlation between SOC and SIC vs MAT is also opposite. SOC decreases with increase in MAT (Fig. 25) while the reverse is observed with SIC vs MAT correlation (Fig. 26)

The general relation between SOC and SIC has earlier been reported as inverse (Bhattacharyya et al. 2000a). Similar observations were found for soils of IGP, India as shown in figure 27.

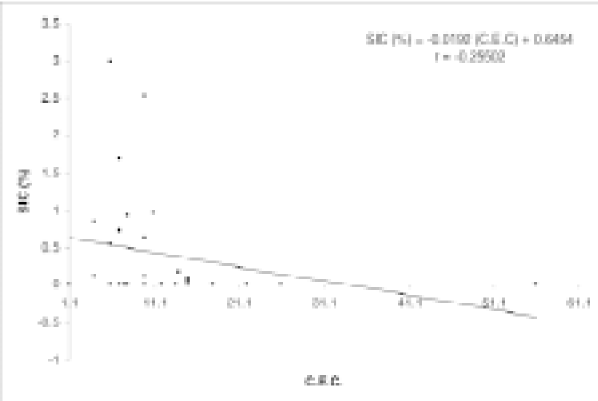


Figure 22. Correlation between SIC and CEC in IGP, India.

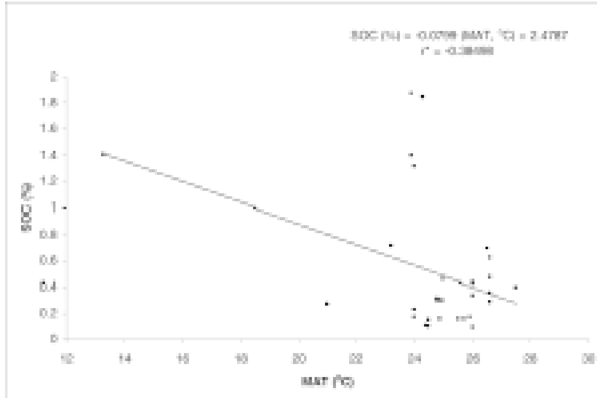


Figure 25. Correlation between SOC and MAT in IGP, India.

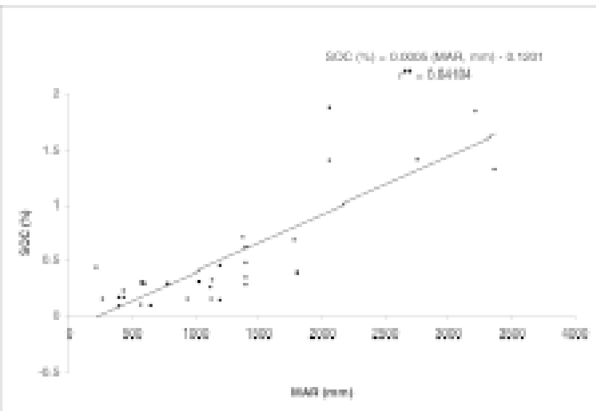


Figure 23. Correlation between SOC and MAR in IGP, India.

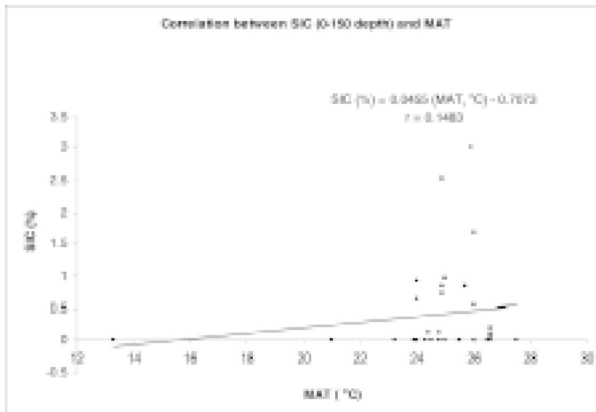


Figure 26. Correlation between SIC and MAT in IGP, India.

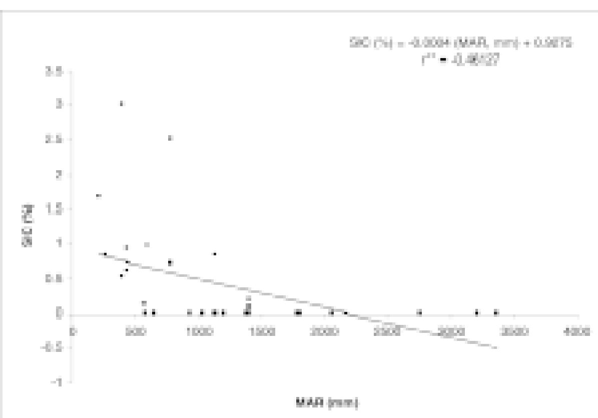


Figure 24. Correlation between SIC and MAR in IGP, India.

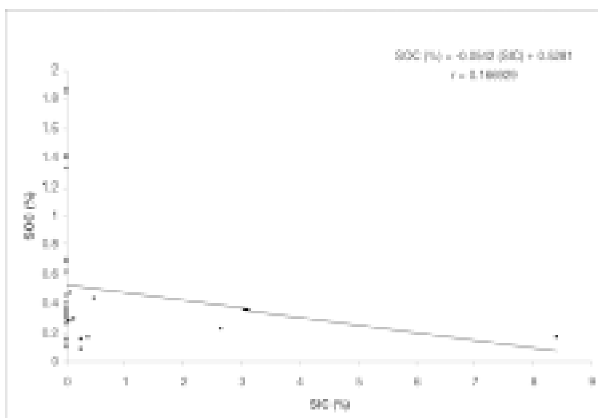


Figure 27. Correlation between SOC and SIC in IGP, India.

