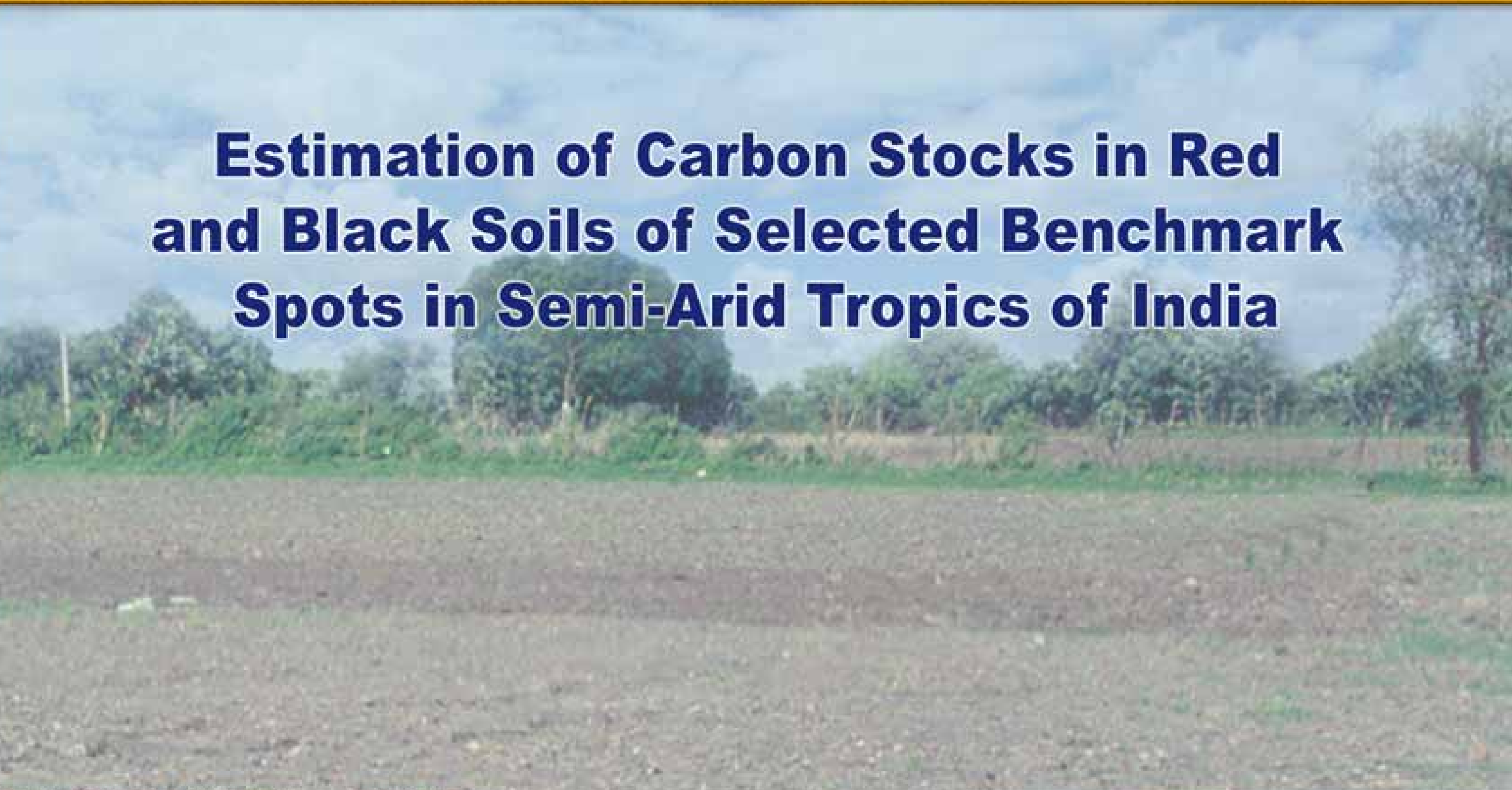
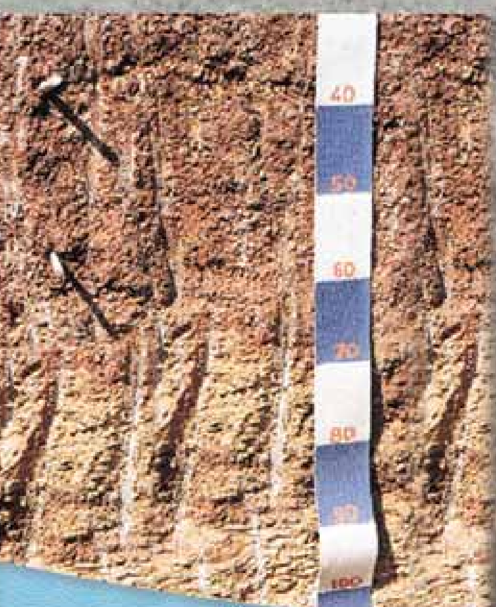
Global Theme on Agroecosystems
Report no. 28

Estimation of Carbon Stocks in Red and Black Soils of Selected Benchmark Spots in Semi-Arid Tropics of India





International Crops Research Institute for the Semi-Arid Tropics

National Bureau of Soil Survey & Land Use Planning (NBSS&LUP)
Central Research Institute for Dryland Agriculture (CRIDA)
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Abstract

Total soil organic carbon (SOC), soil inorganic carbon (SIC) and total carbon (TC) stocks were estimated as 0.47, 0.71 and 1.18 Pg for the black soils and 0.33, 0.50 and 0.83 Pg for the red soils, respectively which cover nearly 15 million ha area in the semi-arid tropics (SAT), India. It is observed that the soils revisited after 25–30 years indicate an overall increasing trend in SOC. On the basis of SOC stock (Pg/M ha) the study helped to identify 22 systems as viable under the present level of management systems. The study also suggests identification of minimum and maximum threshold limit of SOC and bulk density (BD) values in the 22 identified systems. The level of management adopted in the black soils of SAT, India, for the last 20–25 years helped these soils to reach a new higher quasi-equilibrium value in terms of SOC. This indicates that these shrink-swell soils under semi-arid and arid bioclimatic systems respond to controlled management level and are not depleted in SOC.

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Abbreviations

A	Arid
AESRS	Agroecological Subregions
BCS	Black Cotton Soils
BM	Benchmark
CCPI	Cooperating Center Principal Investigator
FM	Farmers' Management
Gg	Gigagram (10^9 g)
HM	High Management
IGP	Indo-Gangetic Plains
ITDA	Integrated Tribal Development Authority
LM	Low Management
NPK	Nitrogen Phosphorous and Pottasiun
OC	Organic Carbon
Pg	Petagram (10^{15} g)
PI	Principal Investigator
QEV	Quasi-Equilibrium Value
SA (d)	Semi-Arid (dry)
SA (m)	Semi-Arid (moist)
SAT	Semi-Arid Tropics
SCD	Surface Change Density
SH (d)	Sub-Humid (dry)
SH (m)	Sub-Humid (moist)
SIC	Soil Inorganic Carbon
SOC	Soil Organic Carbon
TC	Total Carbon

Contents

1. Introduction

The knowledge of soil organic carbon (SOC) in terms of its amount and quality is essential to sustain the quality and productivity of soils. In the recent past the greenhouse effect has created a great concern that has led to several studies on the qualities, kinds, distribution and behavior of SOC (Eswaran et al. 1993; Sombroek et al. 1993; Batjes 1996; Velayutham et al. 2000). The first comprehensive study of organic carbon (OC) status in Indian soils was conducted by Jenny and Raychaudhuri (1960). They studied 500 soil samples collected from different cultivated fields and forests with variable rainfall and temperature patterns. The study confirmed the effects of climate on carbon reserves in the soils. However, these authors did not make any estimate of the total carbon (TC) reserves in the soils.

Gupta and Rao (1994) were the first to estimate the SOC stock which was reported to be 24.3 Pg (1 Pg = 10^{15} g) for the soils ranging from surface to an average subsurface of 44 to 186 cm with the database of 48 soil series. However, the estimate was based on a hypothesis of the enhancement of OC level judging by success stories of afforestation program on some unproductive soils. Later Velayutham et al. (2000) reported the total organic carbon stock over various depth limits such as 0–30 cm, 0–50 cm, 0–100 cm, 0–150 cm following the comprehensive account of soil database of the entire country. Later this estimate on TC stock was revised by Bhattacharyya et al. (2000), who reported nearly 9.8 Pg and 30 Pg SOC stock in Indian soils at 0–30 cm and 0–150 cm soil depths, respectively. The estimate of SOC stock in black cotton soils (BCS) (Vertisols and their intergrades) of Maharashtra was reported separately. It indicates a value of 54 and 171 Gg (1 Gg = 10^{9} g) at 0–30 cm and 0–150 cm soil depth, respectively (Bhattacharyya, Pal, Velayutham, Chandran and Mandal 2001). The SOC stock for BCS of Maharashtra accounts for only 0.008% of the total SOC stock of the entire country. The SOC stock of the Indo-Gangetic Plains (IGP) reported earlier (Bhattacharyya et al. 2000) and revised later (Bhattacharyya et al. 2004; Bhattacharyya and Pal 2003) constitutes 6.06% of the total SOC stock of India (Figure 1.1).

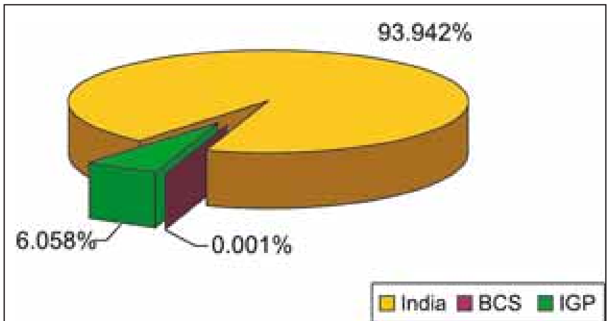


Figure 1.1. Relative proportion of soil organic carbon (SOC) stock in black cotton soils (BCS) and Indo-Gangetic Plains (IGP) as compared to total SOC stock in Indian soils.

The first ever comprehensive report on the soil carbonates in Indian soils indicates two different types of carbonates namely pedogenic and non-pedogenic carbonates (Pal et al. 2000). The first attempt to assess soil inorganic carbon (SIC) in India was made by Bhattacharyya et al. (2000). The total SIC stock in Indian soils is 4.1 Pg and 34 Pg at 0–30 cm and 0–150 cm soil depths, respectively. The SIC stock of the BCS of Maharashtra is 0.01% of total SIC stock of the Indian soils at 0–30 cm soil depth (Bhattacharyya, Pal, Velayutham, Chandran and Mandal 2001). The SIC stock of IGP is 0.13 Pg, which constitutes 3% of the total SIC stock in Indian soils (Bhattacharyya and Pal 2003; Bhattacharyya et al. 2006c, 2004) (Figure 1.2). The relative proportion of the TC stock calculated as the sum of SOC and SIC stocks is shown in figure 1.3.

The present study estimates the total stocks of carbon (both organic and inorganic) in the selected benchmark (BM) spots represented by red and black (Vertisols, Alfisols and their associates) soils in the semi-arid tropics (SAT) of India. The objective is to identify the soils, which reserve maximum

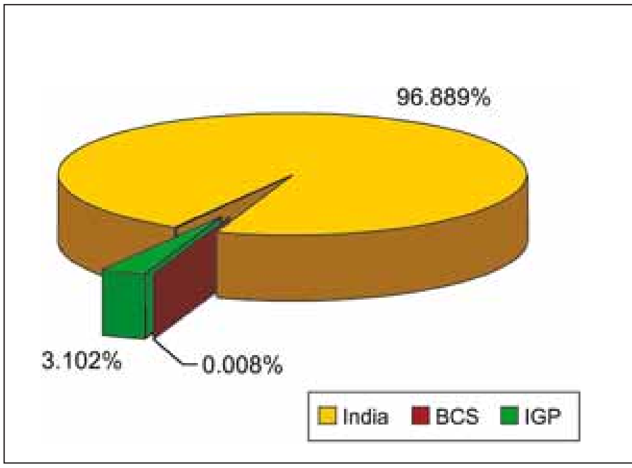


Figure 1.2. Relative proportion of soil inorganic carbon (SIC) stock in black cotton soils (BCS) and Indo-Gangetic Plains (IGP) as compared to total SIC stock in Indian soils.

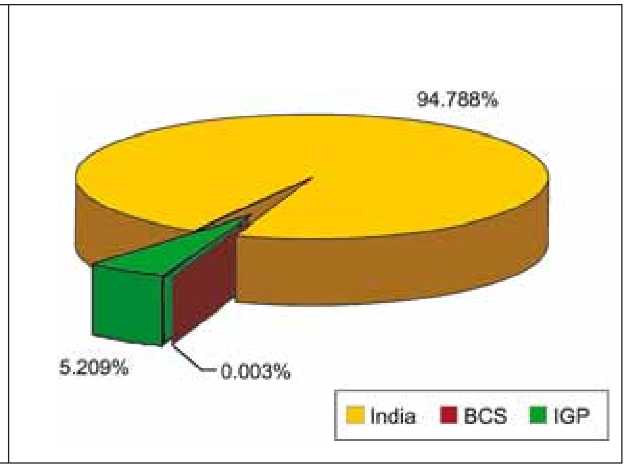


Figure 1.3. Relative proportion of total carbon stock in black cotton soils (BCS) and Indo-Gangetic Plains (IGP) as compared to total carbon (TC) stock in Indian soils.

amount of carbon stocks. Such estimates on different BM soils will help in identifying systems, which sequester relatively higher amount of OC and lower amount of inorganic carbon. This will lead to identifying BM spots sequestering high OC under known management levels, which could be accepted as models to extend this technology to similar soils elsewhere. It is expected that such exercise will help to decide issues, priorities and management of red and black soils in the Indian SAT to increase the productivity of these soils.

2. Materials and Methods

2.1 Materials

2.1.1 Background

Recent studies on ferruginous (red) soils (Saikh et al. 1998) and associated red and black soils (Bhattacharyya and Pal 1998; Naitam and Bhattacharyya 2003) indicate that the SOC content sharply declines when put to cultivation. Reduction of SOC level is significant even within 15 to 25 years of cultivation. The hypothesis is that irrespective of the initial OC levels of these red soils, there is a tendency to reach the quasi-equilibrium value (QEV) of 1 to 2% SOC. These values could be as high as 2–5% for black soils (Bhattacharyya and Pal 1998). Such studies are limited to a specific geographical region and it is not possible to arrive at a generalized view about carbon-carrying capacity of the soils because quality of soil substrate and its surface charge density (SCD) vary from one place to another.

The increase in SOC increases the SCD of soils and the ratio of internal/external exchange sites (Poonia and Niederbudde 1990). It may be mentioned that the dominant soils in the SAT are black soils (Vertisols and their intergrades, with some inclusions of Entisols in the hills and pediments) and associated red soils. All these soils are dominated by smectites and smectite-kaolinite (Bhattacharyya et al. 1993; Pal and Deshpande 1987a&b; Pal et al. 1989, 2000; Chandran et al. 2000). Presence of smectite increases the SCD of soils, which offer greater scope of carbon sequestration in these soils. Black soils, therefore, may reach a higher QEV (>2%) compared to red soils dominated by kaolin with low SCD.

Bhattacharyya and Pal (1998) reported 2–5% of SOC in the black soils of Mandla and Dindori districts, Madhya Pradesh. Dalal and Carter (2000) indicated the scope of higher SOC content in the shrink-swell soils of Australia. To find out the sufficient and deficient zone for SOC in different agro-ecoregions, Velayutham et al. (2000) adopted the lower limit of the QEV of 1%. In view of higher SCD of the dominant soils in the SAT, considering a QEV of 2% of SOC at 0–30 cm soil depth, the SOC stock is 10.5 Pg for an area of 116.4 million hectares (ha). This value is more than 3 times the existing SOC stock of SAT (Bhattacharyya et al. 2000). It, therefore, appears that effective sequestration processes can increase the SOC stock by 3 times or more, suggesting that the SAT could be fruitfully prioritized for carbon management in the Indian subcontinent.

2.1.2 Area

Keeping the above points in view, the study area was chosen in the SAT as well as in the relatively dry sub-humid agro-eco subregions (AESRs 9.1, 9.2, 10.1, 10.2, 10.3, 10.4) (Velayutham et al. 1999). Areawise, the vast plains of sub-humid, semi-arid and arid ecosystems cover 150.9 million ha in the subcontinent. While selecting the soil sites, specific bioclimatic systems were identified keeping in view the rainfall (mean annual) as mentioned below:

Sub-humid (moist) SH(m): >1100 mm
Sub-humid (dry) SH(d): 1100–1000 mm
Semi-arid (moist) SA(m): 1000–850 mm
Semi-arid (dry) SA(d): 850–550 mm
Arid (A): <550 mm
The rainfall variation in different bioclimatic systems is shown in Figure 2.1.

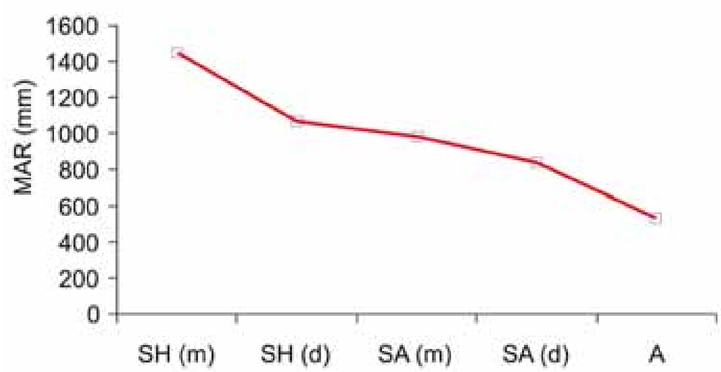


Figure 2.1. Rainfall variation in different bioclimatic systems.

2.1.3 Soils

The soils for the present study were mainly chosen from the established BM sites to ensure that each soil will cover an extensive area in the landscape. This will help in future monitoring program of the BM sites. Though a few selected soils do not belong to the BM sites, each of these soil series cover areas much higher than 20,000 ha (area required for any soil series to have BM status).

