Journal of the Indian Society of Soil Science, Vol. 57, No. 4, pp 461-468 (2009)

Soil Carbon Stocks in India — Issues and Priorities

T. Bhattacharyya, S.K. Ray, D.K. Pal, P. Chandran, C. Mandal and S.P. Wani[1]
National Bureau of Soil Survey and Land Use Planning, Amravati Road, Nagpur, 440010, Maharashtra
[1]International Crop Research Institute for Semi Arid Tropics, Patancheru, Hyderabad, Andhra Pradesh

Restoration of soil health through soil organic carbon (SOC) management is a major concern for tropical soils. Barring its importance for sustainable crop production, the accelerated decomposition of SOC due to agriculture resulting in loss of carbon to the atmosphere and its contribution to the green house effect is a serious global problem. The contributions of SOC on physical, chemical and biological properties of soils in sustaining their productivity are being appreciated since the dawn of human civilization. Important factors controlling SOC levels include climate, hydrology, parent material, soil fertility, biological activity, vegetation patterns and land use (Jenny and Raychaudhuri 1960). SOC is sensitive to impact of human activities *viz.* deforestation, biomass burring land use changes and environmental pollution. It has been estimated that the land use change resulted in the transfer of 1-2 Pg C/yr from terrestrial ecosystem to the atmosphere of which 15-17% carbon is contributed by decomposition of SOC (Houghton and Hackler 1994).

Knowledge of SOC in terms of its amount and quality is essential. In the recent past the green house effect has created a great concern that led to several studies on qualities, kinds distribution and behaviour of SOC (Eswaran *et al*. 1993; Sombroek *et al*. 1993; Batjes 1996; Velayutham *et al*. 2000; Bhattacharyya *et al*. 2000, 2004, 2008; Saxena *et al*. 1999; Giri *et al*. 2008). The first comprehensive study of SOC in Indian soils was conducted using data from different cultivated fields and forests with variable rainfall and temperature patterns (Jenny and Raychaudhuri 1960). The study confirmed the effects of climate on C reserves in the soil. However, this study did not estimate the total C stock in Indian soils. Using ecosystem areas from different sources and representative global average C densities (Ajtay *et al*. 1979; Schlesinger 1983) organic C in Indian soils was estimated as 23.4-27.1 Pg (Dadhwal and Nayak 1993). Using estimated SOC densities and remote sensing-based area of forest types, Chhabra *et al.* (2003) estimated the organic C pool of Indian forest soils as 6.8 Pg in top 1 m. Gupta and Rao (1994) reported an SOC stock in 48 soil series as 24.3 Pg. The first comprehensive report of SOC, SIC (soil inorganic carbon) and TC (total carbon) was carried out by Velayutham *et al.* (2000) and Bhattacharyya *et al.* (2000). Later these estimates were made useful for various mapping schemes (Bhattacharyya *et al.* 2008). The estimates on soil carbon stock at district level are also found (Saxena *et al*. 1999; Giri *et al*. 2009). The present attempt is made to review the work done in this particular aspect of estimates of carbon (both SOC and SIC) in Indian soils and their applications to focus issues and priorities on carbon sequestration in soils.

Methodology

Datasets

The relevant data for SOC, BD and $CaCO_3$(SIC) were drawn from the published and unpublished soil database generated through soil resource mapping of India by NBSS&LUP, Nagpur in 1:250,000 scale, district soil survey programmes in 1:50,000 scale and from various other sources including research articles (Bhattacharyya *et* al. 2000, 2008; Velayutham *et al.* 2000).

Computation of Soil Carbon Stock

The size of total SOC stock estimation involves two steps (Batjes 1996). The first step involves calculation of organic carbon (OC) by multiplying OC (g g^{-1}), bulk density (Mg m^{-3}) and thickness of horizons (m) for individual soil profile with different thickness varying from 0-0.3, 0-0.5, 0-1.0, 0-1.5 m depth. In the second step the total SOC content determined by the first step was multiplied by the area (mha) of the soil unit. The total SOC is expressed in Pg (1Pg = 10^{15} g = 1 billion tonne) as shown in the following equation.