Correlation of carbon content with crops

SOC in various land use systems: Cutting across different AESRs, horticultural system shows highest SOC content (1.12%) in IGP, India (Fig. 28). (Naitam and Bhattacharyya, 2004). Among the agricultural systems some major cropping patterns were studied. These are paddy-wheat, paddy-paddy, cotton-wheat and groundnut (Fig. 28).

It has been generally observed that cereal-based systems contribute to higher accumulation and stabilization of organic matter (West and Post, 2002; Ludwig et al. 2003) especially in paddy-paddy systems. The mechanisms involved in a preferential accumulation of organic matter in wetland paddy soils have been explained mainly due to anaerobiosis and the associated chemical and biochemical changes that take place in submerged soils following their prolonged flooding under water. The decomposition of soil or added organic matter is relatively fast, complete and efficient under aerobic condition where oxygen is the electron acceptor. However, the decomposition of organic matter in the absence of oxygen is slow, incomplete, and inefficient. Besides, the formation of recalcitrant complexes with organic matter in these soils render organic mater less prone to microbial attacks (Sahrawat, 2004). All these factors along with decreased humification of organic matter lead to net accumulation of organic matter in paddy-paddy systems. The SOC built-up under submerged conditions is the reason for maintaining high organic matter and productivity in paddy-paddy systems in IGP, India. The study therefore indicates the benefits of this crop in IGP for maintaining soil health.

SIC in various land use systems

The horticultural system does not contain $CaCO_3$. In general, cotton-wheat cropping pattern registered higher SIC in first 150 cm depth of soils followed by paddy-wheat, groundnut and paddy-paddy cropping patterns (Fig. 29).

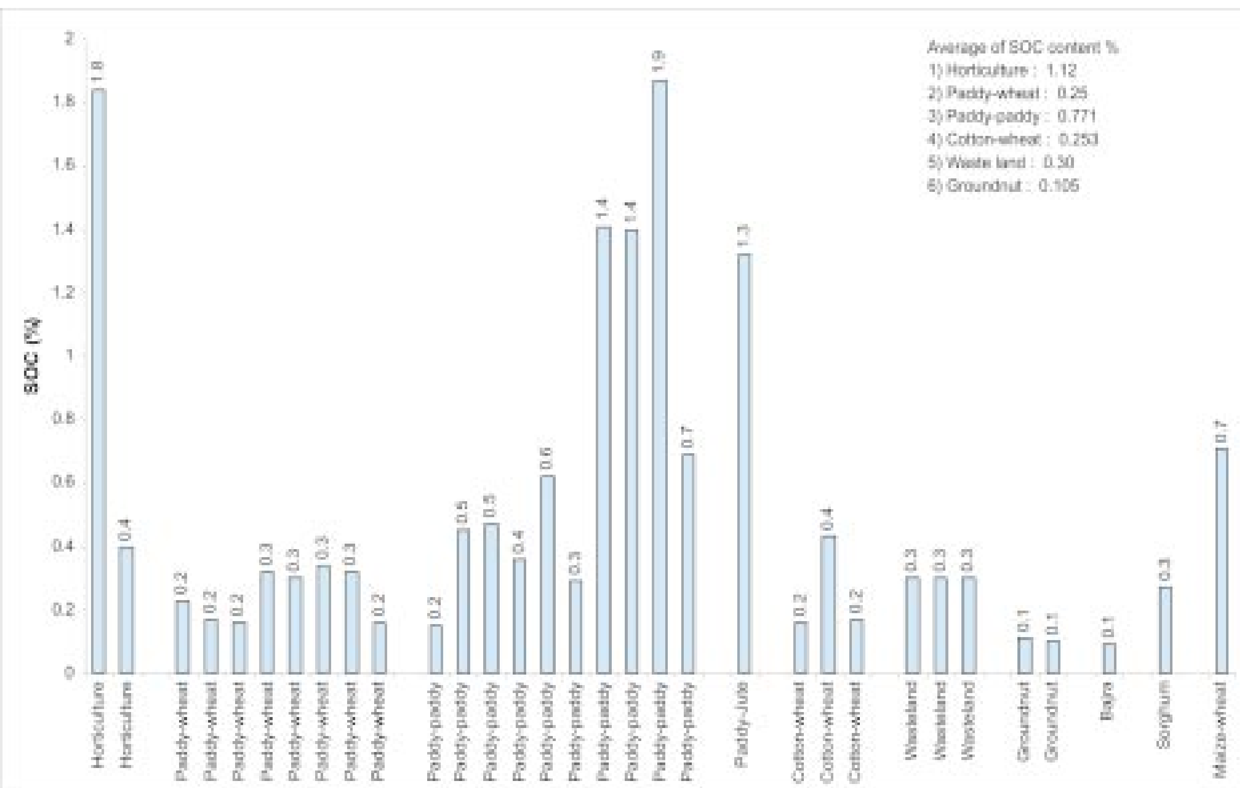


Figure 28. SOC content (0-30 cm) and cropping pattern in IGP, India.