Vertisols and their Vertic intergrades and other BM sites were selected for the study in order to make comparison between the soils, the BM spots and the soil series. Some associated black soils under forest were also, however, taken as control in terms of less anthropogenic interference to change the QEV of SOC. In addition to this some red soils from both cultivated and forest (as control) was selected for the study. These controls were taken to compare the substrate quality vis-à-vis carbon storage capacity of black soils with the red soils.

For the present study 28 BM spots were selected, which included 52 pedon sites. The relative proportion of black and red soils in different BM spots as well as ecosystems is shown in figures 2.2, 2.3, 2.4 and 2.5.

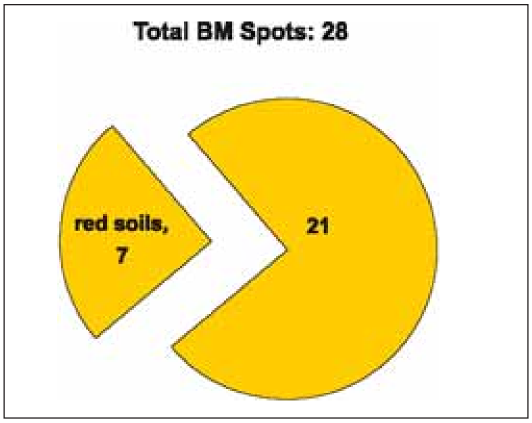


Figure 2.2. Distribution of benchmark spots in the study area.

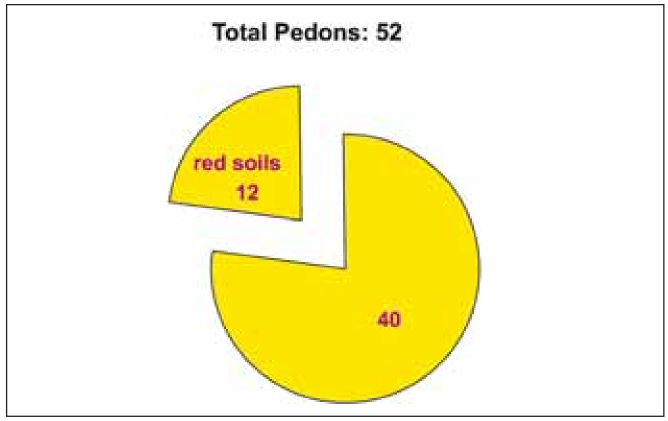


Figure 2.3. Distribution of pedons in the study area.

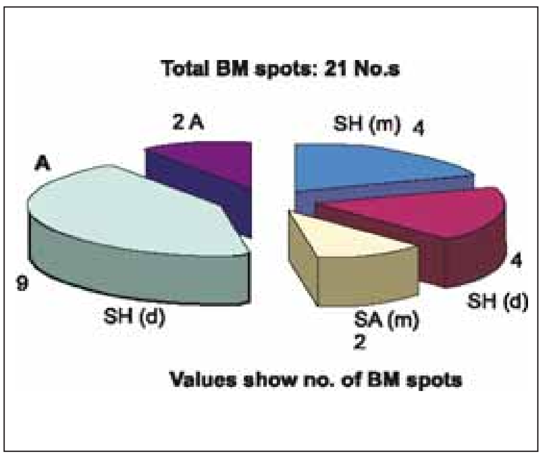


Figure 2.4. Black soil benchmark spots in different bioclimatic systems.

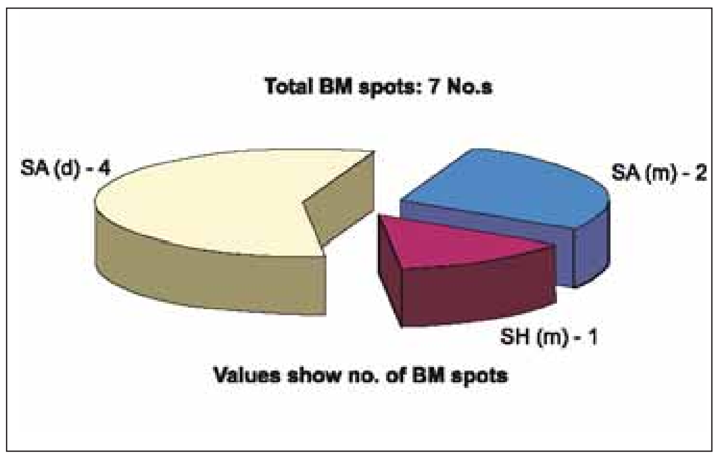


Figure 2.5. Red soil benchmark spots in different bioclimatic systems.

2.1.4 Systems

The selected BM spots in the black and red soils were given another dimension in the form of systems. Five broadly classified systems, viz, agriculture, horticulture, forest, wasteland and permanent fallow were selected. Agricultural system dominates among other systems in terms of the chosen BM spots, as well as in terms of the total number of pedons (Figures 2.6 and 2.7).

The soil series were selected in such a way that in any system (for example, agricultural system under a particular cropping pattern) two representative pedons (under the same soil series) show both farmers' management [generally low management (LM)] and the other HM. Wherever possible within the same soil series, different cropping patterns were also chosen with the same farmers' management (Table 2.1).

Table 2.1. Level of management in different BM sites.

Sl. No.	High Management (HM)	Low Management (LM)
1.	Higher NPK	Lower NPK
2.	Regular application of manures	Manures rarely applied
3.	Intercropping with legumes	Sole crop
4.	Incorporation of residues	Removal of residues and biomass
5.	Soil moisture conservation (ridge furrows, bunding, BBF)	No soil moisture conservation measures

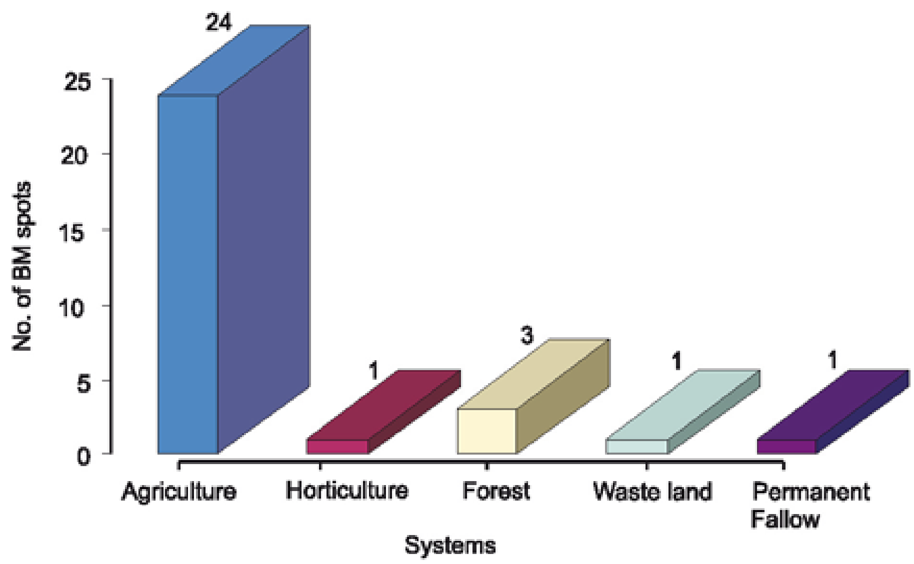


Figure 2.6. Distribution of benchmark spots in different systems.

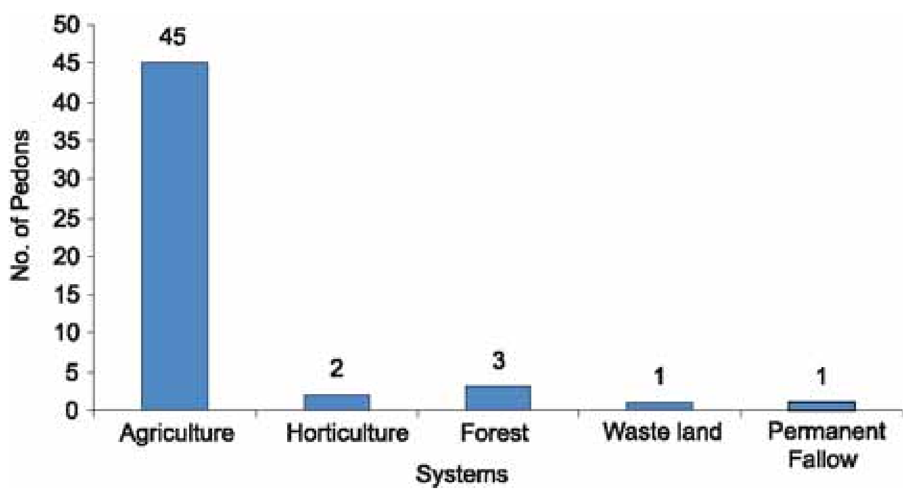


Figure 2.7. Distribution of pedons in different systems.

Within the agricultural system, three major dominant cropping patterns were selected, namely cotton, soybean and cereals. (Tables 2.2, 2.3 and 2.4).

Table 2.2. Agricultural systems with cotton as dominant crop covering 12 pedons.

Cropping pattern	Pedons
Cotton	P4
Cotton + pigeonpea	P48, P49
Cotton + pigeonpea/soybean - chickpea	P12
Cotton + pigeonpea/sorghum	P13, P14
Cotton/green gram + pigeonpea	P10
Cotton + black gram	P21
Cotton/groundnut-wheat	P29
Cotton-pearl millet	P30
Cotton-pearl millet/linseed	P31
Cotton-wheat/chickpea	P51

Table 2.3. Agricultural systems with soybean as dominant crop covering 11 pedons.

Cropping pattern	Pedons
Soybean/paddy-wheat	P28
Soybean-wheat	P5, P6, P7, P8, P32
Soybean	P50
Soybean-chickpea	P9
Soybean-chickpea/wheat	P2
Soybean + pigeonpea	P11, P39

Table 2.4. Agricultural systems with cereals covering 14 pedons.

Cropping Pattern	Pedons
Paddy	
Paddy-wheat	P27, P33
Paddy-paddy	P36, P44
Millets	
Finger millet	P16
Finger millet/pigeonpea/redgram/groundnut	P17
Finger millet	P18
Minor millet/sweet potato	P26
Sorghum	
Sorghum+pigeonpea/black gram-chickpea	P42
Sorghum/pigeonpea+green gram	P35
Sorghum/sunflower/cotton	P19
Sorghum-castor	P37, P38
Maize	
Maize/mustard	P23

Following the entire concept of BM spots, Vertisols and their Vertic intergrades (black soils) and Alfisols (red soils) as pedons representing soil series, various land use systems, the database generated through this project was arranged following mainly the five bioclimatic systems. The detailed array of materials and study area is shown in table 2.5.

Table 2.5. Benchmark spots and their site characteristics in order of decreasing rainfall from sub-humid to arid bioclimatic system.

Sl. No.	BM Spot	District/State	Series	System	Mean Annual Rainfall (mm)	Profile No.
Black Soils						
Sub-humid (moist) mean annual rainfall > 1100 mm						
1.	13	Jabalpur/Madhya Pradesh	Kheri	Agriculture (HM) paddy-wheat	1448	P27
2.	13	Jabalpur/Madhya Pradesh	Kheri 1	Agriculture (LM) soybean/paddy-wheat	1448	P28
3.	7	Nagpur/Maharashtra	Boripani	Forest (teak)	1279	P15
4.	3	Bhopal/ Madhya Pradesh	Nabibagh	Agriculture (HM) soybean-wheat	1209	P5
5.	3	Bhopal/ Madhya Pradesh	Nabibagh	Agriculture (FM) soybean-wheat	1209	P6
6.	2	Nagpur/Maharashtra	Panjri	Agriculture (HM) cotton	1127	P4
Sub-humid (dry) mean annual rainfall 1100–1000 mm						
7.	26	Adilabad/Andhra Pradesh	Nipani	Agriculture (FM) cotton+pigeonpea	1071	P48
8.	27	Adilabad/Andhra Pradesh	Pangidi	Agriculture (FM1) cotton+pigeonpea	1071	P49
9.	27	Adilabad/Andhra Pradesh	Pangidi 1	Agriculture (ITDA) soybean	1071	P50
10.	4	Indore/ Madhya Pradesh	Sarol	Agriculture (HM) soybean-wheat	1053	P7
11.	4	Indore/ Madhya Pradesh	Sarol	Agriculture (FM) soybean-wheat	1053	P8
12.	4	Indore/ Madhya Pradesh	Sarol	Agri-horticulture (HM) soybean-chickpea *in mango orchard*	1053	P9
13.	1	Nagpur/Maharashtra	Linga	Horticulture (HM) C*itrus*	1011	P1
14.	1	Nagpur/Maharashtra	Linga	Horticulture (LM) *C*itrus*	1011	P3
15.	1	Nagpur/Maharashtra	Linga	Agriculture (FM) soybean-chickpea/wheat	1011	P2
Semi-arid (moist) mean annual rainfall 1000–850 mm						
16.	22	Bidar/Karnataka	Bhatumbra	Agriculture (FM) sorghum+pigeonpea/ black gram–chickpea	977	P42
17.	5	Amravati/Maharashtra	Asra	Agriculture (FM) *cotton/green gram + pigeonpea	975	P10
18.	5	Amravati/Maharashtra	Asra	Agriculture (FM) soybean+pigeonpea	975	P11
19.	5	Amravati/Maharashtra	Asra	Agriculture (HM) cotton+ pigeonpea/soybean-chickpea	975	P12
Semi-arid (dry) mean annual rainfall 850–550 mm						
20.	16	Kota/Rajasthan	Jhalipura	Agriculture (FM1) soybean-wheat	842	P32
21.	16	Kota/Rajasthan	Jhalipura	Agriculture (FM2) paddy-wheat	842	P33
22.	6	Akola/Maharashtra	Paral	Agriculture (LM) cotton+pigeonpea /sorghum	794	P13
23.	6	Akola/Maharashtra	Paral	Agriculture (HM) cotton+pigeonpea /sorghum	794	P14

...*continued*

Table 2.5. *Continued...*

Sl. No.	BM Spot	District/State	Series	System	Mean Annual Rainfall (mm)	Profile No.
24.	18	Mehboobnagar/ Andhra Pradesh	Jajapur	Agriculture (FM1) sorghum/pigeonpea + green gram	792	P35
25.	18	Mehboobnagar/ Andhra Pradesh	Jajapur 1	Agriculture (FM2) paddy-paddy	792	P36
26.	20	Medak/Andhra Pradesh	Kasireddipalli	Agriculture (HM) soybean+pigeonpea	764	P39
27.	20	Medak/Andhra Pradesh	Kasireddipalli	Agriculture (TM) fallow-chickpea	764	P40
28.	24	Solapur/Maharashtra	Konheri	Agriculture (FM) pigeonpea/ sunflower-sorghum	742	P45
29.	24	Solapur/Maharashtra	Konheri 1	Agriculture (LM) fallow-sorghum + safflower	742	P46
30.	25	Nashik/Maharashtra	Kalwan	Agriculture (FM) sugarcane/ sorghum-wheat/chickpea	692	P47
31.	9	Tuticorin/Tamil Nadu	Kovilpatti	Agriculture sorghum/sunflower/cotton	660	P19
32.	9	Tuticorin/Tamil Nadu	Kovilpatti 1	Waste land	660	P20
33.	9	Tuticorin/Tamil Nadu	Kovilpatti	Agriculture (HM) cotton + black gram	660	P21
34.	14	Rajkot/Gujarat	Semla	Agriculture cotton/groundnut-wheat	635	P29
35.	23	Bellary/Karnataka	Teligi	Agriculture (LM) paddy-paddy	632	P43
36.	23	Bellary/Karnataka	Teligi 1	Agriculture (HM) paddy-paddy	632	P44
Arid mean annual rainfall < 550 mm						
37.	15	Rajkot/Gujarat	Sokhda	Agriculture (FM1) cotton–pearl millet	533	P30
38.	15	Rajkot/Gujarat	Sokhda 1	Agriculture (FM2) cotton–pearl millet/linseed	533	P31
39.	28	Ahmednagar/Maharashtra	Nimone	Agriculture (HM) cotton-wheat/chickpea	520	P51
40.	28	Ahmednagar/Maharashtra	Nimone	Agriculture (FM) sugarcane-soybean/ wheat/chickpea	520	P52
Red Soils						
Sub-humid (moist) mean annual rainfall >1100 mm						
41.	11	Dindori/ Madhya Pradesh	Dadarghugri	Agriculture (LM) maize/mustard	1420	P23
42.	11	Dindori/ Madhya Pradesh	Dadarghugri	Forest (teak)	1420	P24
43.	12	Umeria/ Madhya Pradesh	Karkeli	Forest (sal)	1352	P25
44.	12	Umeria/ Madhya Pradesh	Karkeli 1	Agriculture (LM) minor millet/sweet potato	1352	P26
Semi-arid (moist) mean annual rainfall 1000–850 mm						
45.	8	Bangalore/Karnataka	Vijaypura	Agriculture (FM) finger millets	924	P16
46.	8	Bangalore/Karnataka	Vijaypura 1	Agriculture *finger millet/pigeonpea/	924	P17

...continued

Table 2.5. ***Continued...***

Sl. No.	BM Spot	District/State	Series	System	Mean Annual Rainfall (mm)	Profile No.
				groundnut		
47.	8	Bangalore/Karnataka	Vijaypura 1	Agriculture (HM) finger millet	924	P18
Semi-arid (dry) mean annual rainfall 1000–850 mm						
48.	19	Rangareddy/ Andhra Pradesh	Hayatnagar	Agriculture (HM) sorghum-castor	764	P37
49.	19	Rangareddy/ Andhra Pradesh	Hayatnagar	Agriculture (LM) sorghum-castor	764	P38
50.	21	Medak/Andhra Pradesh	Patancheru	Permanent Fallow	764	P41
51.	17	Mehboobnagar/ Andhra Pradesh	Kaukuntla	Agriculture (FM) castor+pigeonpea	674	P34
52.	10	Coimbatore/Tamil Nadu	Palathurai	Agriculture horse gram/vegetables	612	P22

* Original BM Spots
Ranges of Rainfall in
· Subhumid (moist) Ecosystem = >1100 mm
· Subhumid (dry) Ecosystem = 1100–1000 mm
· Semi-arid (moist) Ecosystem = 1000–850 mm
· Semi-arid (dry) Ecosystem = 850–550 mm
· Arid Ecosystem = <550 mm

2.1.5 Source of Data

Difference in sampling methods, the exact season for collecting soil samples from different types of landscapes and kinds of vegetation, and above all the methods of soil analyses in the laboratory determine the quality of OC data of soils. Walkley and Black's method (Jackson 1973) was adopted to generate the SOC data by weight to volume. For inorganic carbon the information on calcium carbonate ($CaCO_3$) content in soils was used as the base.