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

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

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

SOC stock in soils =

$$\frac{\underset{(\text{g g}^{-1})}{\text{C content}} \times \underset{(\text{Mg m}^{-3})}{\text{BD}} \times \underset{(\text{Mha})}{\text{area}} \times \underset{(\text{m})}{\text{soil depth}}}{10}$$

For SIC, the same steps were followed using 12 parts of C present in $CaCO_3$ values. The sum of SOC and SIC stock gave the total carbon (TC) stock in soils (Bhattacharyya *et al*. 2008).

Carbon Stock in Indian Soils

Carbon Stock in Soil Orders

Soil carbon stocks (SOC, SIC and TC) in seven different soil orders are shown in table 1. Vertisols, Inceptisols and Alfisols have the major share of SOC stocks in first 30 cm depth of soils. For similar depth Aridisols show low SOC but very high (33%) level of SIC stock.

If Indian soils are broadly classified into five groups, then red soils (Alfisols and Ultisols), alluvial soils (Entisols and Inceptisols) and black soils (Vertisols) are found to store maximum organic carbon. Since carbon stock in soil is controlled by (mainly) content in carbon and the areal extent of soils, therefore, in soil if even carbon content is high the carbon stock will be less due to low areal extent. This is the reason why brown forest soils, represented mostly by Mollisols, contain high carbon, yet show low carbon stock. Table 2 shows the stock of both organic and inorganic carbon in 5 major soils of India.

Distribution of Carbon in Different Regions

It has been shown that level of SOC is determined among other factors, largely by climate (Jenny and Raychaudhuri 1960) and therefore, the density of soil carbon will vary in different climatic zones. Zonation of soil carbon stocks has been detailed earlier (Velayutham *et al*. 2000; Bhattacharyya *et al*. 2000, 2008). Soil organic carbon stock for India was first reported by Velayutham *et al*. (2000). Higher atmospheric temperature associated with low rainfall is responsible for high content of secondary carbonates. Calcium carbonate reported in the humid and perhumid region is considered mostly as inherited material in soils developed from strongly calcareous parent material, usually on young geomorphic surfaces. The SIC stock is relatively high in arid and semi-arid ecosystem (Bhattacharyya *et al*. 2000) (Table 3).

The Himalaya zones (ACZ1 and ACZ2) cover nearly 19% area and contribute 33% of SOC reserves of the country, largely due to thick forest vegetation (Figs. 1). The Indo-Gangetic Plains (IGP) cover four ACZs (3-6) and occupies 15% of the TGA of the country (Fig. 1). Total SOC and SIC stocks in the IGP are 9.0 and 9.7%, respectively. It was reported that the soils under hot, humid and perhumid climates are deficient in SOC due to intensive agriculture (Bhattacharyya *et al*. 2000b). The SOC stocks in the IGP dominated by rice-wheat cropping system were earlier estimated as 0.63 and 2.00 Pg in the first 30 and 150 cm soil depth, respectively (Table 4). Based on SOC content nearly 70% area in the IGP falls under deficient zones (Velayutham *et al*. 2000). Besides, SOC stock in terms of IGP share is only 0.4% of the tropical regions indicating a scope

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

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

Source: Bhattacharyya *et al*. (2005)

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

Bioclimatic Zones	Area		SOC		SIC		TC		Stock per unit area (Pg/mha)	
	Coverage (mha)	TGA (%)	Stock	% of total SOC stock	Stock	% of total SIC stock	Stock	% of total TC stock	SOC	SIC
Cold Arid	15.2	4.6	0.6	6	0.7	17	1.3	10	0.039	0.046
Hot	36.8	11.2	0.4	4	1.0	25	1.4	10	0.011	0.027
Semi-arid	116.4	35.4	2.8	30	2.0	47	4.8	35	0.025	0.016
Subhumid	105.0	31.9	2.4	26	0.33	8	2.73	20	0.024	0.003
Humid to perhumid	34.9	10.6	2.0	21	0.04	1	2.04	15	0.060	0.001
Coastal	20.4	6.2	1.3	13	0.07	2	1.37	10	0.064	0.033