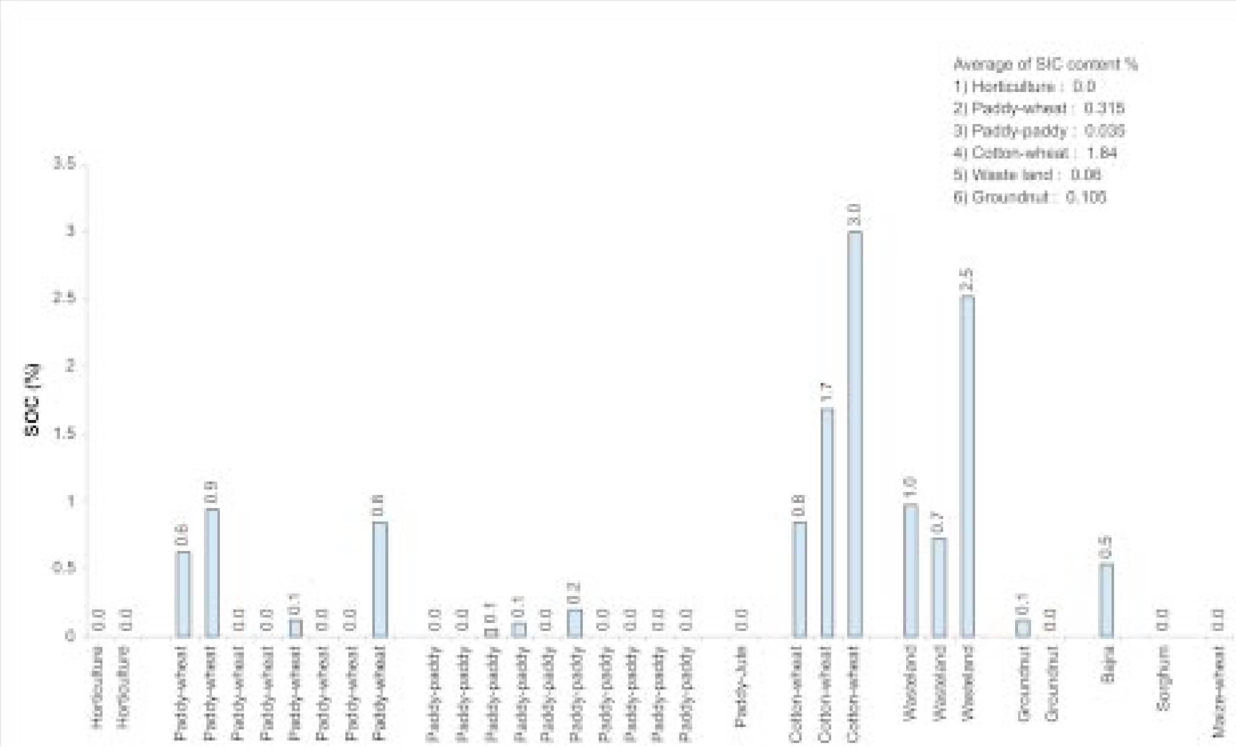


Figure 29. SIC content (0-150 cm) and cropping pattern in IGP, India.

Carbon Transfer Model

Nearly 60 per cent area in the IGP, India falls under arid, semi-arid, and dry sub-humid bioclimatic systems. In India, calcareous soils have been reported to cover 228.8 m ha area which represents 69.4 per cent of total geographical area of the country (Pal et al. 2000). Earlier studies have been conducted on the content, occurrence and nature of $CaCO_3$ in Indian soils (Pal et al. 2000; Pal and Bhattacharyya, 2000; Srivastava et al. 2002). Table 12 shows the bioclimatic system *vis-à-vis* agroecological subregions (AESRs) of India. It is interesting to note that the IGP, India extends with a rainfall of 2800 mm in the east to 218 mm in the far west. Out of 14 AESRs, 7 AESRs show accumulation of $CaCO_3$ in soils (Fig 30). On an average 4.58 Pg of total SIC stock is stored in first 150 cm depth of soils in 29.5 m ha of the IGP which constitute 67.5 per cent area of the IGP, India (Table 1, Fig. 31). This inorganic carbon pool in the IGP is about 8.8 per cent of the total SIC pool of India in first 100 cm depth of soil (Table 11, Fig. 31).

Organic Carbon Sequestration: Figure 32 shows the pathway of conversion of inorganic form of carbon to organic form by plants (through photosynthesis) and by soils (through incorporation of organic matter and its decomposition). The organic matter from plants and decaying animals and microorganisms after decomposition in soil is sequestered in organic form. This is more in per-humid, humid and sub-humid ecosystem with mean annual rainfall of 1500 mm and above. The organic carbon sequestration in soil under natural conditions (without any better agricultural management practice including irrigation) in semi-arid and arid climate also takes place, but its degree is, however, low to very low.

Inorganic Carbon Sequestration : The atmospheric CO_2 alongwith the CO_2 formed by respiration of the roots and soil animals (both micro and macro)

Table 12. Distribution of rainfall in different bioclimatic systems.
[AESR: Agro ecosubregions; H : Humid; PH : Per-humid; SH (m) : Sub-humid (moist); SD (d) : Sub-humid dry; SA (d) : Semi-arid dry; A : Arid]

AESR	BIOCLIMATE	MAR	STATION	STATE
18.5	H	1700	Sagar Island	West Begal
17.2	PH	2065	Agartala	Tripura
16.2	PH	2800	Darjeeling (South)	West Begal
16.1	PH	2800	Baghdogra	West Bengal
15.3	PH	2600	Silchar	West Bengal
15.1	SH (m)	1586	Midnapur	West Bengal
13.2	SH(d)	1355	Pantnagar	Uttaranchal
13.1	SH(m)	1115	Pusa	Bihar
9.2	SA(d)	1254	Phaijabad	Uttar Pradesh
9.1	SA(d)	704	Ludhiana	Punjab
4.3	SA(d)	763	Kanpur	Uttar Pradesh
4.1	SA(d)	799	New Delhi	Delhi
2.3	A	461	Hissar	Haryana
2.1	A	218	Hanumangarh	Rajasthan