The necessary information for the SOC and the SIC were obtained from the databases generated through the project of Bhattacharyya et al. (2006a; 2006b; 2006c). The soil series information for 28 BM spots was obtained from various sources as shown in table 2.6.

Table 2.6. Sources of information related to soil series from different benchmark spots.

Sl. No.	Benchmark Spots	Sources
1.	Teligi	Barde et al. (1974)
2.	Sarol	Murthy et al. (1982); Lal et al. (1994); Tamgadge et al. (1999)
3.	Asra	Anonymous (1999c)
4.	Vijaypura	Murthy et al. (1982); Lal et al. (1994)
5.	Sokhda	Sharma et al. (1988)
6.	Paral	Anonymous (1999c)
7.	Kheri	Murthy et al. (1982); Lal et al. (1994)
8.	Linga	Murthy et al. (1982); Lal et al. (1994)
9.	Kaukuntla	Anonymous (1999a)
10.	Jajapur	Anonymous (1999a)
11.	Semla	Lal et al. (1994); Sharma et al. (1988)
12.	Palathurai	Murthy et al. (1982); Lal et al. (1994)
13.	Kalwan	Challa et al. (1999)
14.	Patancheru	Murthy and Swindale (1990); Lal et al. (1994); Kalbande and Reddy (1972)
15.	Kasireddipalli	Lal et al. (1994)
16.	Nimone	Lal et al. (1994)
17.	Panjri	Anonymous (1990)
18.	Jhalipura	Anonymous (1999b); Shyampura et al. (2002)
19.	Nabibagh	NBSS&LUP Staff (1994)
20.	Nipani	BM spots visited and name proposed by NBSS&LUP (RNPS-25) group
21.	Pangidi	BM spots visited and name proposed by NBSS&LUP (RNPS-25) group
22.	Dadarghugri	Bhattacharyya and Pal (1998); Sehgal et al. (1998)
23.	Boripani	Naitam (2001); Naitam and Bhattacharyya (2003)
24.	Bhatumbra	Shiva Prasad et al. (1998)
25.	Konheri	NBSS&LUP Staff (1995)
26.	Kovilpatti	Kalbande et al. (1992)
27.	Hayatnagar	BM spots visited and name proposed by NBSS&LUP (RNPS-25) group
28.	Karkeli	BM spots visited and name proposed by NBSS&LUP (RNPS-25) group

2.2 Methods

The SOC and $CaCO_3$ (SIC) were determined following standard methods laid out by Jackson (1973).

2.2.1 Computation of soil carbon stock

The size of TC stock is calculated following standard methods described by Batjes (1996) and Bhattacharyya et al. (2000). The first step (Step 1) involves calculation of OC by multiplying OC content (g/g), bulk density (BD) in 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 determined by this process is multiplied by the area (ha) of the soil unit distributed in different agro-ecological subregions (AESR) (Velayutham et al. 1999; 2000). The source of information for the areal extent of the soil series in each BM spots is shown in table 2.7. The total SOC content is calculated in terms of Pg. For the SIC, the calculation was made using 12% C values in $CaCO_3$ using steps 1 and 2.

Table 2.7. Area extent of the soil series and their references.

Sl. No.	Benchmark spots	Area ('000 ha)	Sources
1.	Teligi	659.0	Shiva Prasad et al. (1998)
2.	Sarol	721.0	Tamgadge et al. (1996)
3.	Asra	1866.4	Challa et al. (1995)
4.	Vijaypura	841.0	Shiva Prasad et al. (1998)
5.	Sokhda	604.4	Sharma et al. (1994)
6.	Paral	1185.0	Challa et al. (1995)
7.	Kheri	464.1	Murthy et al. (1982)
8.	Linga	129.5	Sehgal et al. (1994)
9.	Kaukuntla	755.6	Reddy et al. (1996)
10.	Jajapur	1153.3	Reddy et al. (1996)
11.	Semla	485.7	Sharma et al. (1994)
12.	Palathurai	345.1	Natarajan et al. (1997)
13.	Kalwan	618.9	Challa et al. (1995)
14.	Patancheru	1462.5	Reddy et al. (1996)
15.	Kasireddipalli	391.3	Reddy et al. (1996)
16.	Nimone	46.5	Sehgal et al. (1994)
17.	Panjri	635.9	Tamgadge et al. (1996)
18.	Jhalipura	1153.7	Shyampura et al. (1996)
19.	Nabibagh	486.9	NBSS&LUP Staff (1994)
20.	Nipani	533.4	Reddy et al. (1996)
21.	Pangidi	1021.1	Reddy et al. (1996)
22.	Dadarghugri	138.66	Tamgadge et al. (1996)
23.	Boripani	1673.1	Anonymous (1990), Challa et al. (1995)
24.	Bhatumbra	259.9	Shiva Prasad et al. (1998)
25.	Konheri	362.5	Challa et al. (1995)
26.	Kovilpatti	1291.5	Natarajan et al. (1997)
27.	Hayatnagar	1725.2	Reddy et al. (1996)
28.	Karkeli	623.9	Tamgadge et al. (1996)

Results and Discussion

The following sections describe the stocks of carbon (SOC and SIC) in the selected black and red soils in Indian SAT.

3.1 Carbon stock

3.1.1 Carbon stock in black soils

The SOC, SIC and TC stocks of the study area in black soils (14830.26 kha) in HM spots are shown in table 3.1. Total SOC stock is 0.4719 Pg, which is about 0.03 Pg/(million ha). This value [0.03 Pg/(million ha)] is higher than the value of SOC [0.024 Pg/(million ha)] reported on the basis of soils data of 1980s (Bhattacharyya et al. 2000). It shows that during the last 20–25 years, improved management must have helped sequestering more SOC in the black soils of Indian SAT. The SOC, SIC and TC stocks at 0–30 and 0–150 cm soil depths are also shown in figure 3.1a, which clearly indicate an inverse relationship with the SOC and the SIC. Figure 3.1b shows relative proportion of SOC and SIC over TC in black soils. The relative proportion of SOC (over TC) decreases from 40 to 28% from 0–30 cm to 0–150 cm soil depths. The corresponding figure for SIC increases from 60% to 72%. This is due to decrease in SOC content down the depth of profile. Conversely, $CaCO_3$ concentration increases down the depth contributing to more SIC at soil depth 0–150 cm than at 0–30 cm.

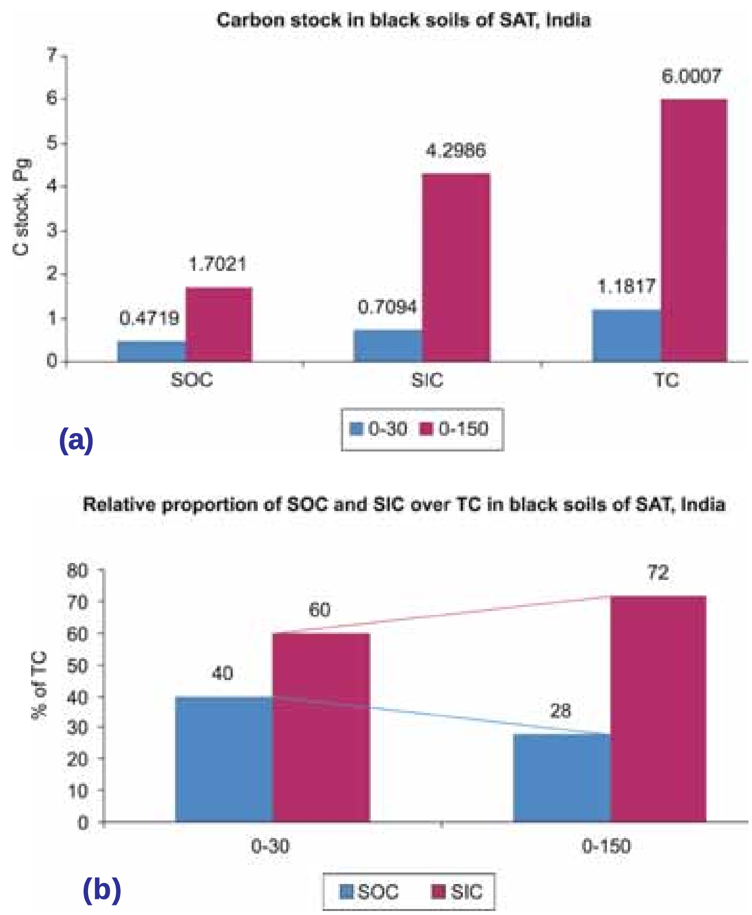


Figure 3.1. SOC, SIC and TC stocks in black soils.

3.1.2 Carbon stock in red soils

The SOC, SIC and TC stocks in the red soils (covering 6.3 million ha) was estimated (Table 3.2). The surface horizons of red soils (0–30 cm) do not contain $CaCO_3$ and therefore total SOC and TC stock of the red soils remain same at 0.33 Pg. The SOC stock at 0–150 cm soil depth becomes almost five times (Table 3.2). Figure 3.2a shows the SOC, SIC and TC stocks in red soils. Relative proportion of SOC and SIC over TC in red soils indicates about 25% in SOC content with depth (Figure 3.2b). It indicates that the SOC in red soils does not change as sharply as is observed in the

Table 3.1. Soil organic carbon (SOC), soil inorganic carbon (SIC) and total carbon (TC) stock in 21 BM spots represented by black soils in SAT, India.

Total area under black soils studied ~15.3 million ha

Pedon No. Area, '000 ha	Series (Bioclimate)*	Soil Classification**	Systems (crop)	Carbon Type	Carbon Stock (Pg) Depth range (cm) 0–30	0-50	0-100	0–150
P27	Kheri	Very fine, smectitic,	Agriculture	SOC	0.01	0.01	0.02	0.04
464.1	SH (m)	hyperthermic,	(paddy-wheat)	SIC	0.00	0.01	0.02	0.04
		Typic Haplusterts	(HM)	TC	0.02	0.03	0.05	0.09
P15	Boripani	Very fine, smectitic,	Forest (teak)	SOC	0.00	0.00	0.00	0.00
138.7	(Maharashtra)	hyperthermic,		SIC	0.00	0.00	0.01	0.02
	SH (m)	*Vertic Haplustepts*		TC	0.00	0.01	0.02	0.03
P4	Panjri	Very fine, smectitic,	Agriculture	SOC	0.00	0.00	0.00	0.00
46.5	SH (m)	hyperthermic,	(cotton) (HM)	SIC	0.00	0.00	0.00	0.00
		Typic Haplusterts		TC	0.00	0.00	0.00	0.01
P5	Nabibagh	Fine, smectitic,	Agriculture	SOC	0.03	0.05	0.10	0.14
1153.7	SH (m)	hyperthermic,	(soybean-wheat)	SIC	0.02	0.05	0.09	0.15
		Typic Haplusterts	(HM)	TC	0.06	0.10	0.20	0.29
P48	Nipani	Fine, smectitic,	Agriculture	SOC	0.01	0.01	0.03	0.05
486.9	SH (d)	hyperthermic,	(cotton-	SIC	0.06	0.11	0.21	0.32
		Typic Haplusterts	pigeonpea) (FM)	TC	0.08	0.12	0.25	0.37
P50	Pangidi	Very fine, smectitic,	Agriculture	SOC	0.01	0.02	0.33	0.03
533.4	SH (d)	hyperthermic,	(soybean) (FM)	SIC	0.01	0.03	0.10	0.17
		Vertic Haplustepts		TC	0.03	0.06	0.13	0.21
P7	Sarol	Very fine, smectitic,	Agriculture	SOC	0.01	0.02	0.04	0.05
721.0	SH (d)	hyperthermic,	(soybean-wheat)	SIC	0.02	0.03	0.07	0.11
		Typic Haplusterts	(HM)	TC	0.04	0.06	0.12	0.17
P1	Linga	Very fine, smectitic,	Horticulture	SOC	0.00	0.00	0.01	0.01
129.5	SH (d)	hyperthermic,	(*Citrus*)	SIC	0.00	0.00	0.01	0.02
		Typic Haplusterts	(HM)	TC	0.00	0.01	0.02	0.03
P42	Bhatumbra	Very Fine, smectitic,	Agriculture	SOC	0.06	0.09	0.18	0.24
1673.1	SA (m)	isohyperthermic,	(sorghum+pigeonpea/	SIC	0.07	0.13	0.26	0.40
		Udic Haplusterts	black gram-chickpea) (FM)	TC	0.13	0.23	0.45	0.65

...continued

Table 3.1. *Continued...*

Total area under black soils studied ~15.3 million ha

Pedon No. Area, '000 ha	Series (Bioclimate)*	Soil Classification**	Systems (crop)	Carbon Type	Carbon Stock (Pg) Depth range (cm) 0–30	0-50	0-100	0–150
P12	Asra	Very fine,smectitic,	Agriculture	SOC	0.07	0.11	0.21	0.29
1866.4	SA (m)	hyperthermic,	(cotton+pigeonpea /	SIC	0.05	0.09	0.19	0.32
		Typic Haplusterts	soybean- (HM) chickpea)	TC	0.13	0.21	0.40	0.61
P32	Jhalipura	Fine, smectitic, hyperthermic,	Agriculture (soybean-wheat)	SOC	0.01	0.01	0.03	0.05
635.9	SA (d)	*Typic Haplusterts*	(FM/1)	SIC	0.01	0.02	0.06	0.11
				TC	0.02	0.04	0.10	0.16
P14	Paral	Very fine, smectitic,	Agriculture (cotton+	SOC	0.03	0.04	0.10	0.12
1185.0	SA (d)	hyperthermic,	pigeonpea/sorghum) (FM)	SIC	0.08	0.14	0.28	0.37
		Sodic Haplusterts		TC	0.11	0.19	0.38	0.50
P35	Jajapur	Fine, smectitic,	Agriculture (sorghum/pigeonpea	SOC	0.02	0.03	0.05	0.07
1153.3	SA (d)	isohyperthermic,	+ green gram) (FM /1)	SIC	0.02	0.04	0.14	0.28
		Vertic Haplustepts		TC	0.04	0.08	0.20	0.35
P39	Kasireddipalli	Fine, smectitic,	Agriculture	SOC	0.01	0.01	0.03	0.04
391.3	SA (d)	isohyperthermic,	(soybean-pigeonpea) (HM)	SIC	0.00	0.01	0.04	0.07
		Sodic Haplusterts		TC	0.01	0.03	0.07	0.11
P45	Konheri	Fine, smectitic, hyperthermic,	Agriculture (pigeonpea/	SOC	0.00	0.00	0.01	0.01
259.9	SA (d)	*Vertic Haplustepts*	sunflower-sorghum) (FM)	SIC	0.01	0.02	0.04	0.09
				TC	0.01	0.02	0.05	0.10
P47	Kalwan	Fine, smectitic, hyperthermic,	agriculture (sugarcane/	SOC	0.02	0.03	0.00	0.06
618.9	SA (d)	*Typic Haplusterts*	sorghum-wheat/chickpea) (FM)	SIC	0.00	0.01	0.07	0.15
				TC	0.03	0.05	0.08	0.21
P21	Kovilpatti	Very fine, smectitic,	Agriculture	SOC	0.00	0.01	0.02	0.02
362.5	SA (d)	isohyperthermic,	(cotton+black gram) (HM)	SIC	0.01	0.02	0.04	0.11
		Gypsic Haplusterts		TC	0.01	0.03	0.06	0.13
P29	Semla	Fine, smectitic,	Agriculture (cotton/	SOC	0.01	0.02	0.04	0.06
485.7	SA (d)	hyperthermic,	groundnut-wheat) (Org)	SIC	0.04	0.07	0.14	0.22
		Typic Haplusterts		TC	0.05	0.09	0.18	0.28

...continued

Table 3.1. *Continued...*

Total area under black soils studied ~15.3 million ha

Pedon No. Area, '000 ha	Series (Bioclimate)*	Soil Classification**	Systems (crop)	Carbon Type	Carbon Stock (Pg) Depth range (cm) 0–30	0-50	0-100	0–150
P44	Teligi	Very fine, smectitic,	Agriculture (paddy-paddy)	SOC	0.02	0.03	0.05	0.07
659.0	SA (d)	isohyperthermic,	(HM)	SIC	0.02	0.05	0.11	0.19
		Sodic Haplusterts		TC	0.05	0.08	0.17	0.27
P30	Sokhda	Fine, smectitic,	Agriculture (cotton-pearl millet)	SOC	0.01	0.01	0.03	0.03
604.4	Arid	hyperthermic,	(FM-1)	SIC	0.07	0.11	0.26	0.42
		Leptic Haplusterts		TC	0.08	0.13	0.29	0.46
P51	Nimone	Very fine, smectitic,	Agriculture (cotton-wheat/	SOC	0.05	0.08	0.15	0.20
1725.2	Arid	isohyperthermic,	chickpea [Irrigated]) (HM)	SIC	0.12	0.21	0.41	0.63
		Sodic Haplusterts		TC	0.17	0.29	0.57	0.84
Total				SOC	0.47	0.71	1.51	1.70
15294				SIC	0.70	1.24	2.66	4.29
				TC	1.18	1.95	3.88	6.00

* SH(m) = sub-humid moist; SH(d) = sub-humid (dry); SA(m) = Semi-arid (moist); SA(d) = Semi-arid (dry); A = Arid
** Calcareous at family level.