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

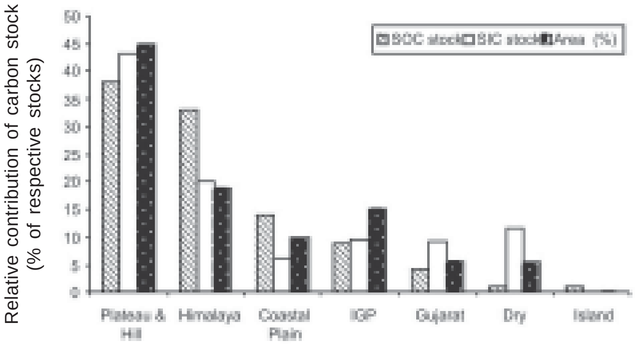

Fig. 1. SOC and SIC stocks and areal extent of seven major agro-climatic zones of India

Table 4. Carbon stocks in the IGP and other parts of the world (values in Pg)

Region	Soil depth (m)	
	0 – 0.3	0 – 1.5
IGP, India[1]	0.63 (6.45/0.3/0.09)[2]	2.00 (6.67/0.32/0.08)[2]
India[3]	9.55	29.92
Tropical Regions[4]	201-213	616-640
World[4]	684-724	2376-2456[5]

[1]Bhattacharyya *et al.* (2004), [2]Parentheses show % of stock in India, Tropical regions and world, respectively,
[3]Bhattacharyya *et al*. (2008), [4]Batjes (1996), [5]For 0-2.0 m soil depth.

to sequester these soils with organic carbon. Revisiting nearly 37 benchmark spots to estimate SOC stock indicate 0.88 Pg C in the first 20 cm soils (Table 5). The IGP has been traditionally considered as a rice growing area. Century model estimates 0.66 Pg SOC in lowland rice soils. Soil C estimated using IPCC method showed little change over 1967-2030. The IPCC method rests on classification of land area into distinct management and land use categories to determine C stocks (Bhattacharyya *et al.* 2007a). Here changes in SOC are controlled by changes in the distribution of area of land use systems over time. There is relatively little land use change in IGP over the period of modelling since almost all the areas are under intensive agriculture. Century model estimates a 21% decrease in SOC stocks in IGP from 1967 to 2030, with a dynamic equilibrium reached during 1990 and changed little thereafter (Fig. 2).

Most parts of the humid and sub-humid regions of the IGP punctuated by 2-3 months of cooler winter, dominated by non-calcareous soils fall under the sufficient zone of SOC (Velayutham *et al.* 2000; Bhattacharyya *et al*. 2000b, 2004) (Fig. 3). It has been reported that the soils of the arid and semi-arid climate occupying more than one-third area of the IGP are poor in SOC and are thus prone to be calcareous and sodic (Pal *et al*. 2000). Proper rehabilitation programmes can make these sodic soils resilient and thus can form an important step for carbon sequestration to improve the soil quality (Gupta and Rao 1994; Bhattacharyya *et al.* 2004). Four ACZs (7-10) constituting plateau and hills occupy 45% of the TGA (Fig. 1) which cover semi-arid tropics (SAT) of the Indian subcontinent. It has been shown that the carbon storage capacity of soils depends on the quality of soil substrate and its surface charge density (SCD) (Fig. 3). The increase of SOC again enhances the SCD of soils and the ratio of internal/external exchange sites. The soils in these plateau (Vertisols and their intergrades) are dominated by smectites and smectite-kaolinite interstratified minerals (Pal *et al.* 2000; Bhattacharyya *et al*. 1993). This region has maximum reserves of carbon in soil, which is due to large areal coverage as well as greater carbon sequestration potential of the soils (38 to 43% for SOC and SIC stocks, Fig. 1). The coastal plains, Gujarat plains and hills, western dry and islands have relatively less contribution of SOC and SIC stocks (Fig. 1).

Table 5. Estimates of soil organic carbon in rice-wheat cropping systems of IGP

Soil/System	Method	Year of estimate	SOC stock (Pg)
Soil Series of IGP	Soil Survey[1]	1980	0.66[2]
Soil Series of IGP	Soil Survey (Resampling)[3]	2005	0.88[2]
Soil Series of IGP	Secondary data extrapolation[4]	1990	0.572-0.587[5]
IPCC	Soil, climate and land use classification[3]	2000	0.97[5]
Century C model	Simulation[3]	2000	1.44[2]

[1]Bhattacharyya *et al.* (2004), [2]For 0-20 cm soil depth, [3]Bhattacharyya *et al.* (2007a), [4]Batjes *et al.* (2004), Chandran *et al.* (2005), [5]For 0-30 cm soil depth.