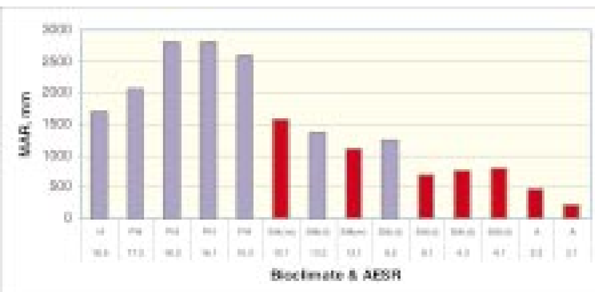


Figure 30. Rainfall distribution in different AESRs showing accumulation of $CaCO_3$ (Red coloured areas)

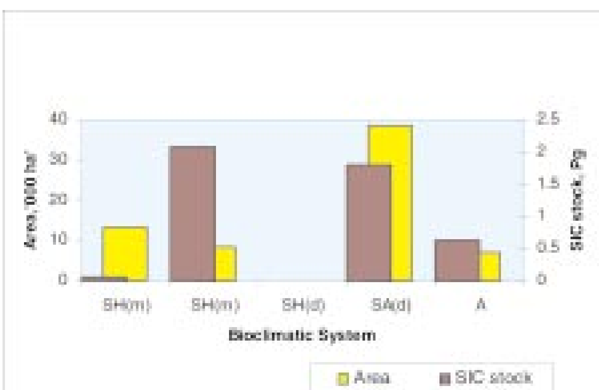


Figure 31. SIC stock in different bioclimatic system in the IGP.

forms H_2CO_3 in an aqueous solution in soil

$$CO_2\,(g) + H_2O\,(liquid) \rightleftharpoons H_2CO_3\,(liquid)$$

The generally higher level of soluble and exchangeable Ca^{2+} ions react with H_2CO_3 to form soluble $Ca(HCO_3)_2$ in the soil environment.

$$Ca^{2+} + H_2CO_3 \rightleftharpoons Ca(HCO_3)_2$$

Calcium bicarbonate moves down the soil profile in per-humid, humid and sub-humid (moist) bioclimate and depending on the quantity of rainfall $Ca(HCO_3)_2$ gets concentrated deep down in the soils. Thus, it is not generally observed in soil profiles within 150 cm depth which is usually the lower limit of profile depth examined in the field.

With the onset of dry climate, the pedoenvironment also gets dry. The dry pedoenvironment initiates the formation of calcium carbonate as powdery lime which gets accumulated over time and increase in size to form lime concretions (*conca*). The amount of such *conca* increases with depth. With lesser rainfall the concentration of these *concas* increase and gradually cover the entire depth of soil profile. The genesis