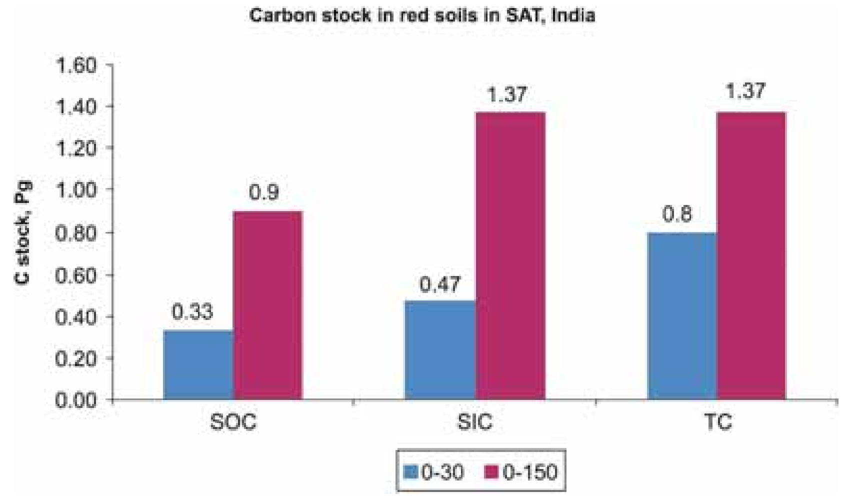
Table 3.2. Soil organic carbon (SOC), soil inorganic carbon (SIC) and total carbon (TC) stock in seven benchmark spots represented by red soils (under HM) in SAT, India.

Total area under black soils studied ~15.3 million ha

Pedon No. Area, '000 ha	Series (Bioclimate)	Soil Classification	Systems (crop)	Carbon Type	Carbon Stock (Pg) Depth range (cm) 0–30	0-50	0-100	0–150
P23 1021.1	Dadarghugri SH (m)	Clayey-skeletal, mixed, hyperthermic *Typic Haplustalfs*	Agriculture (Maize/Mustard) (FM)	SOC	0.08	0.11	0.17	0.23
				SIC	0.00	0.00	0.00	0.00
				TC	0.08	0.11	0.17	0.23
P25 623.9	Karkeli SH (m)	Coarse-loamy, mixed, hyperthermic, *Typic Paleustalfs*	Reserve Forest(Sal)	SOC	0.04	0.05	0.06	0.07
				SIC	0.00	0.00	0.00	0.00
				TC	0.04	0.05	0.06	0.07
P18 841.0	Vijaypura SA (m)	Fine-loamy, kaolinitic, isohyperthermic, *Typic Haplustalfs*	Agriculture (Finger millet) (HM)	SOC	0.03	0.05	0.07	0.08
				SIC	0.00	0.00	0.00	0.00
				TC	0.03	0.05	0.07	0.08
P37 1291.5	Hayatnagar SA (d)	Loamy-skeletal, mixed, isohyperthermic, *Typic Rhodustalfs*	Agriculture (Sorghum-Castor) (HM)	SOC	0.05	0.08	0.12	0.16
				SIC	0.00	0.03	0.08	0.13
				TC	0.05	0.08	0.12	0.16
P41 1462.5	Patancheru SA (d)	Fine, mixed, isohyperthermic, *Typic Rhodustalfs*.	Permanent Fallow	SOC	0.10	0.14	0.21	0.25
				SIC	0.04	0.06	0.14	0.17
				TC	0.14	0.20	0.35	0.42
P34 755.6	Kaukuntla SA (d)	Fine, mixed, isohyperthermic, *Vertic Haplustalfs*	Agriculture (Castor+Pigeonpea) (FM)	SOC	0.02	0.04	0.06	0.07
				SIC	0.43	0.05	0.08	0.09
				TC	0.02	0.04	0.06	0.07
P22 345.1	Palathurai SA (d)	Fine-loamy (cal), mixed, isohyperthermic *Typic Haplustalfs*	Agriculture (Horse Gram / vegetable) (Org)	SOC	0.01	0.02	0.03	0.03
				SIC	0.00	0.01	0.05	0.08
				TC	0.01	0.03	0.07	0.12
Total 6340.7				SOC	0.33	0.47	0.71	0.90
				SIC	0.47	0.15	0.35	0.47
				TC	0.80	0.62	1.06	1.37

black soils of Indian SAT. Interestingly relative contribution of SIC in red soils decreases from 60% to 35% over depth. This is in sharp contrast to black soils and points to the fact that $CaCO_3$ in red soils are often concentrated on the surface horizons due to more clay content than on the sub-surface horizons. (Figures 3.2a and 3.2b).

(a)



(b)

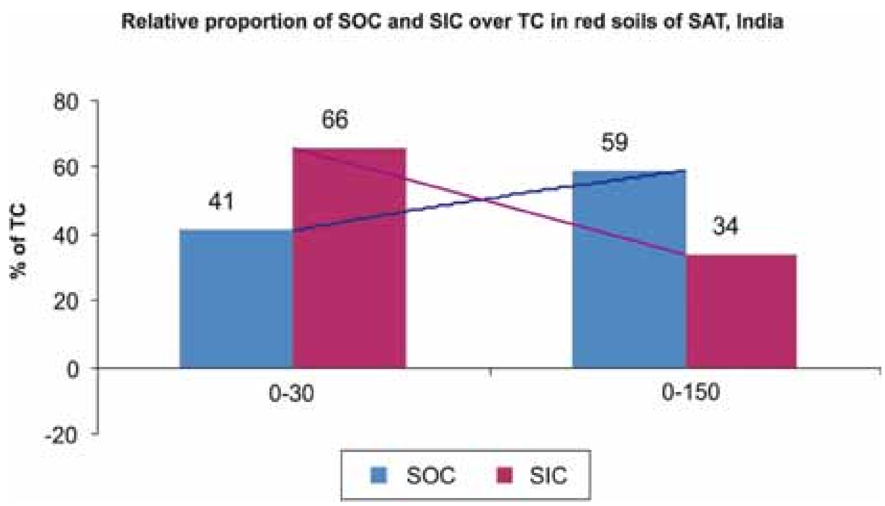


Figure 3.2. Stock of organic, inorganic, and total carbon in red soils of SAT, India.

3.1.3 Carbon stock in different bioclimatic systems

Carbon stock in soil depends largely on the areal extent of the soils besides other factors such as carbon content, the depth and the BD of soils. Even with a relatively small amount of SOC content (0.2–0.3%), the SOC stock of arid and semi-arid tract indicated very high value (Bhattacharyya et al. 2000). This is due to large area of dry tracts under these two bioclimatic systems. Unfortunately carbon stock, per se, does not directly indicate the influence of soil (parameters) and management systems (crops, etc.) to sequester carbon. Therefore, the carbon stock per unit area seems to convey a better dataset, which could be utilized for identifying the influence of soil and/or management parameters for both organic and inorganic carbon sequestration in soils.

The SOC, SIC and TC stocks is estimated per unit area and is expressed in Pg/(million ha). The TC stock depends on the SOC and SIC stocks; with low SOC stock and high SIC stock, the TC stock may be very high. Moreover for many soils, the SIC may be nil or negligible in the surface soils. It is therefore, prudent to consider the SOC stock per unit area for identifying systems for better carbon sequestration.

Figures 3.3, 3.4, 3.5, 3.6 and 3.7 show the SOC, SIC and TC stocks in sub-humid (moist), sub-humid (dry), semi-arid (moist), semi-arid (dry) and arid bioclimatic systems.

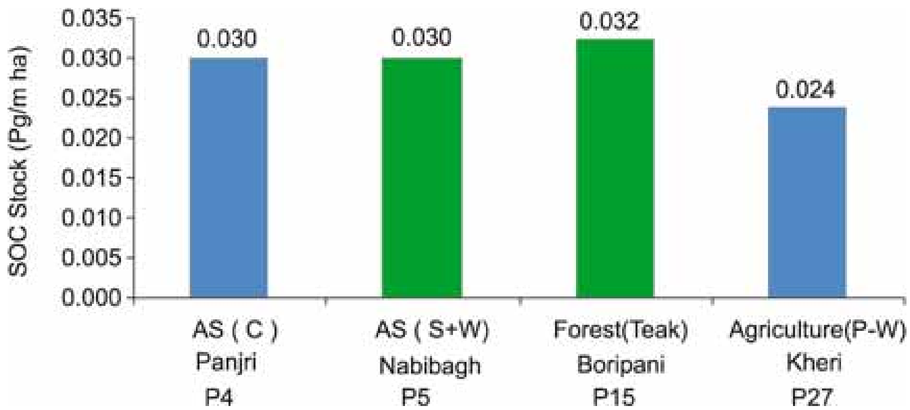


Figure 3.3. SOC stock in sub-humid (moist) bioclimatic system (0–30 cm) in black soils.

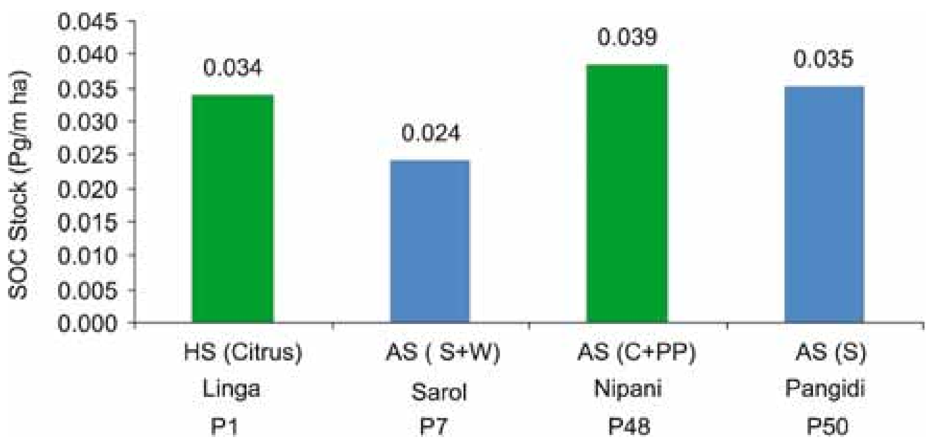


Figure 3.4. SOC stock in sub-humid (dry) bioclimatic system (0–30 cm) in black soils.

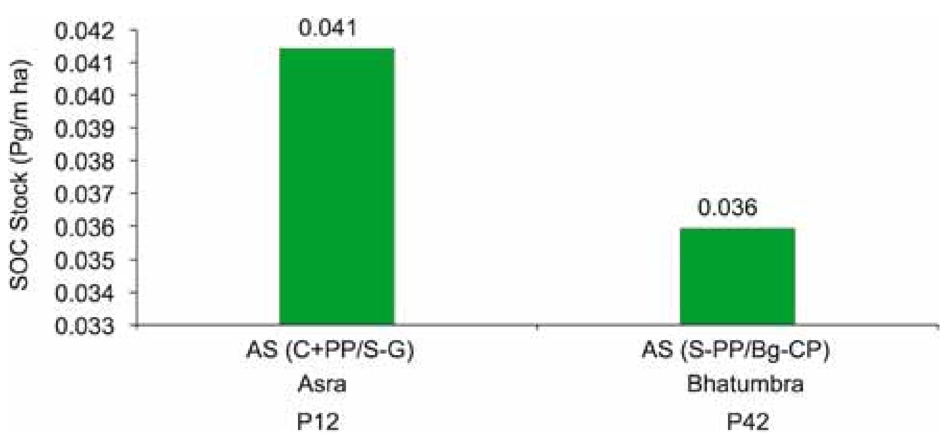


Figure 3.5. SOC stock in semi-arid (moist) bioclimatic system (0–30 cm) black soils.

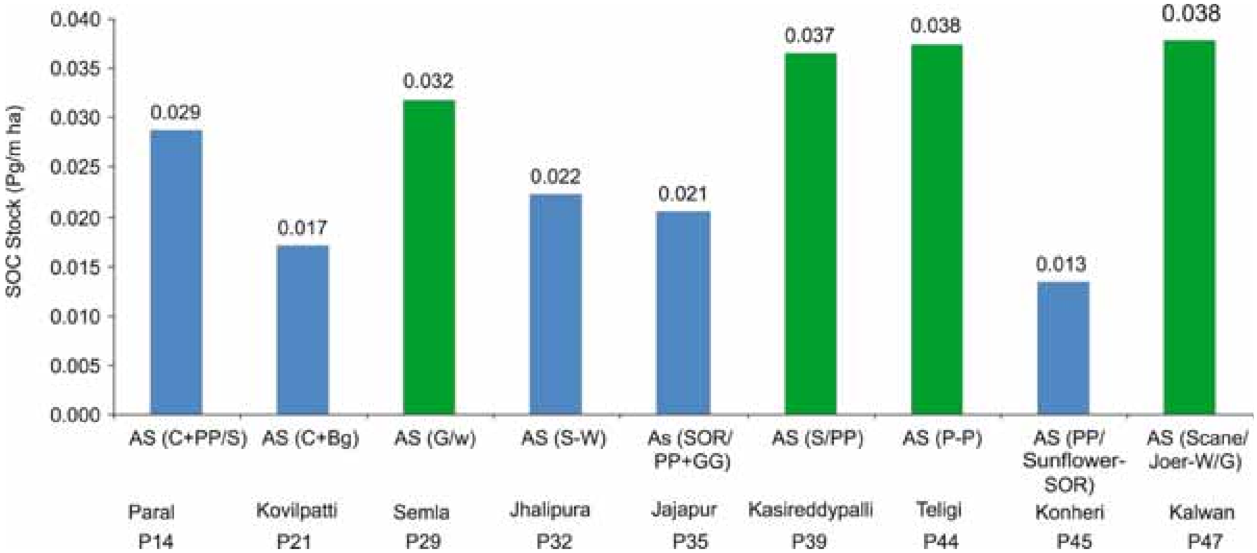


Figure 3.6. SOC stock in semi-arid (dry) bioclimatic system (0–30 cm) in black soils.

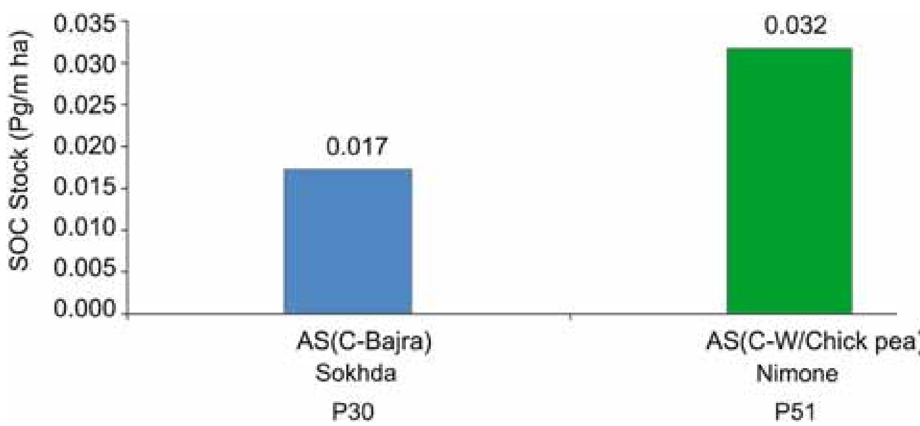


Figure 3.7. SOC stock in arid bioclimatic system (0–30 cm) in black soils.

Earlier, it was reported that the first 30 cm soil contains 9.77 Pg OC stock in India (Bhattacharyya et al. 2000). This value corresponds to 0.03 Pg OC per million ha in India. Taking a constant value of BD of 1.5 Mg/m^3, the total SOC stock of 0.03 Pg/(million ha) again corresponds to nearly 0.6% SOC at 0–30 cm soil depth.

Keeping in view of higher (on a relative scale) SOC content, 14 systems were earlier identified and reported as viable for OC sequestration (Bhattacharyya et al. 2006c). On the basis of OC (in Pg) present per unit area (in million ha), a total of 22 systems were selected as potential areas for OC sequestration. A few representative systems in sub-humid (moist) (P5, P15), sub-humid (dry) (P1, P48), semi-arid (moist) (P12, P42), semi-arid (dry) (P29, P39, P44, P47), and arid (P51) under black soils and sub-humid (moist) (P24, P25), semi-arid (moist) (P18), and semi-arid (dry) (P37, P41) under red soils are shown in figures 3.3 to 3.10. Besides these 16 systems, P3 (sub-humid moist), P8 (sub-humid dry), P13, P38, P43 (semi-arid dry) and P52 (arid) systems were also included to make the total identified systems as 22. The reason for their selection is elaborated in Chapter 4. There are a few systems, which register greater than 0.03 Pg/(million ha) SOC stock. But they were not selected as ideal systems for carbon sequestration due to shallow depth (P22, P34, P50), high SIC (P14) and monocropping system (P4) under cotton (Naitam and Bhattacharyya 2003).

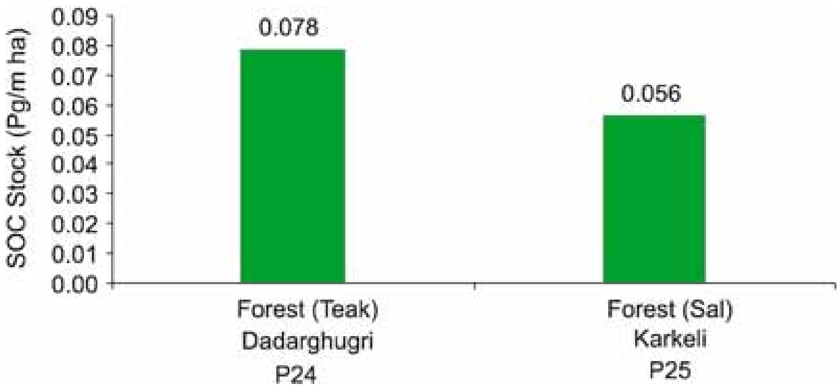


Figure 3.8. SOC stock in sub-humid (moist) bioclimatic system (0–30 cm) in red soils.

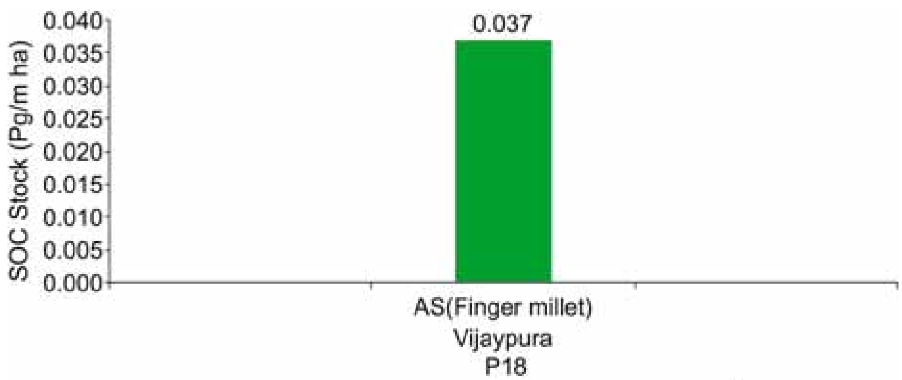


Figure 3.9. SOC stock in semi-arid (moist) bioclimatic system (0–30 cm) in red soils, India.