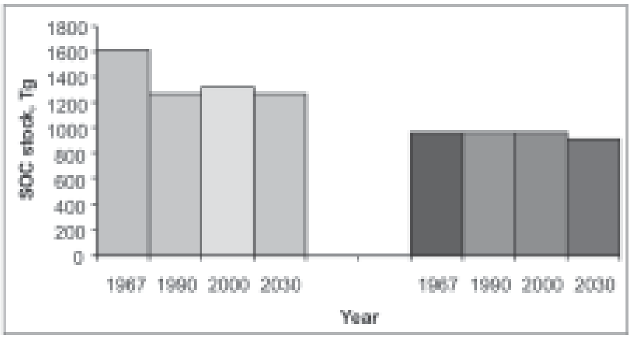

Fig. 2. GEFSOC modelling systems (IPCC & Century) to assess SOC stocks in IGP

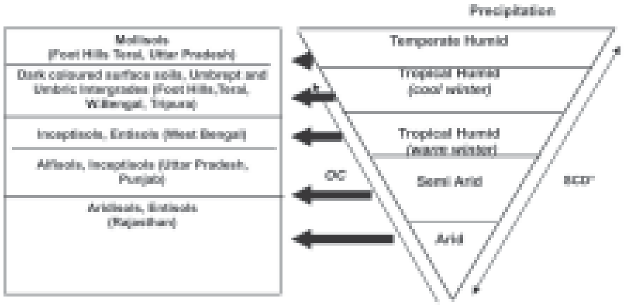

Fig. 3. Accumulation of organic carbon (OC) in IGP soils as influenced by precipitation, temperature and substrate quality (Bhattacharyya *et al.* 2000b, 2004) (* SCD: Surface charge density)

Soil Carbon Stock in Identifying Systems in SAT

Out of 155.8 Mha prioritized for carbon management (Bhattacharyya *et al.* 2008) 21.63 Mha of semi-arid tropics was selected to identify systems for carbon sequestration. Carbon stock in soil depends largely on the areal extent of the soils besides other factors such as carbon content, depth and BD of soils. Carbon stock per unit area has been found to be a better dataset to identify the influence of soil and/or management parameters for both organic and inorganic carbon sequestration in soils (Bhattacharyya *et al.* 2000b, 2008). On the basis of SOC stock per unit area, 22 systems representing 16 black soils and 6 red soils were identified as viable in the existing level of management in SAT. Through this systematic studies a minimum and maximum threshold limit of SOC, SIC and BD were established (Bhattacharyya *et al.* 2007c).

Carbon Trading

Carbon sequestration is one of the important mitigation strategy to cope with the impacts of climate change by reducing the atmospheric concentration of carbon dioxide emissions. The Kyoto Protocol brought the mechanism of trading carbon units as a global mechanism to address the issue of reducing the emissions by various countries to meet the mandatory requirements.

Trading C units with a “market value” needs to be established through carbon budgeting to indicate whether the emissions are reduced or more C is fixed. Another mechanism put in place for trading of carbon units is the Clean Development Mechanism (CDM) where C sequestering or CO_2 emission reducing technologies are promoted and financially supported irrespective of the country or the region where they are implemented. The companies or countries that support the CDM projects get the credit for the amount of C emissions reduced due to efficient technologies or due to increased C sequestration. The tropical developing countries’ potential to harness CDM projects is vast and remains to be tapped. At present Brazil, China, and India are leading the pack for the CDM projects approved.

Reputed organizations and individuals verify the activities of communities that undertake C sequestering or reducing C emissions and are awarded the VERs (verified emission reduction) and the costs are paid to the communities. Through this mechanism the poor communities are able to harness the benefits of global C trading and the communities are able to improve their incomes as well as undertake the environment stewardships. International Crops Research Institute for the Semi Arid Tropics, (ICRISAT) has facilitated the sale of VERs from the rural community based organizations (CBOs) to the World Bank, private companies and individuals benefiting the rural community (D’ Silva *et al.* 2004).