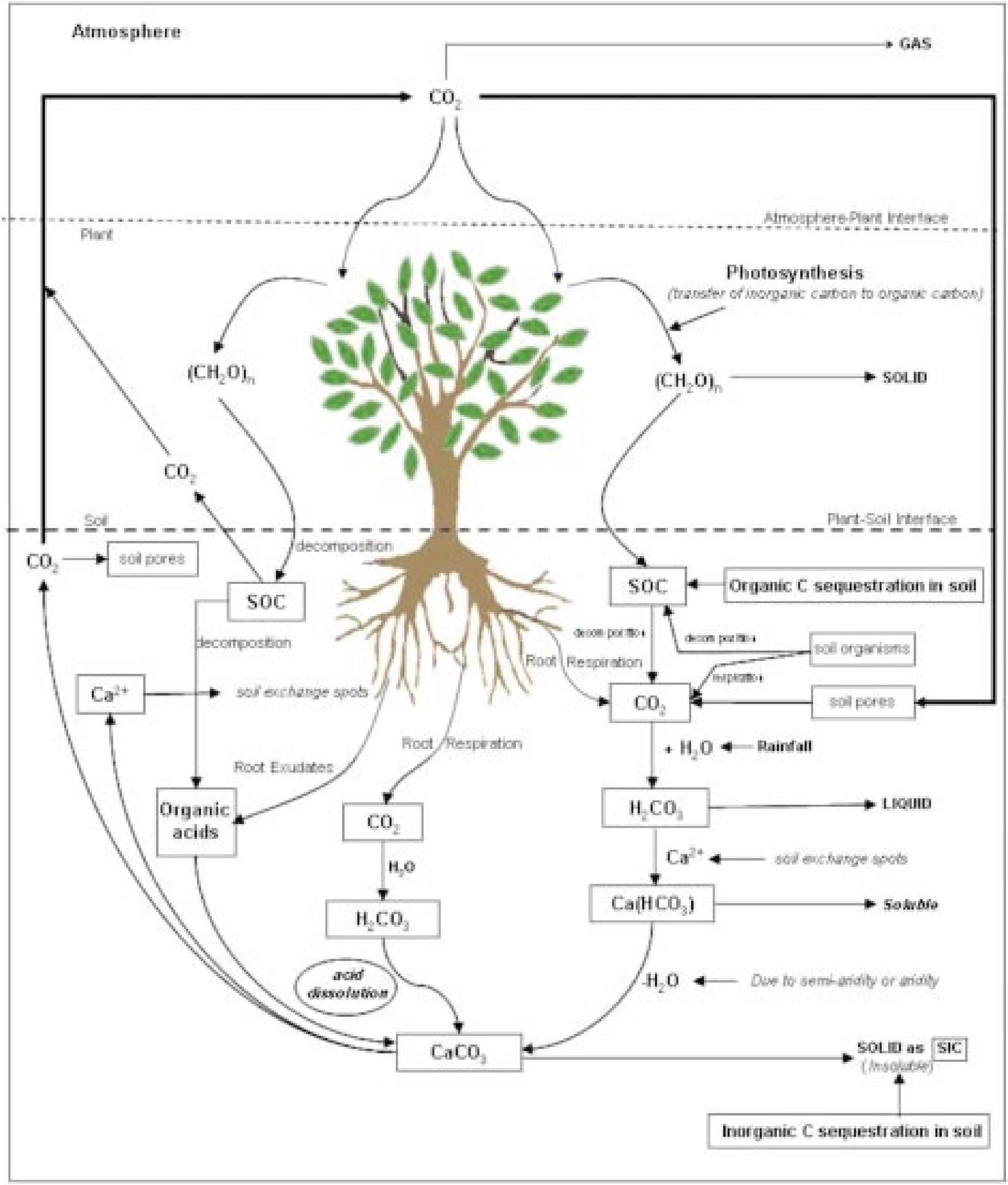


Figure 32. Carbon transfer model showing organic and inorganic carbon sequestration in soil.

and characteristics of these *concas* called pedogenic carbonates have been detailed elsewhere (Pal et al. 2000; Srivastava et al. 2002). Influence of biotic control in the formation of pedogenic $CaCO_3$ has also been reported (Monger and Gallegos, 2000). This is the reason why $CaCO_3$ becomes common in soils of arid to sub-humid (moist) bioclimatic systems.

Dissolution of Pedogenic Calcium Carbonate: It has been reported that in soils of dry bioclimate exchangeable sodium percentage (ESP) and $CaCO_3$ content increase with pedon depth (Pal et al. 2000). This depth function suggests that due to the formation of $CaCO_3$ sodicity develops initially in the subsoil regions. The subsoil sodicity impairs the HC of soils (Pal et al. 2000) and with the passage of time entire soil profile becomes sodic.

The native source of $CaCO_3$ gets dissolved through the actions of acidic root exudates and carbonic acid formed due to evolved carbon-di-oxide from root respiration in aqueous solution. The formation of calcium bicarbonate takes place.

$$\underset{\substack{\text{organic acid}\\\text{(root exudates)}}}{CaCO_3 \rightarrow H_2CO_3} \,\&\, Ca(HCO_3)_2 \rightarrow Ca^{2+} + H_2O + CO_2\uparrow$$

The soluble $Ca(HCO_3)_2$ helps restoring 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 atmosphere and thus makes the cycle complete (Fig. 17). This model of C-transfer from inorganic (atmospheric CO_2) to organic (CH_2O), organic (CH_2O) to inorganic (CO_2 in soil and then to $CaCO_3$ and again from inorganic ($CaCO_3$) to inorganic (CO_2), which indirectly help in better vegetative growth (organic) in improved soil environment, is largely active in all the bioclimatic systems in the IGP, India with drier climate showing more inorganic carbon sequestration. It may be mentioned that a few AESRs did not show $CaCO_3$ in soils within 150 cm depth (Fig. 30).

It has been stated that inorganic carbon sequestration in soils through the formation of pedogenic $CaCO_3$ is a bane and requires management interventions. Chemical treatments of soils alongwith vegetative cover (either plantations and/or agriculture/horticulture) help in dissoluting the native $CaCO_3$ as explained above. This may save these soils from further degradation (Fig. 33 a and b).

Correlation between SOC and SIC in the Dry Tracts of the IGP, India: A negative correlation between SOC and SIC in the arid (AESRs 2.1 and 2.3), semi-arid (AESRs 4.1 and 4.3), sub-humid (dry) (AESR 9.1) and sub-humid (moist) (AESR 13.1) is generally observed (Fig. 34). The regression equations are shown in Table 13. The relationships indicate the driving effect of SOC in the dissolution of carbonate and subsequent mobilization enhancing Ca nutrition, better soil structure, better hydraulic properties thus indirectly promoting a better crop growth. Better crop growth in turn initiate more roots to increase partial pressure of CO_2 to further the process of dissolution of native $CaCO_3$. Getting dissolved in water, the soil CO_2 concentrated from SOC decomposition can thus be transformed to the precipitated carbonate *via* bicarbonate in solution.

Validation of Carbon Transfer Model

The soil scientists, agronomists, environmental experts, forest experts, botanists and zoologists have always stressed on the source of OC as far as plant nutrition and health of soils are concerned. Despite the availability of various estimates of the world storage of SOC, there is very little effort to estimate the carbon stored in inorganic form, primarily as calcium carbonate. Efforts have, however, been made to take stock of the inorganic carbon mass in desert soils and in the soils of the world (Batjes, 1996). It has been stated that the soils, which store large quantity of carbonates, play