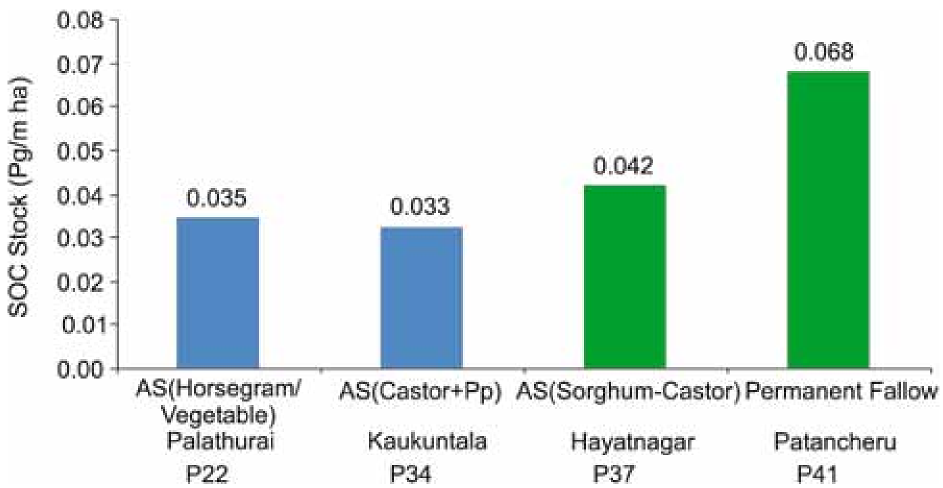


Figure 3.10. Soil organic carbon (SOC) stock in semi-arid (dry) bioclimatic system (0–30 cm) in red soils, India.

3.1.4 Influence of management on carbon stock

Organic, inorganic and TC stocks in selected BM spots represented by black soils under high- and low-management are given in tables 3.3 and 3.4, respectively. Figure 3.11 shows almost similar SOC values under both the management systems. However, there is a tendency of low SIC accumulations in soils under high management (HM), which could be due to more vegetation and external source of irrigation effecting dissolution of native $CaCO_3$ (Bhattacharyya et al. 2006c). Table 3.5 shows SOC, SIC and TC stocks in selected BM spots in red soils under LM. Tables 3.6 to 3.13 show the carbon stock of the BM spots in different bioclimatic systems for black and red soils.

Table 3.3. SOC, SIC and TC stock in selected benchmark spots represented by black soils under high management in SAT, India.

Pedon No. Area, '000 ha	Series	Soil Classification	Systems (crop)	Carbon Type	Carbon Stock (Pg) Depth range (cm) 0–30	0-50	0-100	0–150
P27	Kheri	Very fine, smectitic,	Agriculture	SOC	0.01	0.01	0.02	0.04
464.1	SH (m)	hyperthermic,	(paddy-wheat)	SIC	0.00	0.01	0.02	0.04
		Typic Haplusterts	(HM)	TC	0.02	0.03	0.05	0.09
P4	Panjri	Very fine, smectitic,	Agriculture (cotton)	SOC	0.00	0.00	0.00	0.00
46.5	SH (m)	hyperthermic,	(HM)	SIC	0.00	0.00	0.00	0.00
		Typic Haplusterts		TC	0.00	0.00	0.00	0.01
P5	Nabibagh	*Fine, smectitic,*	Agriculture	SOC	0.03	0.05	0.10	0.14
1153.7	SH (m)	hyperthermic,	(soybean-wheat)	SIC	0.02	0.05	0.09	0.15
		Typic Haplusterts	(HM)	TC	0.06	0.10	0.20	0.29
P50	Pangidi	Very fine, smectitic,	Agriculture	SOC	0.01	0.02	0.33	0.03
533.4	SH (d)	hyperthermic,	(soybean) (ITDA)	SIC	0.01	0.03	0.10	0.17
		Vertic Haplustepts		TC	0.03	0.06	0.13	0.21
P7	Sarol	Very fine, smectitic,	Agriculture	SOC	0.01	0.02	0.04	0.05
721.0	SH (d)	hyperthermic,	(soybean-wheat)	SIC	0.02	0.03	0.07	0.11
		Typic Haplusterts	(HM)	TC	0.04	0.06	0.12	0.17
P1	Linga	Very fine, smectitic,	Horticulture	SOC	0.00	0.00	0.01	0.01
129.5	SH (d)	hyperthermic,	(Citrus) (HM)	SIC	0.00	0.00	0.01	0.02
		Typic Haplusterts		TC	0.00	0.01	0.02	0.03
P12	Asra	Very fine, smectitic,	Agriculture (cotton +	SOC	0.07	0.11	0.21	0.29
1866.4	SA (m)	hyperthermic,	pigeonpea/soybean-chickpea)	SIC	0.05	0.09	0.19	0.32
		Typic Haplusterts	(HM)	TC	0.13	0.21	0.40	0.61
P141	Paral	Very fine, smectitic,	Agriculture (cotton+	SOC	0.03	0.05	0.10	0.12
185.0	SA (d)	hyperthermic,	pigeonpea/sorghum)	SIC	0.08	0.14	0.28	0.37
		Sodic Haplusterts	(FM)	TC	0.11	0.19	0.38	0.50
P39	Kasireddipalli	Fine, smectitic,	Agriculture	SOC	0.01	0.01	0.03	0.04
391.3	SA (d)	isohyperthermic,	(soybean-pigeonpea) (HM)	SIC	0.00	0.01	0.04	0.07
		Sodic Haplusterts		TC	0.01	0.03	0.07	0.11
P33	Jhalipura	Fine, smectitic,	Agriculture (paddy-wheat)	SOC	0.01	0.02	0.03	0.04
635.9	SA (d)	hyperthermic,	(FM/2)	SIC	0.03	0.08	0.17	0.26
		Typic Haplusterts		TC	0.05	0.10	0.21	0.31
P36	Jajapur	Fine-loamy, smectitic,	Agriculture (paddy-paddy)	SOC	0.05	0.07	0.08	0.09
1153.3	SA (d)	isohyperthermic,	(FM/2)	SIC	0.01	0.03	0.18	0.33
		Vertic Haplustepts		TC	0.07	0.10	0.27	0.42
P29	Semla	Fine, smectitic,	Agriculture	SOC	0.01	0.02	0.04	0.06
485.7	SA (d)	hyperthermic,	(cotton/groundnut-wheat)	SIC	0.04	0.07	0.14	0.22
		Typic Haplusterts		TC	0.05	0.09	0.18	0.28
P21	Kovilpatti	Very fine, smectitic,	Agriculture	SOC	0.00	0.01	0.02	0.02
362.5	SA (d)	isohyperthermic,	(cotton+black gram)	SIC	0.01	0.02	0.04	0.11
		Gypsic Haplusterts	(HM)	TC	0.01	0.03	0.06	0.13
P44	Teligi	Very Fine, smectitic,	Agriculture	SOC	0.02	0.03	0.05	0.07
659.0	SA (d)	isohyperthermic,	(paddy-paddy) (HM)	SIC	0.02	0.05	0.11	0.19
		Sodic Haplusterts		TC	0.05	0.08	0.17	0.23
P45	Konheri	Fine, smectitic,	Agriculture (pigeonpea/	SOC	0.00	0.00	0.01	0.01
259.9	SA (d)	hyperthermic,	sunflower-sorghum) (FM)	SIC	0.01	0.02	0.04	0.09
		Vertic Haplustepts		TC	0.01	0.02	0.05	0.10
P31	Sokhda	Fine, smectitic,	Agriculture	SOC	0.01	0.02	0.04	0.05

...continued

Table 3.3. *Continued...*

Pedon No. Area '000 ha	Series	Soil Classification	Systems (crop)	Carbon Type	Carbon Stock (Pg) Depth range (cm) 0–30	0-50	0-100	0–150
604.4	Arid	hyperthermic,	(cotton-pearl millet/linseed)	SIC	0.06	0.11	0.25	0.37
		Sodic Haplusterts	(FM-2)	TC	0.07	0.13	0.29	0.42
P51	Nimone	Very fine, smectitic,	Agriculture	SOC	0.05	0.08	0.15	0.20
1725.2	Arid	isohypethermic,	(cotton-wheat/chickpea	SIC	0.12	0.21	0.41	0.63
		Sodic Haplusterts	[Irrigated]) (HM)	TC	0.17	0.29	0.57	0.84
Total				SOC	0.40	0.60	1.32	1.36
12376.8				SIC	0.55	1.01	2.22	3.53
				TC	0.96	1.61	3.24	4.90
			SOC [Pg/(million ha)]		0.03	0.04	0.10	0.11
			SIC [Pg/(million ha)]		0.04	0.08	0.17	0.28
			TC [Pg/(million ha)]		0.07	0.13	0.26	0.39

Table 3.4. SOC, SIC and TC stock in 28 benchmark spots represented by black soils under low management in SAT, India.

Pedon No. Area, '000 ha	Series	Systems (crop)	Carbon Type	Carbon stock (Pg) Depth range (cm) 0–30	0-50	0-100	0–150
P28	Kheri	Agriculture (soybean/paddy-wheat) (LM)	SOC	0.01	0.01	0.03	0.05
464.1			SIC	0.00	0.01	0.04	0.06
			TC	0.02	0.03	0.07	0.01
P6	Nabibagh	Agriculture (soybean-wheat) (FM)	SIC	0.02	0.04	0.08	0.12
1153.7			SOC	0.02	0.03	0.08	0.12
			TC	0.05	0.08	0.17	0.25
P48	Nipani	Agriculture (cotton+pigeonpea) (FM)	SOC	0.01	0.01	0.03	0.05
486.9			SIC	0.06	0.11	0.21	0.32
			TC	0.08	0.12	0.25	0.37
P49	Pangidi	Agriculture (cotton+pigeonpea) (FM 1)	SOC	0.01	0.03	0.06	0.07
533.4			SIC	0.01	0.02	0.05	0.08
			TC	0.03	0.05	0.11	0.15
P3	Linga	Horticulture (Citrus) (LM)	SOC	0.00	0.00	0.01	0.01
129.5			SIC	0.00	0.00	0.01	0.02
			TC	0.00	0.01	0.02	0.04
P42	Bhatumbra	Agriculture (sorghum+pigeonpea/	SOC	0.06	0.09	0.18	0.24
1673.1		black gram-chickpea) (FM)	SIC	0.07	0.13	0.26	0.40
			TC	0.13	0.23	0.45	0.65
P13	Paral	Agriculture (cotton+pigeonpea/sorghum) (LM)	SOC	0.03	0.05	0.11	0.16
1185			SIC	0.06	0.11	0.22	0.33
			TC	0.10	0.16	0.33	0.49
P40	Kasireddipalli	Agriculture (fallow-chickpea) (TM)	SOC	0.00	0.01	0.02	0.03
391.3			SIC	0.01	0.02	0.04	0.07
			TC	0.01	0.03	0.07	0.11
P46	Konheri	Agriculture (pigeonpea/sunflower-sorghum)	SOC	0.00	0.01	0.02	0.02
259.9		(LM)	SIC	0.01	0.02	0.07	0.13
			TC	0.02	0.04	0.09	0.15

...continued

Table 3.4. *Continued...*

Pedon No. Area, '000 ha	Series	Systems (crop)	Carbon Type	Carbon stock (Pg) Depth range (cm) 0–30	0-50	0-100	0–150
P29	Semla	Agriculture (cotton/groundnut-wheat) (Org)	SOC	0.01	0.02	0.04	0.06
485.7			SIC	0.04	0.07	0.14	0.22
			TC	0.05	0.09	0.18	0.28
P43	Teligi	Agriculture (paddy-paddy) (LM)	SOC	0.02	0.04	0.07	0.10
659.0			SIC	0.03	0.06	0.11	0.19
			TC	0.06	0.11	0.18	0.29
Total			SOC	0.23	0.37	0.70	0.96
6957.50			SIC	0.37	0.62	1.26	2.00
			TC	0.60	0.99	1.97	2.86
		SOC [Pg/(million ha)]		0.03	0.05	0.10	0.13
		SIC [Pg/(million ha)]		0.05	0.09	0.18	0.28
		TC [Pg/(million ha)]		0.08	0.14	0.28	0.41

Table 3.5. SOC, SIC and TC stock in selected benchmark spots represented by red soils (under LM) in SAT, India.

Pedon No. Area, '000 ha	Series	Systems (crop)	Carbon Type	Carbon stock (Pg) Depth range (cm) 0–30	0-50	0-100	0–150
P24	Dadarghugri	Forest(teak)*	SOC	0.08	0.11	0.18	0.25
1021.1			SIC	0.00	0.00	0.00	0.00
			TC	0.08	0.11	0.18	0.25
P26	Karkeli	Agriculture (minor millet/sweet potato) (LM)	SOC	0.01	0.03	0.05	0.06
623.9			SIC	0.00	0.00	0.00	0.00
			TC	0.01	0.03	0.05	0.06
P16	Vijaypura	Agriculture (finger millet) (FM)*	SOC	0.03	0.04	0.07	0.08
841.0			SIC	0.00	0.00	0.00	0.00
			TC	0.03	0.04	0.07	0.08
P38	Hayatnagar	Agriculture (sorghum-castor) (LM)	SOC	0.05	0.08	0.13	0.17
1291.5			SIC	0.02	0.05	0.10	0.14
			TC	0.08	0.13	0.23	0.31
P41	Patancheru	Permanent Fallow	SOC	0.09	0.14	0.20	0.24
1462.5			SIC	0.03	0.06	0.13	0.17
			TC	0.13	0.20	0.34	0.42
P34	Kaukuntla	Agriculture (castor+pigeonpea) (FM)	SOC	0.02	0.03	0.05	0.07
755.6			SIC	0.42	0.05	0.07	0.09
			TC	0.45	0.09	0.13	0.16
P22	Palathurai	Agriculture (horse gram /vegetable) (Org)	SOC	0.01	0.01	0.02	0.03
345.1			SIC	0.00	0.01	0.04	0.08
			TC	0.01	0.03	0.07	0.11
Total			SOC	0.32	0.47	0.73	0.92
6340.7			SIC	0.49	0.18	0.36	0.49
			TC	0.82	0.66	1.10	1.41

*Considered as LM (also see Bhattacharyya et al. 2006a)

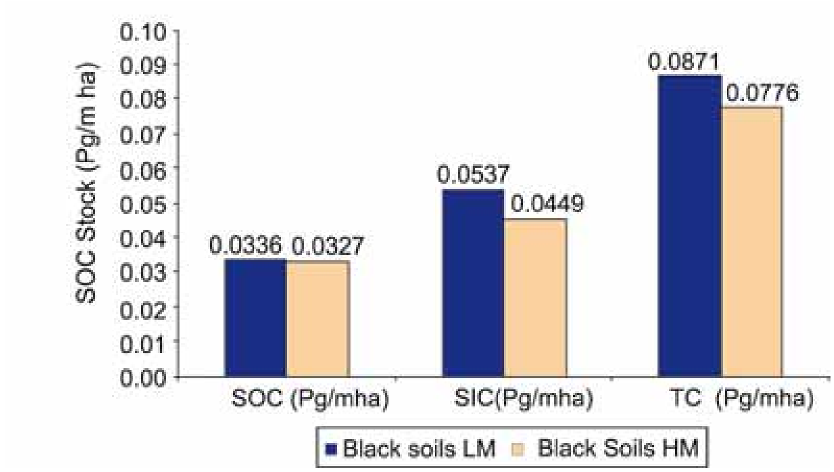


Figure 3.11. Carbon stock in unit area: effect of management (0–30 cm).

3.1.5 Influence of climate on carbon stock

Humid tropical climate with hyperthermic temperature regime punctuated by cool winter months (December, January and February) and relatively high rainfall [>1150 mm mean annual rainfall (MAR)] help in more OC sequestration (Velayutham et al. 2000). It is, therefore, logical that the SOC stock should indicate a decreasing trend from sub-humid (moist) to arid climate. Since accumulation of OC also depends on quality and quantity of inorganic substrate of soil, the present study was restricted to those soils, which are similar in terms of substrate (Bhattacharyya et al. 2006a, 2006b). Figure 3.12 shows the increasing trend of mean annual temperature (MAT) and decreasing trend of MAR from sub-humid (moist) to arid as shown by marginal decrease of SOC stock from wet to dry bioclimate.

Drier climate normally influences more accumulation of $CaCO_3$ (Pal et al. 2000). The trend of SOC and SIC stocks is usually opposite (Bhattacharyya et al. 2000). The present study also indicates a similar trend (Figure 3.12). The TC stock in different bioclimate increases from wet to dry bioclimatic system mainly due to the contribution of higher SIC in semi-arid and arid tracts under study (Figure 3.12). Figure 3.13 shows the trend of SOC, SIC and TC stocks per unit area in the red soils of SAT, India.

3.1.6 Changes in level of carbon in soils over time

NBSS&LUP documented information on soils in different spots during 1970s and 1980s (Murthy et al. 1982; NBSS&LUP staff, 1995, 1996; Lal et al. 1995; Anonymous 1990; Anonymous 1999a, 1999b, 1999c). Later these datasets were revised (Lal et al. 1994; Sehgal et al. 1988). During the present study ten BM spots were revisited. The observations indicate several changes in terms of management and land uses (Bhattacharyya et al. 2006a). Except for a few reports on changes of carbon level in Indian soils under long term fertilizer trials (Swarup et al. 2000) and because of changes in land use (Saikh et al. 1998), no changes of carbon status over a long period of time were reported. Following paragraphs indicate the changes in carbon stock (SOC and SIC) and the QEC of carbon in selected red and black soils in Indian SAT.