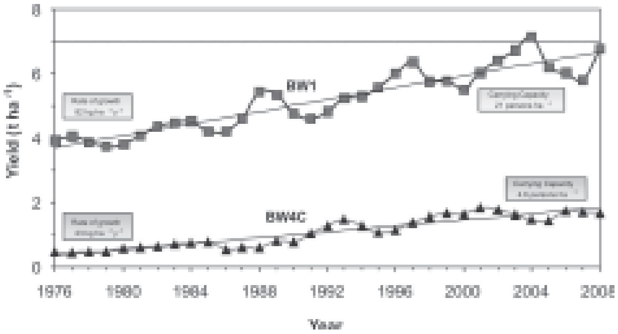

Fig. 4. Three-year moving average of sorghum and pigeonpea grain yield under improved and traditional management in a deep Vertisol catchment at Patancheru, India

The benefits to the general community of trading emission in a market include: (i) reduction in overall cost of meeting emission reduction targets; (ii) opportunity to generate income from activities that previously attracted no additional revenue; (iii) ability to use revenue from carbon sequestration to help fund additional planting of trees and other vegetation, for benefits such as salinity amelioration, biodiversity enhancement, conversion to greenhouse gas friendly fuels, and (iv) energy, and employment and wealth creation in rural areas.

Soils and trees are major sinks for carbon and this potential remains untapped. The agricultural soils in the world particularly in the tropics and sub-humid regions are major C sinks and with suitable management practices and cropping systems their C sequestration potential can be harnessed (Bhattacahryya *et al.* 2007b,c, Wani *et al.* 2003,2009). It is argued that increase in soil organic carbon pool favourably influences crop productivity by increasing water holding capacity of the soil, improving soil biological activity and nutrient cycling along with physical properties, especially soil-water-air relations and improved supply of nutrients (Johnston, 1986; Wani *et al.* 2003; Hudson 1994; Emerson 1995; Pathak *et al.* 2005). The updated results from long-term study at ICRISAT (Fig. 5) showed that the average grain yield of the improved cropping system over 30 years was 5.1 t ha^{-1} y^{-1}, nearly a five-fold increase in the yield over the traditional cropping system (average yield about 1.1 t ha^{-1} y^{-1}). The annual gain in yield in the improved system was 82 kg ha^{-1} yr^{-1} compared with 23 kg ha^{-1} yr^{-1} in the traditional system (Fig. 5). The improved system had a higher carrying capacity (21 persons ha^{-1}) than the traditional system (4.6 persons ha^{-1}).

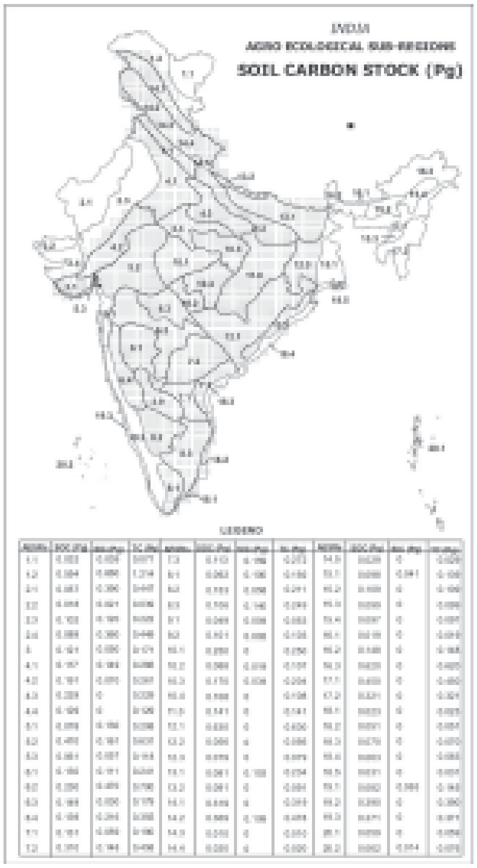

Fig. 5. Soil carbon stock map in different agro-ecological sub-regions showing prioritized areas (shaded areas) for carbon sequestration (0-0.3 m soil depth)