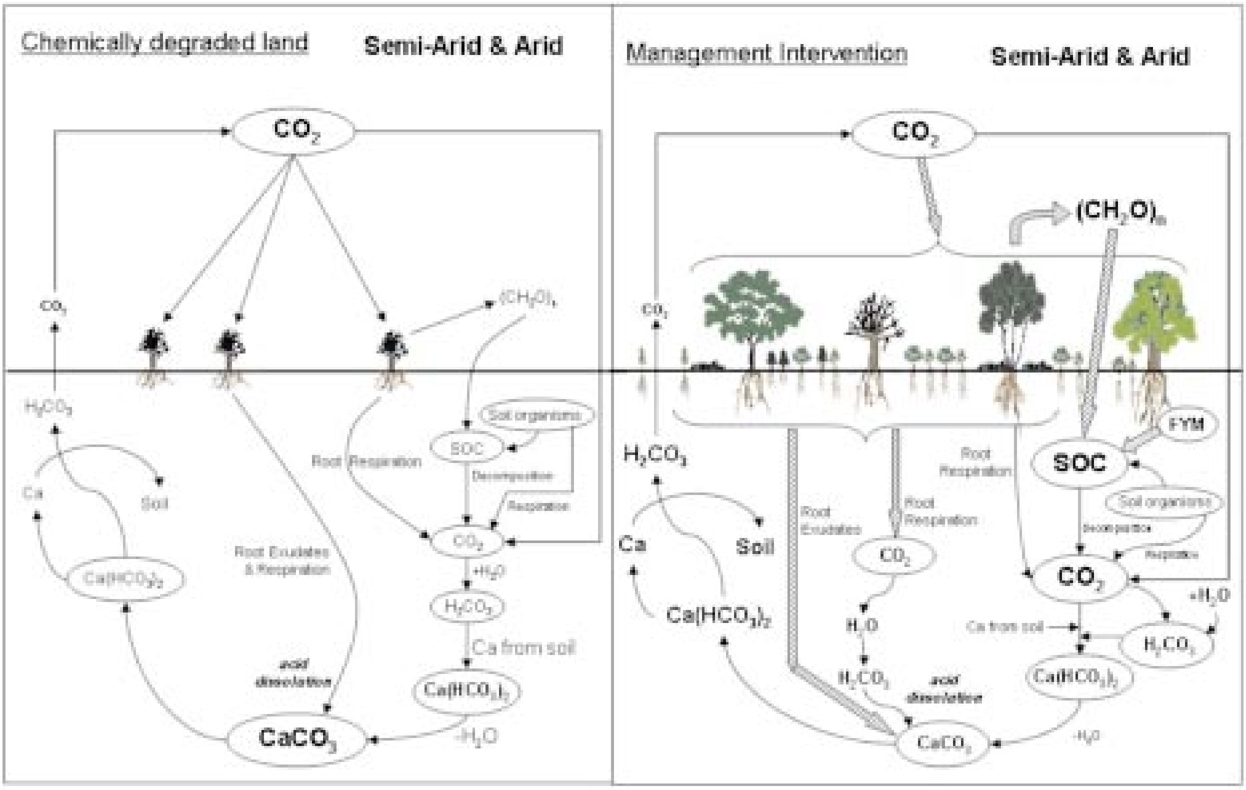


Figure 33. Carbon transfer in semi-arid and arid bioclimatic systems of (a) chemically degraded land, and (b) areas showing management intervention (the size of circle and letters indicate relative proportion of individual component)

an important role in the global carbon cycle. However, the role of these carbonates as a probable source of calcium nutrition in soils of India was reported only recently (Pal et al. 2000; Bhattacharyya et al. 2001). The huge source of $CaCO_3$ in arid and semi-arid ecosystem seems to be useful during the establishment of vegetation by appropriate ameliorative methods in these soils as the plant roots can dissolve the immobile $CaCO_3$ and can ultimately trigger the process of Ca release in the soils and thus can act as a natural ameliorant for the sodic soils. Importance of calcium as environmental sensor was reported recently (Nayyar, 2003).

After 30 months of reclamation of sodic soils of the IGP with gypsum followed by rice cropping in the reclaimed sodic soils showed that rice as first crop creates an environment for the dissolution of native $CaCO_3$ as reflected in the increase of Ca^{2+} and Mg^{2+} ions in the exchange complex and simultaneous decrease in native $CaCO_3$ (Sharma and Bhargava, 1981) (Table 14). During 30 months of cultural practice the dissolution of $CaCO_3$ (<2 mm) was 224 mg per 100g soil in the first 100 cm of profile (Pal et al. 2000). These sodic soils were reclaimed by this improved the activity of urease and dehydrogenase by about three fold (Rao and Ghai, 1985). These examples demonstrate that although the presence of $CaCO_3$ has been considered of doubtful significance as displacement of exchangeable Na by Ca (from $CaCO_3$) in soils with pH 8.0, it can be greatly affected by factors like management interventions (Gupta and Abrol, 1990) through which SOC content increased considerably (Swarup et al. 2000). This fact assumes importance on considering the fact that the SIC stock in the IGP is more than double the SOC stock in first 150 cm depth (Table 4). This huge SIC stock in the IGP remains as a hidden treasure in terms of available