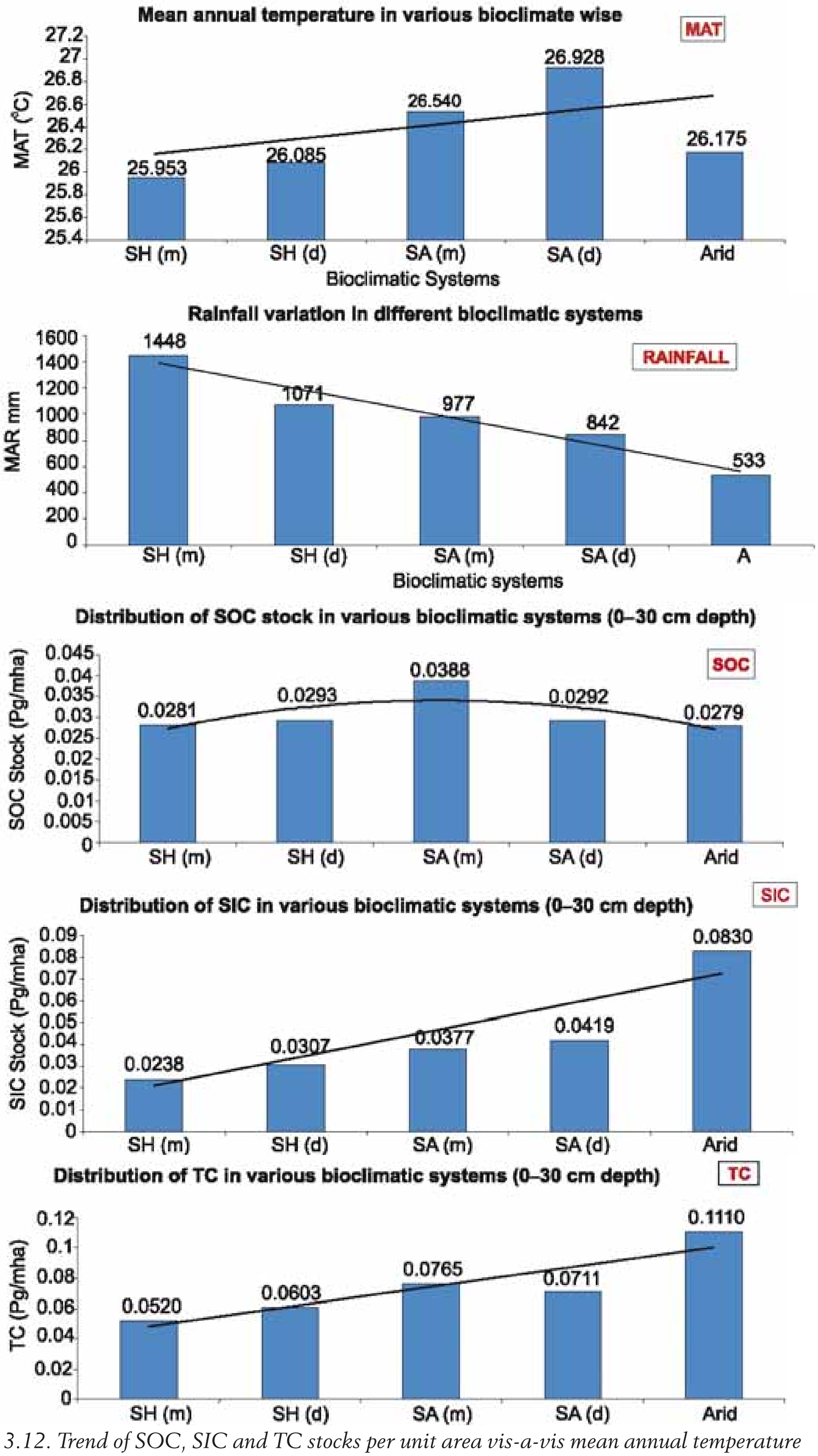


Figure 3.12. Trend of SOC, SIC and TC stocks per unit area vis-a-vis mean annual temperature (MAT) and mean annual rainfall (MAR) of black soils in five bioclimatic systems of SAT, India.

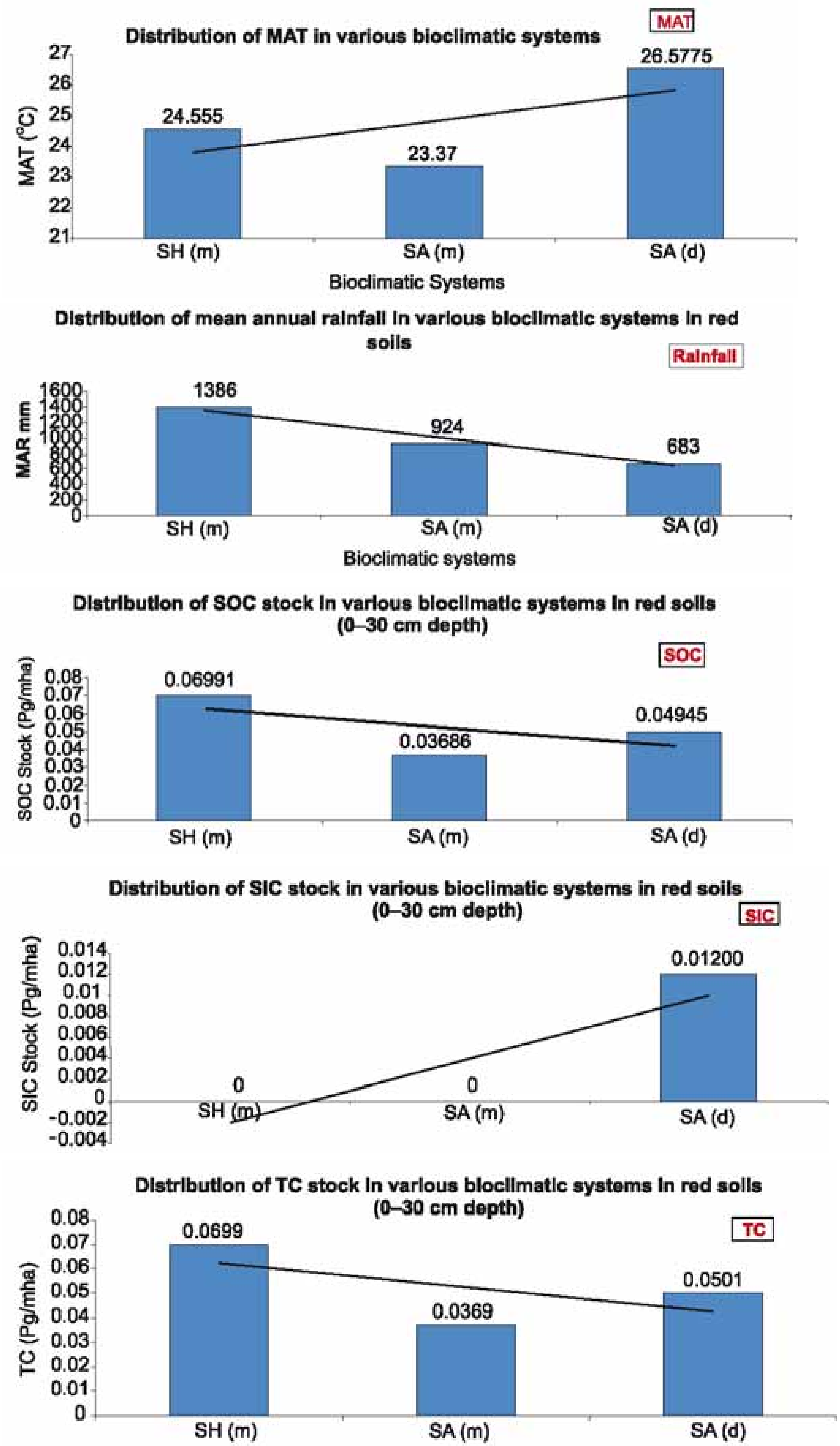


Figure 3.13. Trend of SOC, SIC and TC stocks per unit area vis-à-vis mean annual temperature (MAT) and mean annual rainfall (MAR) of red soils in three bioclimatic systems of SAT, India.

Table 3.6. Total carbon stock in black soils (sub-humid moist) of SAT, India.

Representative pedons	Soil Series	System (Management)	SOC/SIC/BD*/ Area and C stocks	Depth Range (cm)			
				0–30	0–50	0–100	0–150
P4	Panjri	Agriculture (cotton)	SOC (g/100 g)	0.64	0.60	0.51	0.46
		(HM)	SIC (g/100 g)	0.64	0.69	0.77	0.80
			BD (Mg m^{-3})	1.60	1.55	1.50	1.48
			Area ('000 ha)	46.50	46.50	46.50	46.50
			SOC Stock (Pg)	0.00	0.00	0.00	0.00
			SIC Stock (Pg)	0.00	0.00	0.00	0.00
			TC Stock (Pg)	0.00	0.00	0.00	0.01
P5	Nabibagh	Agriculture	SOC (g/100 g)	0.75	0.71	0.65	0.62
		(soybean-wheat)	SIC (g/100 g)	0.66	0.67	0.64	0.64
		(HM)	BD (Mg m^{-3})	1.30	1.30	1.33	1.35
			Area ('000 ha)	1153.70	1153.70	1153.70	1153.70
			SOC Stock (Pg)	0.03	0.05	0.10	0.14
			SIC Stock (Pg)	0.02	0.05	0.09	0.15
			TC Stock (Pg)	0.06	0.10	0.20	0.29
P6	Nabibagh	Agriculture	SOC (g/100 g)	0.65	0.59	0.54	0.51
		(soybean-wheat)	SIC (g/100 g)	0.47	0.49	0.49	0.52
		(FM)	BD (Mg m^{-3})	1.30	1.33	1.41	1.42
			Area ('000 ha)	1153.70	1153.70	1153.70	1153.70
			SOC Stock (Pg)	0.02	0.04	0.08	0.12
			SIC Stock (Pg)	0.02	0.03	0.08	0.12
			TC Stock (Pg)	0.05	0.08	0.17	0.25
P15	Boripani	Forest	SOC (g/100 g)	0.80	0.76	0.47	0.34
	(Maharashtra)	(teak)	SIC (g/100 g)	0.48	0.53	0.90	1.04
			BD (Mg m^{-3})	1.35	1.34	1.32	1.32
			Area ('000 ha)	138.66	138.66	138.66	138.66
			SOC Stock (Pg)	0.00	0.00	0.00	0.00
			SIC Stock (Pg)	0.00	0.00	0.01	0.02
			TC Stock (Pg)	0.00	0.01	0.02	0.03
P27	Kheri	Agriculture	SOC (g/100 g)	0.53	0.46	0.43	0.44
		(paddy-wheat)	SIC (g/100 g)	0.44	0.44	0.40	0.41
		(HM)	BD (Mg m^{-3})	1.50	1.50	1.50	1.60
			Area ('000 ha)	464.10	464.10	464.10	464.10
			SOC Stock (Pg)	0.01	0.01	0.02	0.04
			SIC Stock (Pg)	0.00	0.01	0.02	0.04
			TC Stock (Pg)	0.02	0.03	0.05	0.09
P28	Kheri	Agriculture	SOC (g/100 g)	0.64	0.59	0.54	0.53
		(soybean/paddy-wheat)	SIC (g/100 g)	0.48	0.48	0.62	0.65
		(LM)	BD (Mg m^{-3})	1.40	1.40	1.42	1.45
			Area ('000 ha)	464.10	464.10	464.10	464.10
			SOC Stock (Pg)	0.01	0.01	0.03	0.05
			SIC Stock (Pg)	0.00	0.01	0.04	0.06
			TC Stock (Pg)	0.02	0.03	0.07	0.01

* BD = Bulk density

Table 3.7. Total carbon stock in black soils sub-humid dry in SAT, India.

Representative pedons	Soil Series	System(Management)	SOC/SIC/BD*/ Area and C stocks	Depth Range (cm) 0–30	0–50	0–100	0–150
P1	Linga	Horticulture	SOC (g/100 g)	0.75	0.70	0.63	0.53
		(Citrus)	SIC (g/100 g)	0.76	0.76	0.81	0.90
		(HM)	BD (Mg m^{-3})	1.50	1.46	1.38	1.38
			Area ('000 ha)	129.50	129.50	129.50	129.50
			SOC Stock (Pg)	0.00	0.00	0.01	0.01
			SIC Stock (Pg)	0.00	0.00	0.01	0.02
			TC Stock (Pg)	0.00	0.01	0.02	0.03
P2	Linga	Agriculture	SOC (g/100 g)	0.83	0.74	0.60	0.51
		(soybean-chickpea/	SIC (g/100 g)	0.74	0.70	0.69	0.68
		wheat) (FM)	BD (Mg m^{-3})	1.50	1.50	1.48	1.47
			Area ('000 ha)	129.50	129.50	129.50	129.50
			SOC Stock (Pg)	0.00	0.00	0.01	0.01
			SIC Stock (Pg)	0.00	0.00	0.01	0.01
			TC Stock (Pg)	0.00	0.01	0.02	0.03
P3	Linga	Horticulture	SOC (g/100 g)	0.86	0.78	0.66	0.59
		(Citrus)	SIC (g/100 g)	0.87	0.87	0.93	0.99
		(LM)	BD (Mg m^{-3})	1.40	1.40	1.43	1.44
			Area ('000 ha)	129.50	129.50	129.50	129.50
			SOC Stock (Pg)	0.00	0.00	0.01	0.01
			SIC Stock (Pg)	0.00	0.00	0.01	0.02
			TC Stock (Pg)	0.00	0.01	0.02	0.04
P7	Sarol	Agriculture	SOC (g/100 g)	0.54	0.48	0.42	0.37
		(soybean-wheat)	SIC (g/100 g)	0.73	0.75	0.73	0.74
		(HM)	BD (Mg m^{-3})	1.49	1.46	1.44	1.45
			Area ('000 ha)	721.00	721.00	721.00	721.00
			SOC Stock (Pg)	0.01	0.02	0.04	0.05
			SIC Stock (Pg)	0.02	0.03	0.07	0.11
			TC Stock (Pg)	0.04	0.06	0.12	0.17
P8	Sarol	Agriculture	SOC (g/100 g)	0.76	0.71	0.59	0.51
		(soybean-wheat)	SIC (g/100 g)	0.77	0.77	0.76	0.79
		(FM)	BD (Mg m^{-3})	1.40	1.40	1.40	1.40
			Area ('000 ha)	721.00	721.00	721.00	721.00
			SOC Stock (Pg)	0.02	0.03	0.06	0.07
			SIC Stock (Pg)	0.02	0.03	0.07	0.12
			TC Stock (Pg)	0.04	0.07	0.13	0.19
P9	Sarol	Agriculture	SOC (g/100 g)	0.73	0.63	0.56	0.48
		(soybean-chickpea)	SIC (g/100 g)	0.66	0.67	0.72	0.76
		(FM)	BD (Mg m^{-3})	1.40	1.40	1.40	1.40
			Area ('000 ha)	721.00	721.00	721.00	721.00
			SOC Stock (Pg)	0.02	0.03	0.05	0.07
			SIC Stock (Pg)	0.02	0.03	0.07	0.11
			TC Stock (Pg)	0.04	0.06	0.13	0.18
P48	Nipani	Agriculture	SOC (g/100 g)	0.82	0.70	0.55	0.46
		(cotton-pigeonpea)	SIC (g/100 g)	3.04	3.03	3.00	3.00
		(FM)	BD (Mg m^{-3})	1.57	1.50	1.47	1.50
			Area ('000 ha)	486.90	486.90	486.90	486.90
			SOC Stock (Pg)	0.01	0.01	0.03	0.05
			SIC Stock (Pg)	0.06	0.11	0.21	0.32
			TC Stock (Pg)	0.08	0.12	0.25	0.37

...continued

Table 3.7. *Continued...*

Representative pedons	Soil Series	System(Management)	SOC/SIC/BD*	Depth Range (cm) 0–30	0–50	0–100	0–150
P49	Pangidi	Agriculture (cotton-pigeonpea) (FM 1)	SOC (g/100 g)	1.05	1.03	0.93	0.82
			SIC (g/100 g)	0.76	0.76	0.78	0.84
			BD (Mg m^{-3})	1.15	1.16	1.20	1.20
			Area ('000 ha)	533.40	533.40	533.40	533.40
			SOC Stock (Pg)	0.01	0.03	0.06	0.07
			SIC Stock (Pg)	0.01	0.02	0.05	0.08
			TC Stock (Pg)	0.03	0.05	0.11	0.15
P50	Pangidi	Agriculture (soybean) (ITDA)	SOC (g/100 g)	0.90	0.75	0.47	0.38
			SIC (g/100 g)	0.71	1.08	1.54	1.69
			BD (Mg m^{-3})	1.30	1.30	1.30	1.30
			Area ('000 ha)	533.40	533.40	533.40	533.40
			SOC Stock (Pg)	0.01	0.02	0.33	0.03
			SIC Stock (Pg)	0.01	0.03	0.10	0.17
			TC Stock (Pg)	0.03	0.06	0.13	0.21

Table 3.8. Total carbon stock in black soils (semi-arid moist) of SAT, India.

Representative pedons	Soil Series	System(Management)	SOC/SIC/BD* /Area and C stocks	Depth Range (cm) 0–30	0–50	0–100	0–150
P10	Asra	Agriculture (cotton/green gram+ pigeonpea) (FM) (org)	SOC (g/100 g)	0.75	0.7080	0.64	0.58
			SIC (g/100 g)	1.12	1.1500	1.26	1.43
			BD (Mg m^{-3})	1.60	1.6200	1.57	1.56
			Area ('000 ha)	1866.40	1866.4000	1866.40	1866.40
			SOC Stock (Pg)	0.06	0.1070	0.18	0.25
			SIC Stock (Pg)	0.03	0.1738	0.37	0.62
			TC Stock (Pg)	0.10	0.2808	0.56	0.88
P11	Asra	Agriculture (soybean + pigeonpea) (FM)	SOC (g/100 g)	0.75	0.6980	0.64	0.60
			SIC (g/100 g)	1.01	1.0900	1.13	1.16
			BD (Mg m^{-3})	1.50	1.5000	1.53	1.55
			Area ('000 ha)	1866.40	1866.4000	1866.40	1866.40
			SOC Stock (Pg)	0.06	0.0977	0.18	0.26
			SIC Stock (Pg)	0.08	0.1526	0.32	0.50
			TC Stock (Pg)	0.15	0.2503	0.50	0.77
P12	Asra	Agriculture (cotton + pigeonpea / soybean-chickpea) (HM)	SOC (g/100 g)	0.92	0.8520	0.75	0.70
			SIC (g/100 g)	0.64	0.6500	0.68	0.76
			BD (Mg m^{-3})	1.50	1.5000	1.50	1.50
			Area ('000 ha)	1866.40	1866.4000	1866.40	1866.40
			SOC Stock (Pg)	0.07	0.1193	0.21	0.29
			SIC Stock (Pg)	0.05	0.0910	0.19	0.32
			TC Stock (Pg)	0.13	0.2103	0.40	0.61
P42	Bhatumbra	Agriculture (sorghum+ pigeonpea/black gram-chickpea) (FM)	SOC (g/100 g)	0.88	0.8740	0.82	0.74
			SIC (g/100 g)	1.16	1.1800	1.21	1.23
			BD (Mg m^{-3})	1.36	1.3500	1.32	1.31
			Area ('000 ha)	1673.10	1673.1000	1673.10	1673.10
			SOC Stock (Pg)	0.06	0.0987	0.18	0.24
			SIC Stock (Pg)	0.07	0.1333	0.26	0.40
			TC Stock (Pg)	0.13	0.2320	0.45	0.65

Table 3.9. Total carbon stock in black soils (semi-arid dry) of SAT, India.