More importantly, under the improved catchment management system, along with improved soil fertility, the soil contained 46.8 t OC ha^{-1} in the 0-120 cm soil profile as compared to the traditional management practices that contained 39.5 t OC ha^{-1} . This amounted to a gain of about 7.3 t OC ha^{-1} over the 24-year period ending in 2000. Overall, the improved system showed increased rainwater use efficiency (65% *vs* 40%), reduced runoff from 220 mm to 91 mm and soil loss from 6.64 t ha^{-1} to 1.5 t ha^{-1} along with increased crop productivity, carrying capacity of land (both of men and animals), C sequestration and soil quality (Wani *et al*. 2003). Similarly, legume-based systems and bio-fuel plantation of *Jatropha* and *Pongamia* (Wani *et al.* 2009) on Vertisols were more sustainable and contained two folds higher N mineralization potential and organic C content (Bhattacharyya *et al.* 2005) than the only cereal systems (Wani *et al*. 1994; Rego *et al.* 2003).

Since agricultural systems are not yet accepted for C trading under the Kyoto Protocol we need to build good data sets and establish that agricultural systems and particularly so in the tropics are potential C sequestering sinks like the tropical forests.

Biofuel plantations of *Jatropha* and *Pongamia* have good potential to sequester carbon and also C replacement by using oil as a source of energy. Wani *et al*. (2009) recorded 1 t ha^{-1} C addition to the soil through leaf fall in case of *Jatropha* in addition to the renewable energy.

Usefulness of Soil Carbon Stock Data Sets — Issues and Priorities

Criteria of carbon stock as well as point data for individual soils indicate that vast areas in the arid (AESR 3), semi-arid and drier sub-humid parts (AESRs 4.1-4.4, 5.1-5.3, 6.1-6.4, 7.1-7.3, 8.1-8.3, 9.1, 9.2, 10.1-10.4) of the sub-continent are low in SOC and high in SIC stock and thus should get priority for organic carbon management. The total prioritized area has been worked out as 155.8 Mha (arid : 49 Mha, semi-arid : 116.4 Mha and subhumid : 34.5 Mha, Fig. 5).

The relation between SOC and SIC with depth has been negative. The role of SIC seems to be huge in dry climates in controlling SOC (Bhattacharyya *et al*. 2000b). In the ecoregion of high rainfall virtually there is no role of SIC in accumulation of SOC. This further strengthens the fact indicated earlier (Pal *et al*. 2000) that with the climatic adversity (in terms of decreasing rainfall and increasing atmospheric temperature) the natural degradation in terms of formation of pedogenic $CaCO_3$ (SIC) with a concomitant formation of sodicity (ESP), increase in soil pH, reduction in hydraulic conductivity (HC) will reduce the possibility of growing successful crops making the soils impoverished with SOC. This is schematically presented in figure 6.

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

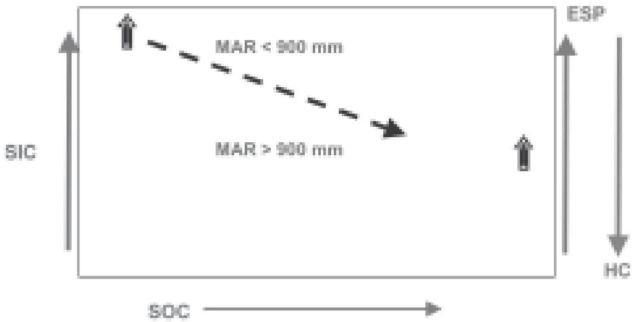

Fig. 6. Schematic diagram showing relation between SIC, SOC and other soil and climatic parameters