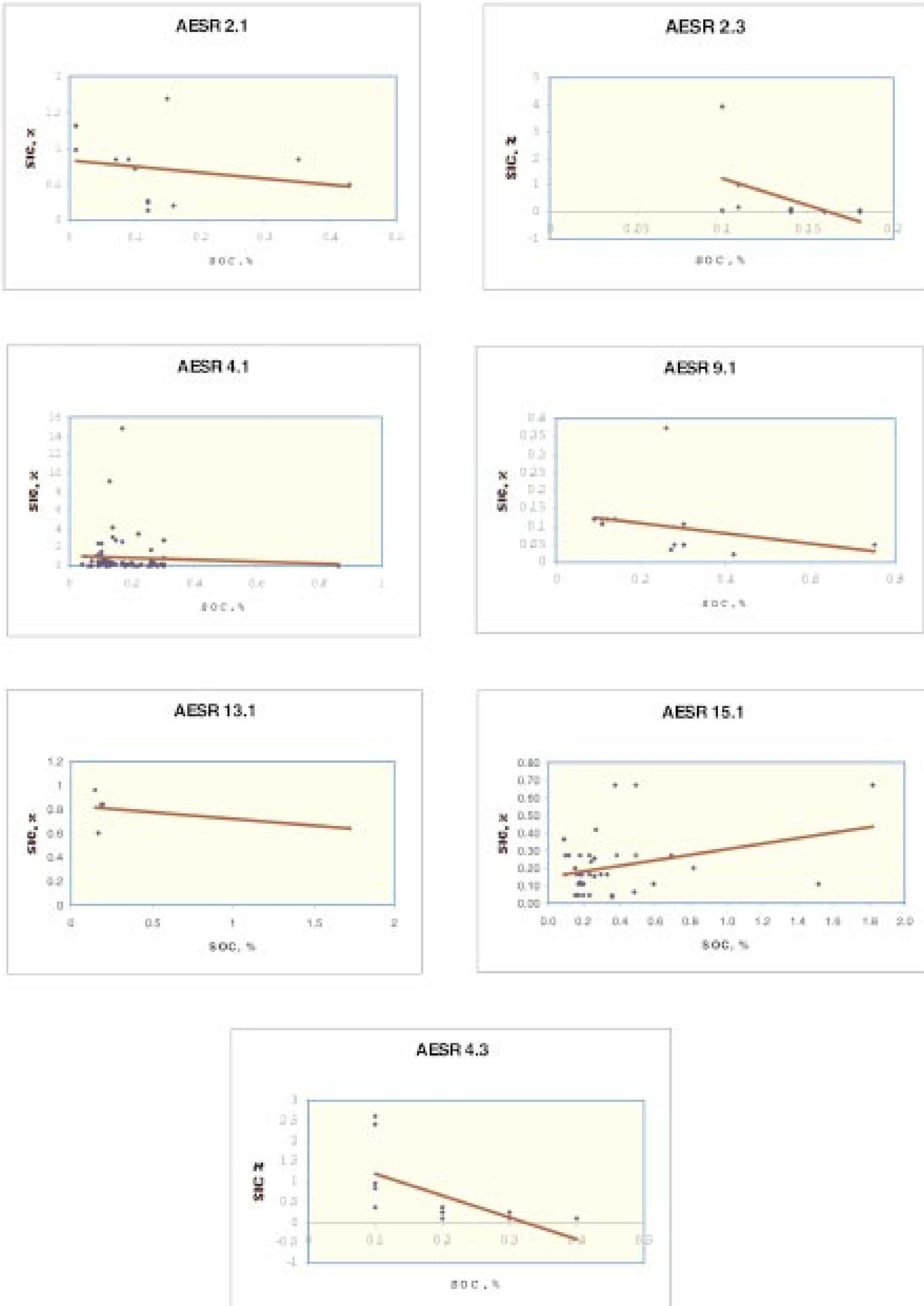


Figure 34. Correlation of SOC and SIC in different agro-ecological subregions in the IGP.

Table 13. Relation between SOC and SIC in selected BM spots in IGP, India.

AESRs	Districts	State	Parent Materials	Climate MAR (mm)	Climate MAT (°C)	Regression Equation	r	No. of obser-vations
2.1	Hanumangarh	Rajasthan	Ghaggar alluvium (Siwalik)	270	24.9	(SIC) = -0.8289 (SOC) + 0.8335	-0.22	12
2.3	Jodhpur	Rajasthan	Aeolian/ Alluvium	250-300	26.7	(SIC)= -20.354 (SOC) + 3.2915	-0.51	12
	Hisar	Haryana	Alluvium	440	24.5	(SIC) = -1.0026 (SOC) + 1.089	-0.05	79
4.1	Sangrur	Punjab	Alluvium	435	24.0			
	Patiala			650	24.5			
	Karnal	Haryana		600-700	25.0			
	Gurgaon			780	23.9			
		Delhi		714	23.8			
4.3	Aligarh, Etah	U.P.	Alluvium	763	25	(SIC) = -5.4183 (SOC) + 1.7509	-0.63	13
9.1	Patiala Kapurthala	Punjab	Alluvium	700-1000 700-1000	24.5 24.8	(SIC) = -0.144 (SOC) + 0.139	-0.30	15
13.1	Bahraich Pantnagar	U.P.	Alluvium	1200	25.0	(SIC) = -0.1174 (SOC) + 0.8373	-0.17	6
15.1	Bardhaman	West Bengal	Alluvium	1400	26.6	(SIC) = -0.1554 (SOC) + 0.1499	0.33	43

calcium for plants. By improving vegetative cover these soils could be ameliorated with two fold gains. Firstly, the vegetation itself will help soils in sequestering organic carbon and secondly dissolution of $CaCO_3$ by root exudates will improve soil drainage with better soil structure (Pal et al. 2000; Bhattacharyya et al. 2000a).

Conclusions

Recent studies on forest soils indicate that the OC content of soils sharply declines when put to cultivation even within 15 years of cultivation. Irrespective of the initial carbon level of soils, there is a tendency of soils to reach a quasi-equilibrium which has been reported as 1-2 per cent for red soils of eastern India (Saikh et al. 1998) and about 0.5 to 0.8 per cent in black soils of central India (Naitam and Bhattacharyya, 2004). The huge inorganic carbon stock in the form of $CaCO_3$ appears to be immobile since its apparent insolubility in the arid to semi-arid climate. It has been mentioned that the inorganic carbon present in sub-humid to humid ecosystem can be made available to plants by the dissolution of $CaCO_3$ through root exudates. Logically, vegetation in the arid and semi-arid ecosystem might have a strong influence in slow dissolution of calcium carbonate which can not only provide necessary nutrition to plants but also can trigger the process of natural amelioration of these sodic soils in semiarid and aridic ecosystem.