Representative pedons	Soil Series	System(Management)	SOC/SIC/BD* /Area and C stocks	Depth Range (cm) 0–30	0–50	0–100	0–150
P13	Paral	Agriculture	SOC (g/100 g)	0.63	0.61	0.60	0.59
		(cotton+pigeonpea/	SIC (g/100 g)	1.18	1.20	1.22	1.24
		sorghum)	BD (Mg m^{-3})	1.60	1.57	1.53	1.52
		(LM)	Area ('000 ha)	1185.00	1185.00	1185.00	1185.00
			SOC Stock (Pg)	0.03	0.05	0.11	0.16
			SIC Stock (Pg)	0.06	0.11	0.22	0.33
			TC Stock (Pg)	0.10	0.16	0.33	0.49
P14	Paral	Agriculture	SOC (g/100 g)	0.60	0.57	0.52	0.45
		(cotton+pigeonpea/	SIC (g/100 g)	1.43	1.48	1.49	1.33
		sorghum)	BD (Mg m^{-3})	1.60	1.60	1.60	1.60
		(FM)	Area ('000 ha)	1185.00	1185.00	1185.00	1185.00
			SOC Stock (Pg)	0.03	0.05	0.10	0.12
			SIC Stock (Pg)	0.08	0.14	0.28	0.37
			TC Stock (Pg)	0.11	0.19	0.38	0.50
P19	Kovilpatti	Agriculture	SOC (g/100 g)	0.38	0.37	0.33	0.29
		(sorghum/sunflower/	SIC (g/100 g)	0.58	0.66	0.94	1.24
		cotton)	BD (Mg m^{-3})	1.26	1.33	1.39	1.39
		(Org)*	Area ('000 ha)	362.50	362.50	362.50	362.50
			SOC Stock (Pg)	0.00	0.00	0.01	0.02
			SIC Stock (Pg)	0.00	0.01	0.04	0.09
			TC Stock (Pg)	0.01	0.02	0.06	0.11
P20	Kovilpatti	Waste Land	SOC (g/100 g)	0.47	0.48	0.43	0.39
			SIC (g/100 g)	0.78	1.14	1.18	1.03
			BD (Mg m^{-3})	1.40	1.40	1.35	1.33
			Area ('000 ha)	362.50	362.50	362.50	362.50
			SOC Stock (Pg)	0.00	0.01	0.02	0.02
			SIC Stock (Pg)	0.01	0.02	0.05	0.07
			TC Stock (Pg)	0.01	0.04	0.07	0.10
P21	Kovilpatti	Agriculture	SOC (g/100 g)	0.43	0.41	0.40	0.32
		(cotton+black gram)	SIC (g/100 g)	0.84	0.85	0.93	1.48
		(HM)	BD (Mg m^{-3})	1.33	1.36	1.38	1.38
			Area ('000 ha)	362.50	362.50	362.50	362.50
			SOC Stock (Pg)	0.00	0.01	0.02	0.02
			SIC Stock (Pg)	0.01	0.02	0.04	0.11
			TC Stock (Pg)	0.01	0.03	0.06	0.13
P29	Semla	Agriculture	SOC (g/100 g)	0.75	0.73	0.64	0.59
		(cotton/groundnut-	SIC (g/100 g)	1.99	2.07	1.98	2.05
		wheat)	BD (Mg m^{-3})	1.40	1.40	1.45	1.50
		(Org)	Area ('000 ha)	485.70	485.70	485.70	485.70
			SOC Stock (Pg)	0.01	0.02	0.04	0.06
			SIC Stock (Pg)	0.04	0.07	0.14	0.22
			TC Stock (Pg)	0.05	0.09	0.18	0.28
P32	Jhalipura	Agriculture	SOC (g/100 g)	0.43	0.39	0.34	0.32
		(soybean-wheat)	SIC (g/100 g)	0.45	0.53	0.66	0.72
		(FM/1)	BD (Mg m^{-3})	1.70	1.59	1.64	1.66
			Area ('000 ha)	635.90	635.90	635.90	635.90
			SOC Stock (Pg)	0.01	0.01	0.03	0.05
			SIC Stock (Pg)	0.01	0.02	0.06	0.11
			TC Stock (Pg)	0.02	0.04	0.10	0.16

* Org: Original BM spot.

...continued

Table 3.9. *Continued...*

Representative pedons	Soil Series	System (Management)	SOC/SIC/BD /Area and C stocks	Depth range (cm) 0–30	0–50	0–100	0–150
P33	Jhalipura	Agriculture	SOC (g/100 g)	0.53	0.45	0.35	0.30
		(paddy-wheat)	SIC (g/100 g)	1.09	1.58	1.61	1.64
		(FM / 2)	BD (Mg m^{-3})	1.70	1.67	1.67	1.69
			Area ('000 ha)	635.90	635.90	635.90	635.90
			SOC Stock (Pg)	0.01	0.02	0.03	0.04
			SIC Stock (Pg)	0.03	0.08	0.17	0.26
			TC Stock (Pg)	0.05	0.10	0.21	0.31
P35	Jajapur	Agriculture	SOC (g/100 g)	0.38	0.34	0.30	0.26
		(sorghum/pigeonpea	SIC (g/100 g)	0.41	0.48	0.72	0.97
		+green gram)	BD (Mg m^{-3})	1.80	1.77	1.70	1.66
		(FM /1)	Area ('000 ha)	1153.30	1153.30	1153.30	1153.30
			SOC Stock (Pg)	0.02	0.03	0.05	0.07
			SIC Stock (Pg)	0.02	0.04	0.14	0.28
			TC Stock (Pg)	0.04	0.08	0.20	0.35
P36	Jajapur	Agriculture	SOC (g/100 g)	0.88	0.64	0.40	0.30
		(paddy-paddy)	SIC (g/100 g)	0.26	0.32	0.88	1.05
		(FM/2)	BD (Mg m^{-3})	1.90	1.90	1.85	1.83
			Area ('000 ha)	1153.30	1153.30	1153.30	1153.30
			SOC Stock (Pg)	0.05	0.07	0.08	0.09
			SIC Stock (Pg)	0.01	0.03	0.18	0.33
			TC Stock (Pg)	0.07	0.10	0.27	0.42
P39	Kasireddypalli	Agriculture	SOC (g/100 g)	0.76	0.62	0.52	0.51
		(soybean-pigeonpea)	SIC (g/100 g)	0.52	0.60	0.68	0.79
		(HM)	BD (Mg m^{-3})	1.60	1.60	1.57	1.54
			Area ('000 ha)	391.30	391.30	391.30	391.30
			SOC Stock (Pg)	0.01	0.01	0.03	0.04
			SIC Stock (Pg)	0.00	0.01	0.04	0.07
			TC Stock (Pg)	0.01	0.03	0.07	0.11
P40	Kasireddypalli	Agriculture	SOC (g/100 g)	0.48	0.44	0.42	0.37
		(fallow-chickpea)	SIC (g/100 g)	0.72	0.72	0.74	0.79
		(TM)	BD (Mg m^{-3})	1.60	1.60	1.60	1.61
			Area ('000 ha)	391.30	391.30	391.30	391.30
			SOC Stock (Pg)	0.00	0.01	0.02	0.03
			SIC Stock (Pg)	0.01	0.02	0.04	0.07
			TC Stock (Pg)	0.01	0.03	0.07	0.11
P43	Teligi	Agriculture	SOC (g/100 g)	1.03	0.92	0.80	0.70
		(paddy-paddy)	SIC (g/100 g)	1.30	1.34	1.15	1.40
		(LM)	BD (Mg m^{-3})	1.40	1.47	1.45	1.44
			Area ('000 ha)	659.00	659.00	659.00	659.00
			SOC Stock (Pg)	0.02	0.04	0.07	0.10
			SIC Stock (Pg)	0.03	0.06	0.11	0.19
			TC Stock (Pg)	0.06	0.11	0.18	0.29
P44	Teligi	Agriculture	SOC (g/100 g)	0.80	0.69	0.59	0.53
		(paddy-paddy)	SIC (g/100 g)	0.96	1.04	1.16	1.39
		(HM)	BD (Mg m^{-3})	1.56	1.54	1.46	1.43
			Area ('000 ha)	659.00	659.00	659.00	659.00
			SOC Stock (Pg)	0.02	0.03	0.05	0.07
			SIC Stock (Pg)	0.02	0.05	0.11	0.19
			TC Stock (Pg)	0.05	0.08	0.17	0.27

...continued

Table 3.9. *Continued...*

Representative pedons	Soil Series	System (Management)	SOC/SIC/BD/ Area and C stocks	Depth range (cm) 0–30	0–50	0–100	0–150
P45	Konheri	Agriculture	SOC (g/100 g)	0.30	0.30	0.26	0.25
		(pigeonpea /	SIC (g/100 g)	1.07	1.12	1.20	1.51
		sunflower-sorghum)	BD (Mg m^{-3})	1.50	1.53	1.53	1.55
		(FM)	Area (‘000 ha)	259.90	259.90	259.90	259.90
			SOC Stock (Pg)	0.00	0.00	0.01	0.01
			SIC Stock (Pg)	0.01	0.02	0.04	0.09
			TC Stock (Pg)	0.01	0.02	0.05	0.10
P46	Konheri	Agriculture	SOC (g/100 g)	0.84	0.82	0.71	0.51
		(pigeonpea /	SIC (g/100 g)	1.76	1.74	2.00	2.30
		sunflower-sorghum)	BD (Mg m^{-3})	1.30	1.30	1.38	1.45
		(LM)	Area (‘000 ha)	259.90	259.90	259.90	259.90
			SOC Stock (Pg)	0.00	0.01	0.02	0.02
			SIC Stock (Pg)	0.01	0.02	0.07	0.13
			TC Stock (Pg)	0.02	0.04	0.09	0.15
P47	Kalwan	Agriculture	SOC (g/100 g)	0.90	0.81	0.60	0.45
		(sugarcane/sorghum-	SIC (g/100 g)	0.37	0.41	0.87	1.14
		wheat/chickpea)	BD (Mg m^{-3})	1.40	1.40	1.44	1.42
		(FM)	Area (‘000 ha)	618.90	618.90	618.90	618.90
			SOC Stock (Pg)	0.02	0.03	0.00	0.06
			SIC Stock (Pg)	0.00	0.01	0.07	0.15
			TC Stock (Pg)	0.03	0.05	0.08	0.21

Table 3.10. Total carbon stock in black soils (arid) of SAT, India.

Representative pedons	Soil Series	System (Management)	SOC/SIC/BD/ Area and C stocks	Depth range (cm) 0–30	0–50	0–100	0–150
P30	Sokhda	Agriculture	SOC (g/100 g)	0.36	0.34	0.30	0.2400
		(cotton-pearl millet)	SIC (g/100 g)	2.41	2.47	2.55	2.6590
		(FM-1)	BD (Mg m^{-3})	1.60	1.60	1.69	1.7600
			Area (‘000 ha)	604.40	604.40	604.40	604.4000
			SOC Stock (Pg)	0.01	0.01	0.03	0.0383
			SIC Stock (Pg)	0.07	0.11	0.26	0.4243
			TC Stock (Pg)	0.08	0.13	0.29	0.4626
P31	Sokhda	Agriculture	SOC (g/100 g)	0.50	0.47	0.43	0.3860
		(cotton-pearl millet/	SIC (g/100 g)	2.60	2.60	2.60	2.5600
		linseed)	BD (Mg m^{-3})	1.40	1.45	1.59	1.6000
		(FM-2)	Area (‘000 ha)	604.40	604.40	604.40	604.4000
			SOC Stock (Pg)	0.01	0.02	0.04	0.0560
			SIC Stock (Pg)	0.06	0.11	0.25	0.3713
			TC Stock (Pg)	0.07	0.13	0.29	0.4273
P51	Nimone	Agriculture	SOC (g/100 g)	0.76	0.72	0.66	0.5900
		(cotton-wheat/	SIC (g/100 g)	1.71	1.75	1.76	1.8170
		chickpea[irrigated])	BD (Mg m^{-3})	1.39	1.38	1.36	1.3600
		(HM)	Area (‘000 ha)	1725.20	1725.20	1725.20	1725.2000
			SOC Stock (Pg)	0.05	0.08	0.15	0.2076
			SIC Stock (Pg)	0.12	0.21	0.41	0.6395
			TC Stock (Pg)	0.17	0.29	0.57	0.8471
P52	Nimone	Agriculture	SOC (g/100 g)	0.75	0.73	0.63	0.5320
		(sugarcane[ratoon]-	SIC (g/100 g)	2.64	2.65	2.72	2.8600
		soybean/wheat/	BD (Mg m^{-3})	1.30	1.38	1.39	1.3700
		chickpea)	Area (‘000 ha)	1725.20	1725.20	1725.20	1725.2000
		(FM)	SOC Stock (Pg)	0.05	0.08	0.15	0.1886
			SIC Stock (Pg)	0.17	0.31	0.65	1.0139
			TC Stock (Pg)	0.22	0.40	0.80	1.2025

Table 3.11. Total carbon stock in red soils (sub-humid moist) of SAT, India.

Representative Pedons	Soil Series	System (Management)	SOC/SIC/BD /Area and C stocks	Depth Range (cm) 0–30	0–50	0–100	0–150
P23	Dadarghugri	Agriculture (maize/mustard) (FM)	SOC (g/100 g)	2.10	1.79	1.37	1.25
			SIC (g/100 g)	0.00	0.00	0.00	0.00
			BD (Mg m^{-3})	1.22	1.18	1.19	1.19
			Area ('000 ha)	1021.10	1021.10	1021.10	1021.10
			SOC Stock (Pg)	0.07	0.10	0.16	0.22
			SIC Stock (Pg)	0.00	0.00	0.00	0.00
			TC Stock (Pg)	0.07	0.10	0.16	0.22
P24	Dadarghugri	Forest (teak)	SOC (g/100 g)	2.42	2.05	1.62	1.48
			SIC (g/100 g)	0.00	0.00	0.00	0.00
			BD (Mg m^{-3})	1.08	1.11	1.12	1.13
			Area ('000 ha)	1021.10	1021.10	1021.10	1021.10
			SOC Stock (Pg)	0.08	0.11	0.18	0.25
			SIC Stock (Pg)	0.00	0.00	0.00	0.00
			TC Stock (Pg)	0.08	0.11	0.18	0.25
P25	Karkeli	Reserve Forest (sal)	SOC (g/100 g)	1.09	0.84	0.57	0.48
			SIC (g/100 g)	0.00	0.00	0.00	0.00
			BD (Mg m^{-3})	1.73	1.71	1.65	1.62
			Area ('000 ha)	623.90	623.90	623.90	623.90
			SOC Stock (Pg)	0.03	0.04	0.05	0.07
			SIC Stock (Pg)	0.00	0.00	0.00	0.00
			TC Stock (Pg)	0.03	0.04	0.05	0.07
P26	Karkeli	Agriculture (minor millet / sweet potato) (LM)	SOC (g/100 g)	0.60	0.60	0.54	0.44
			SIC (g/100 g)	0.00	0.00	0.00	0.00
			BD (Mg m^{-3})	1.69	1.62	1.54	1.52
			Area ('000 ha)	623.90	623.90	623.90	623.90
			SOC Stock (Pg)	0.01	0.03	0.05	0.06
			SIC Stock (Pg)	0.00	0.00	0.00	0.00
			TC Stock (Pg)	0.01	0.03	0.05	0.06

Table 3.12. Total carbon stock in red soils (semi-arid moist) of SAT, India.