In the present scenario of differing climatic parameters such as the rising of temperatures and shrinking of annual rainfall in some areas of the country, it will continue to remain as a potential threat for tropical soils of the Indian subcontinent (Jenny and Raychaudhuri 1960; Sombroek *et al*. 1993). Therefore, the arid climate will continue to remain as a bane for Indian agriculture since it will cause soil degradation in terms of depletion of OC, formation of pedogenic $CaCO_3$ with the concomitant development of sodicity and/or salinity (Velayutham *et al*. 2000; Eswaran and van der Berg 1992). To combat such situation, the restoration of OC balance and efforts to enlarge the soil carbon pool by appropriate management techniques also to encourage agro-forestry should form the strategic perspective to sustain the soil health of Indian soils. The most unfavourable natural endowment is the climatic adversity and this will ever demand for extra resources to support targeted yields in the Indian agriculture and thus may retard the pace of rehabilitation programme required to restore the soil productivity. Despite this fact research attention for soils of arid and semi-arid climates sponsored through national agenda needs to be an immediate concern. In absence of such programme, deforestation will continue to increase the area under agriculture and obviously this may reduce the carbon level of soils. Thus the information of carbon stock can act as a single-most important parameter in judging the soil health to prioritize areas for better management of soils.

References

Ajtay, G.L., Ketner, P., Duvigneaud, P. (1979) Terrestrial primary production and phytomass. In : *The Global Carbon Cycle* (B. Bolin, E.T. Degues, S. Kempa and P. Ketner, Eds.) John Wiley, Chichester, pp.129-181.

Allen, D.L. and Hajek, B.F. (1989) Mineral occurrence in soil environments. In *Mineral in Soil Environment* (J.B. Dixon and S.B. Weed, Eds.) Soil Science Society of America, Madison, Wisconsin, pp.99-278.

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

Batjes, N.H. (1996) Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* **47**, 151-163.

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

Batjes, N.H., Bhattacharyya, T., Mandal, C., Dijkshoorn, K., Pal, D.K., Milne, E. and Gajbhiye, K.S. (2004) Soil data derived from SOTER for studies of carbon stocks and change in the Indo-Gangetic Plains (India) (Ver. 1.0, GEFSOC Project). Report 2004/06. ISRIC-World Soil Information, Wageningen and NBSS&LUP (ICAR), India, 26pp.

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

Bhattacharyya, T., Chandran, P., Ray, S.K., Pal, D.K., Venugopalan, M.V., Mandal, C., Wani, S.P., Manna, M.C. and Ramesh, V. (2007b) Carbon sequestration in red and black soils. III. Identifying systems through carbon stock and bulk density of soils. *Agropedology* **17,** 26-34.

Bhattacharyya, T., Chandran, P., Ray, S.K., Pal, D.K., Venugopalan, M.V., Mandal, C. and Wani, S.P. (2007c) Changes in levels of carbon in soils over years of two important food production zones of India. *Current Science* **93,** 1854-1863.

Bhattacharyya, T., Pal, D.K., Chandran, P., Mandal, C., Ray, S.K., Gupta, R.K. and Gajbhiye, S.K. (2004) Managing soil carbon stocks in the Indo-Gangetic Plains, India, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, pp.44.

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

Bhattacharyya, T., Pal, D.K., Chandran, P., Ray, S.K., Mandal, C. and Telpande, B. (2008) Soil carbon storage capacity as a tool to prioritise areas for carbon sequestration. *Current Science* **95,** 482-494.

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

Chhabra, A., Patria, S., and Dadhwal, V.K. (2003) Soil organic carbon pool in Indian forests, *Forest Ecological Mangement*, **173,**187-199.

Chandran, P., Bhattacharyya, T., Ray, S.K., Durge, S.L., Mandal, C., Sarkar, D., Sahoo, A.K., Singh, S.P., Jagat Ram, Ram Gopal, Pal, D.K., Gajbhiye, K.S., Milne, E., Aurangabadker, B., Mendhekar, P. and Singh, B. (2005) SOTER (Soil and Terrain Digital Databases) IGP, India. Special Publication for GEFSOC Project "Assessment of Soil Organic Carbon Stocks and Change at National Scale". NBSS&LUP, India. 101pp.

Chandran, P., Ray, S.K., Durge, S.L., Raja, P., Nimkar, A.M., Bhattacharyya, T. and Pal, D.K. (2009) Scope of horticultural land use system in enhancing C sequestration in ferruginous soils of semi-arid tropics. *Current Science* (in press).

Dadhwal, V.K. and Nayak, S.R. (1993) A preliminary estimate of biogeochemical cycle of carbon for India. *Science and Culture* **59**, 9-13.