Higher accumulation of SOC is related to vegetative cover supported by high rainfall and it is observed in eastern parts of the IGP under humid to per-humid AER. However, due to intensive

Table 14. Difference in soil properties after gypsum treatment.*

Depth (cm)	pH (1:2)	ECe (dS m^{-1})	Anionic composition of the saturation extract (cmol dm^{-1})				SAR	Exchangeable cations (cmol(p+)kg^{-1})				ESP	$CaCO_3$ equiv. <2mm (%)
			CO_3	HCO_3	Cl	SO_4		Ca	Mg	Na	K		
Untreated sodic soil													
0-13	10.3	8.3	10.0	50.0	16.0	12.0	79.4	Nil	Nil	6.2	0.6	89.8	1.0
13-29	10.4	8.9	29.0	40.6	20.0	7.9	96.9	—	—	5.6	0.4	93.3	2.1
29-59	10.0	4.8	7.4	29.0	15.0	8.0	44.7	0.2	0.2	6.5	0.4	87.8	1.8
59-89	9.6	2.5	0.7	22.0	5.0	8.0	31.7	0.3	Nil	8.2	0.3	93.1	1.0
89-116	9.6	2.5	0.5	6.5	6.0	20.0	14.8	1.0	0.6	5.9	0.2	73.7	1.2
116-160	9.6	—	1.5	6.0	4.0	10.5	12.8	0.6	0.7	1.8	0.1	8.2	4.6
Gypsum treated sodic soil													
0-14	8.6	1.2	Nil	3.5	4.0	10.0	5.5	3.3	2.1	0.7	0.5	11.6	0.8
14-31	9.1	1.4	—	6.0	3.0	8.3	15.6	2.6	1.6	2.1	0.3	30.8	1.2
31-62	9.4	1.9	—	5.0	4.0	11.1	8.3	2.2	1.0	5.8	0.3	55.2	1.0
62-88	9.4	1.7	0.4	8.0	4.0	7.5	17.4	2.5	1.8	7.1	0.3	60.6	0.9
88-121	9.5	2.0	2.0	9.5	3.2	9.6	13.6	1.3	1.2	7.7	0.2	75.4	2.7
121-165	9.6	2.3	4.0	9.0	2.0	10.0	14.3	0.5	0.7	1.9	0.2	55.9	6.9

**Source:* Sharma and Bhargava, 1981

agricultural practices, these areas have become impoverished in SOC over time (Bhattacharyya et al. 2000). The cooler humid and humid to per-humid climate have been found to be the most conducive situation for soils to be enriched in SOC as observed in Mollisols of the sub Himalayan region, Central and Western India (Bhattacharyya and Pal, 1998; Velayutham, et al. 2000). This suggests that there is a greater scope of OC sequestration of soils under semi-arid and humid tracts of the IGP. In this regard, continuous application of FYM and green manure in rice-wheat cropping system in calcareous sodic soils of the IGP has improved the OC status substantially (Goswami et al. 2000). The sequestration of OC in calcareous sodic soils of the IGP is also possible not only through agricultural practice but also through agroforestry and silviculture (Gupta and Rao, 1994).

The knowledge on both SOC and SIC stock can thus decide the areas for actual rehabilitation mechanisms in terms of OC sequestration. This technique for OC sequestration will also trigger the hidden carbonate resources. Such areas can be easily identified through the maps generated to show sufficient and deficient zones in term of SOC content, SOC and SIC stocks and other maps generated through this study. Such exercise can eventually help in developing a support system for the decision makers in terms of land use management.

Perspective

The present scenario of change in climate, like the rising of temperature and shrinking of annual rainfall in major geographical areas of the country will continue to remain as a potential threat for tropical soils of Indian subcontinent specially in view of the phenomenon of global warming (Gadgil, 1995). Situations of this nature will therefore demand careful management interventions to dissolve native $CaCO_3$ in the soils of the IGP (Fig. 18) in terms of restoring and maintaining soil health for a sustainable agricultural productivity (Bhattacharyya and Pal, 2003). This will require periodic monitoring of benchmark spots to assess the level of changes in soil properties with special reference to organic and inorganic form of carbon in soils.

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Rice-Wheat Consortium for the Indo-Gangetic Plains

The Consortium is an Ecoregional Program of the Consultative Group on International Agricultural Research (CGIAR), managed by CIMMYT, involving the National Agricultural Research Systems, the International Agricultural Research Centers, and the Advanced Research Institutions. Its main objective is to promote research on issues that are fundamental to enhance the productivity and sustainability of rice-wheat cropping systems in South Asia.

These objectives are achieved through:

- Setting priorities for focused research on problems affecting many farmers.
- Promoting linkages among rice-wheat research specialists and other branches of research and extension.
- Encouraging interdisciplinary team approach to understand field problems and to find solutions.
- Fostering quality work and excellence among scientists.
- Enhancing the transfer of improved technologies to farmers through established institutional linkages.

Financial support for the Consortium's research agenda currently comes from many sources, including the Governments of Netherlands, New Zealand, Australia and the Department for International Development (DFID), the International Fund for Agricultural Development (IFAD), the United States Agency for International Development (USAID), the World Bank and the Asian Development Bank (ADB).

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