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

D'Silva, E., Wani, S.P. and Nagnath, B. (2004) The making of new Powerguda : community empowerment and new technologies transform a problem village in Andhra Pradesh Global Theme on Agroecosystems Report No. 11, Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 28 pp.

Du Pont, G. (1997) Tree microclimate effects on under vegetation : their impact on spatial and temporal modelling of pasture production in Queensland. *Masters Thesis*, University of Queensland, Brisbane.

Emerson, W.W. (1995) Water retention, organic carbon and soil texture. *Australian Journal of Soil Research* **33,** 241-251.

Eswaran, H. and van den Berg, E. (1992) Impact of building of atmospheric CO_2 on length of growing season in the Indian sub-continent. *Pedologie* **42**, 289-296.

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

Giri, J.D., Singh, S.K., Singh, R.S. and Shyampura, R.L. (2007) Carbon stock and its distribution in soils of Ajmer district and management strategies for carbon sequestration. *Agropedology* **18**, 21-32.

Gupta, R.K. and Rao, D.L.N. (1994) Potential of wastelands for sequestering carbon by reforestation. *Current Science* **66**, 378-380.

Gupta, S.P. (Ed.) (2002) *Report of the Committee on Indian Vision 2020*, Planning Commission of the Government of India, New Delhi, India.

Houghton, R.A. and Hackler (1994) The net flux of carbon from deforestration and degradation in south and southeast Asia. In: *Effects of Land-Use Change on Atmospheric CO_2 concentrations : South and Southeast Asia as a Case Study* (V. Dale, Ed.), Springer Verlag, New York, pp.304-327.

Hudson, B.D. (1994) Soil organic matter and available water capacity. *Journal of Soil and Water Conservation* 48, 188-193.

Jenny, H. and Raychaudhuri, S.P. (1960) *Effect of Climate and Cultivation on Nitrogen and Organic Matter Reserves in Indian Soils*. ICAR, New Delhi, India, p.126.

Johnston, A.E. (1986). Soil organic matter: effects on soils and crops. *Soil Use and Management*, **2**, 97-105.

Pal, D.K., Dasog, G.S., Vadivelu, S., Ahuja, R.L. and Bhattacharyya, T. (2000) Secondary calcium carbonate in soils of arid and semi-arid regions of India. In *Global Climate Change and Pedogenic Carbonates* (R. Lal, J.M. Kimble, H. Eswaran and B.A. Stewart, Eds.), Lewis Publishers, Boca Raton, Fl, pp.149-185.

Pathak, P., Sahrawat, K.L., Rego, T.J. and Wani, S.P. (2005) Measurable biophysical indicators for impact assessment: changes in soil quality. In *Natural Resource Management in Agriculture: Methods for Assessing Economic and Environmental Impacts* (B. Shiferaw, H.A. Freeman and S.M. Swinton, Eds.), Wallingford, UK: CAB International, pp. 75-96.

Saxena, R.K., Verma, K.S. and Kharche, V.K. (1999). Organic carbon stock in soils of Patiala district of the Indo-Gangetic alluvial plain. *Agropedology* **9**, 131-142.

Schlesinger, W.H. (1983) The world carbon pool in soil organid matter: source of atmospheric carbon dioxide. In *The Role of Terrestrial Vegetation in the Global Carbon Cycle : Measurements by Remote Sensing* (G.M. Woodwell, Ed.) SCOPE Wiley, New York, pp.111-127.

Sombroek, W.G., Nachtergache, F.D. and Habel, A. (1993) Amounts, dynamics and sequestration of carbon in tropical and subtropical soils. *Ambio* **22**, 417-427.

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

Wani, S.P., Pathak, P., Jangawad, L.S., Eswaran, H. and Singh, P. (2003) Improved management of Vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration, *Soil Use and Management* **19**, 217-222.

Wani, S.P., Sreedevi, T.K., Marimuthu, S., Kesava Rao, A.V.R. and Vineela, C. (2009) Harnessing potential of *Jatropha* and *Pongamia* plantations for improving Livelihoods and Rehabilitating Degraded lands, In *Proceedings of 6th International Biofuels Conference*, March 4-5, 2009, Winrock International, New Delhi, pp 256-273.