Representative Pedons	Soil Series	System(Management)	SOC/SIC/BD/ Area and C stocks	Depth Range (cm) 0–30	0–50	0–100	0–150
P16	Vijaypura	Agriculture (finger millet) (FM)	SOC (g/100 g)	0.90	0.72	0.52	0.41
			SIC (g/100 g)	0.00	0.00	0.00	0.00
			BD (Mg m^{-3})	1.67	1.64	1.59	1.56
			Area ('000 ha)	841.00	841.00	841.00	841.00
			SOC Stock (Pg)	0.03	0.04	0.07	0.08
			SIC Stock (Pg)	0.00	0.00	0.00	0.00
			TC Stock	0.03	0.04	0.07	0.08
P17	Vijaypura	Agriculture (finger millets / pigeonpea / groundnut) (Org)	SOC (g/100 g)	0.50	0.50	0.47	0.37
			SIC (g/100 g)	0.00	0.00	0.00	0.00
			BD (Mg m^{-3})	1.46	1.41	1.36	1.36
			Area ('000 ha)	841.00	841.00	841.00	841.00
			SOC Stock (Pg)	0.01	0.02	0.05	0.06
			SIC Stock (Pg)	0.00	0.00	0.00	0.00
			TC Stock	0.01	0.02	0.05	0.06
P18	Vijaypura	Agriculture (finger millet) (HM)	SOC (g/100 g)	0.81	0.73	0.59	0.44
			SIC (g/100 g)	0.00	0.00	0.00	0.00
			BD (Mg m^{-3})	1.51	1.48	1.43	1.40
			Area ('000 ha)	841.00	841.00	841.00	841.00
			SOC Stock (Pg)	0.03	0.04	0.07	0.07
			SIC Stock (Pg)	0.00	0.00	0.00	0.00
			TC Stock	0.03	0.04	0.07	0.07

Table 3.13. **Total carbon stock in red soils (semi-arid dry) of SAT, India.**

Pedon No	Soil Series	System (Management)	SOC/SIC/BD /Area and C stocks	Depth range (cm) 0–30	0–50	0–100	0–150
P22	Palathurai	Agriculture	SOC (g/100 g)	0.75	0.64	0.47	0.41
		(horse gram /	SIC (g/100 g)	0.15	0.49	0.88	1.08
		vegetable)	BD (Mg m^{-3})	1.53	1.54	1.52	1.51
		(Org)	Area ('000 ha)	345.10	345.10	345.10	345.10
			SOC Stock (Pg)	0.01	0.01	0.02	0.03
			SIC Stock (Pg)	0.00	0.01	0.04	0.08
			TC Stock (Pg)	0.01	0.03	0.07	0.11
P34	Kaukuntala	Agriculture	SOC (g/100 g)	0.72	0.62	0.47	0.38
		(castor+pigeonpea)	SIC (g/100 g)	1.25	0.93	0.63	0.49
		(FM)	BD (Mg m^{-3})	1.51	1.54	1.63	1.70
			Area ('000 ha)	755.60	755.60	755.60	755.60
			SOC Stock (Pg)	0.02	0.03	0.05	0.07
			SIC Stock (Pg)	0.42	0.05	0.07	0.09
			TC Stock (Pg)	0.45	0.09	0.13	0.16
P37	Hayatnagar	Agriculture	SOC (g/100 g)	0.93	0.79	0.66	0.61
		(sorghum-castor)	SIC (g/100 g)	0.35	0.37	0.45	0.50
		(HM)	BD (Mg m^{-3})	1.51	1.46	1.41	1.38
			Area ('000 ha)	1291.50	1291.50	1291.50	1291.50
			SOC Stock (Pg)	0.05	0.07	0.12	0.16
			SIC Stock (Pg)	0.00	0.03	0.08	0.13
			TC Stock (Pg)	0.06	0.11	0.20	0.29
P38	Hayatnagar	Agriculture	SOC (g/100 g)	0.96	0.87	0.70	0.60
		(sorghum-castor)	SIC (g/100 g)	0.49	0.55	0.54	0.49
		(LM)	BD (Mg m^{-3})	1.52	1.49	1.47	1.46
			Area ('000 ha)	1291.50	1291.50	1291.50	1291.50
			SOC Stock (Pg)	0.05	0.08	0.13	0.17
			SIC Stock (Pg)	0.02	0.05	0.10	0.14
			TC Stock (Pg)	0.08	0.13	0.23	0.31
P41	Patancheru	Permanent Fallow	SOC (g/100 g)	1.42	1.18	0.86	0.65
			SIC (g/100 g)	0.55	0.54	0.56	0.45
			BD (Mg m^{-3})	1.60	1.62	1.66	1.72
			Area ('000 ha)	1462.50	1462.50	1462.50	1462.50
			SOC Stock (Pg)	0.09	0.14	0.20	0.24
			SIC Stock (Pg)	0.03	0.06	0.13	0.17
			TC Stock (Pg)	0.13	0.20	0.34	0.42

Org= Orginal

Soil systems attain a quasi-equilibrium stage after accumulation of dry matter as well as loss of SOC over time depending on land use system. Thus SOC levels often show tooth-like cycles of accumulation and loss. After each change in land use system, a period of constant management is required to reach a new quasi-equilibrium stage. In this way, the SOC is stabilized to another QEV, characteristic of that changed situation, in terms of new land use pattern, vegetative cover and management practice. Under natural vegetation, the SOC values tend to attain QEVs with varying duration of 500–1000 years in a forest system (Jenny 1950; Dickson and Crocker 1953), 30–50 years in agricultural systems after forest cutting (Arrouays et al. 1995; Johnson et al. 1995; Batjes 2001), 5–15 years in agricultural system after forest cutting in red soils in Orissa (Saikh et al. 1998), agricultural system with cotton (20 years), with cotton and pigeonpea (50 years) and horticultural system (orange) (30 years) (Naitam and Bhattacharyya 2004). Such reports confirm changes in SOC due to changes in land use systems.

On the basis of available data on soils collected during 1980s, the shrink-swell soils (Vertisols and associated soils) in India under agricultural system reached a QEV of 0.5 to 0.6% in the surface layers (Naitam and Bhattacharyya 2004). These soils occupy the deficient zone of the SOC map of India (Velayutham et al. 2000). The present effort to revisit the BM spots in black and red soils provided an opportunity to find out the changes in SOC and SIC stocks over the last 25–30 years. Besides, it also permits to look into the new QEV of SOC in black and red soils. Following the logic stated above, an attempt was made to find out the QEV of SIC in a few selected BM spots.

3.1.6.1 Changes in carbon stock and quasi-equilibrium value (QEV) in sub-humid (moist) bioclimatic system in black soils

The Kheri soils representing sub-humid (moist) bioclimate show a new QEV of SOC – 0.53%, which shows an increase of 30% over SOC values during 1982 at 0–30 cm soil depth. During the last 20 years the land use system has not changed in this area. Interestingly, these soils show the presence of $CaCO_3$ that was not present at 0–30 cm soil depth during 1982. Continuous use of well water for irrigation must have influenced the SIC build-up even on the surface soils (Figure 3.14). In terms of carbon stock, the SOC stock registers 88% increase and the SIC stock shows a 17% increase at 0–150 cm soil depth (Figure 3.15). Table 3.14 gives the detail changes in QEV and carbon stock over the last 20 years.

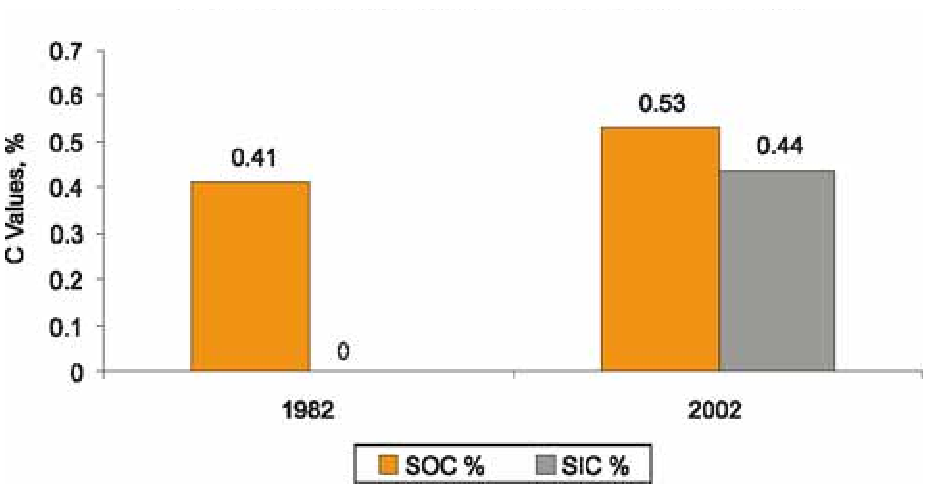


Figure 3.14. Carbon quasi-equilibrium value (0–30 cm soil depth) in Kheri series soils.

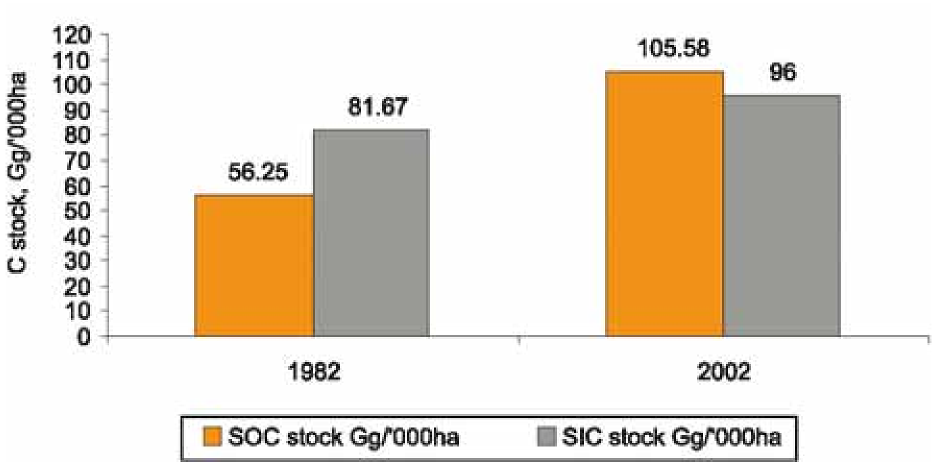


Figure 3.15. Organic and inorganic carbon stocks (0–150 cm soil depth) in Kheri series soils.

Table 3.14. Changes in carbon stock and QEV in sub-humid (moist) bioclimatic system in black soils (P27 Kheri soils).

1982 Land use: Paddy, Wheat, Chickpea	Quasi-equilibrium values	2002 Land use: Paddy-Wheat
0.41	SOC (0–30)	0.53
0.25	(0–150)	0.44
0	SIC (0–30)	0.44
0.363	(0–150)	0.40
0.41	TC (0–30)	0.97
0.61	(0–150)	0.84
	C Stock (Gg/'000 ha)	
18.45	SOC (0–30)	23.90
56.25	(0–150)	105.58
0.00	SIC (0–30)	19.80
81.67	(0–150)	96.00
18.45	TC (0–30)	43.70
137.97	(0–150)	201.58
NA*	BD (0–30)	1.5
NA*	(0–150)	1.5

*Assumed as 1.5 g/cc

3.1.6.2 Changes in carbon stock and QEV in sub-humid (dry) bioclimatic system in black soils

The Linga soils represents sub-humid (dry) bioclimate. The land use at these BM spot has remained the same as horticulture (C*itrus sp*). The new QEV of SOC although indicates a positive sign of increase in trend to the tune of 67% at 0–30 cm soil depth, yet 153% increase in SIC appears to be alarming in terms of soil health (Figure 3.16). This observation also finds support from more than 34% and 38% increase in both SOC and SIC stocks respectively over the last 22 years at 0–150 cm soil depth (Figure 3.17). Table 3.15 gives changes in QEV and carbon stocks during 1980 and 2002.

Table 3.15. Changes in carbon stock and QEV in sub-humid (dry) bioclimatic system in black soils (P3 Linga series).

1980 Land use: Citrus	Quasi-equilibrium values	2002 Land use: Citrus
0.4913	SOC (0–30)	0.8203
0.4223	(0–150)	0.5591
0.3456	SIC (0–30)	0.8760
0.6853	(0–150)	0.9467
0.83	TC (0–30)	1.6963
0.1076	(0–150)	1.5775
	C Stock (Gg / '000 ha)	
22.11	SOC (0–30)	36.29
95.02	(0–150)	127.41
15.55	SIC (0–30)	26.25
154.19	(0–150)	215.44
37.66	TC (0–30)	62.54
249.21	(0–150)	342.85
NA*	BD (0–30)	1.50
NA*	(0–150)	1.47

*Assumed as 1.50 g/cc

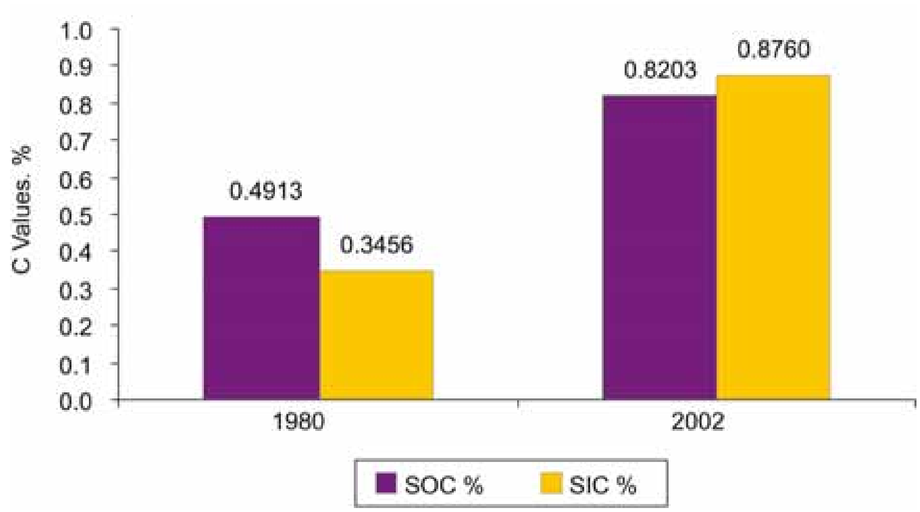


Figure 3.16. Carbon quasi-equilibrium values (0–30 cm soil depth) in Linga series soil.

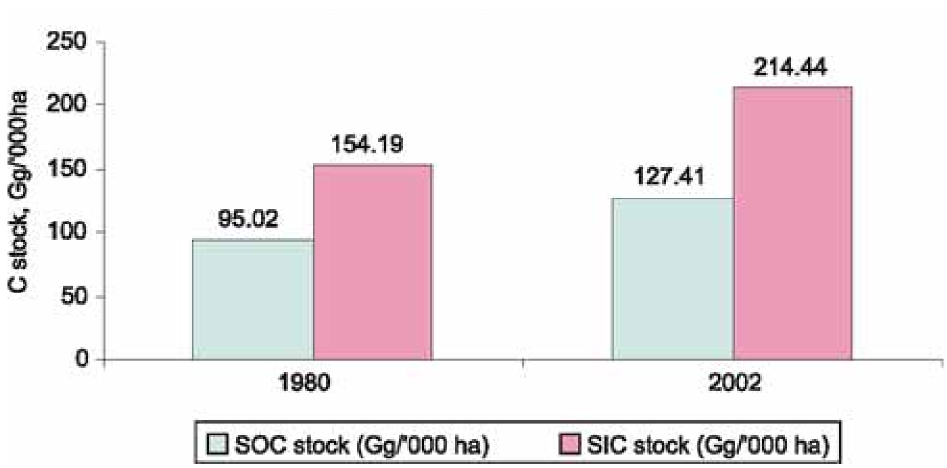


Figure 3.17. Organic and inorganic carbon stocks (0–150 cm soil depth) in Linga series soil.

3.1.6.3 Changes in carbon stock and QEV in semi-arid (moist) bioclimatic system in black soils

This bioclimatic system is represented by Asra soils. Since 1982, the land use has changed from sorghum, groundnut, chickpea and wheat to cotton/green gram+pigeonpea system (Table 3.16). A new QEV of SOC indicates an increase of 143%; the corresponding value for SIC is 211% (Figure 3.18). The SOC and SIC stocks have also risen from 63.0 Gg/'000 ha to 136.4 Gg/'000 ha (1 Gg = 10^{-9} g) and from 110.25 Gg/'000 ha to 336.31 Gg/'000 ha, respectively (Figure 3.19). The influence of aridity affecting more $CaCO_3$ precipitation is getting better than the corresponding increase in SOC level. These lands need to be kept under vegetative cover to reduce the influence of dry climate and to help in dissolution of native $CaCO_3$ (Bhattacharyya et al. 2006c).

Table 3.16. Changes in carbon stock and QEV in semi-arid (moist) bioclimatic system in black soils (P10 Asra soils).

1982 Land use: Sorghum, groundnut, chickpea, wheat	Quasi-equilibrium values	2002 Land use: Cotton/ green gram + Pigeonpea
0.30	SOC (0–30)	0.73
0.28	(0–150)	0.57
0.36	SIC (0–30)	1.12
0.49	(0–150)	1.42
0.66	TC (0–30)	1.85
0.77	(0–150)	1.99
	C Stock (Gg/'000 ha)	
13.50	SOC (0–30)	36.00
63.00	(0–150)	136.41
16.20	SIC (0–30)	18.06
110.25	(0–150)	336.31
29.70	TC (0–30)	54.06
173.25	(0–150)	472.72
NA*	BD (0–30)	1.6
NA*	(0–150)	1.568

*Assumed as 1.5 g/cc

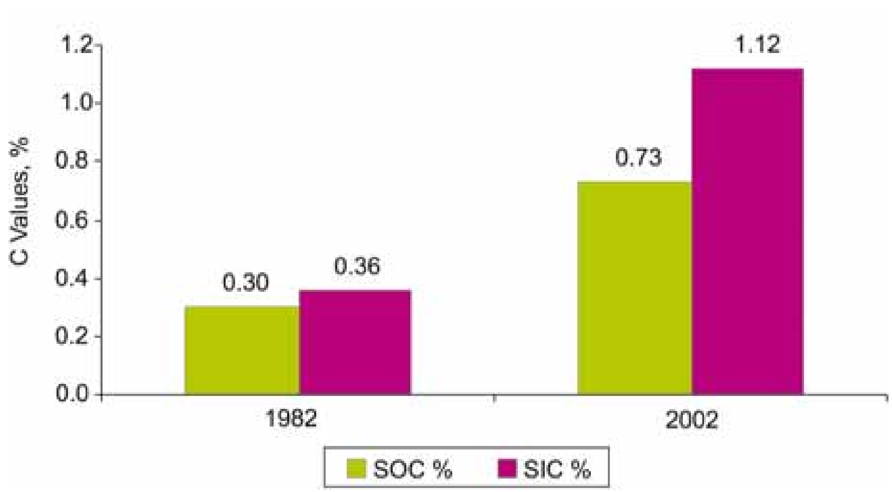


Figure 3.18. Carbon quasi-equilibrium values (0–30 cm soil depth) in Asra series soils.

3.1.6.4. Changes in carbon stock and QEV in semi-arid (dry) bioclimatic system in black soils

Two soil series [Semla (P29) and Teligi (P43)] represent the semi-arid (dry) bioclimatic system.

Semla soils: Although crop selection has changed since 1978, Semla soils are utilized mainly for the cultivation of cotton. The SOC quasi-equilibrium value in cotton dominated system has changed only marginally from 0.65 to 0.76%. The corresponding SIC values, however, show a negative trend (Figure 3.20). Interestingly, the SOC stock has registered a low value mainly due to decreasing BD of soils collected during 2002 (Figure 3.21). Table 3.17 gives the detail changes in QEV and carbon stock over the last 25 years.

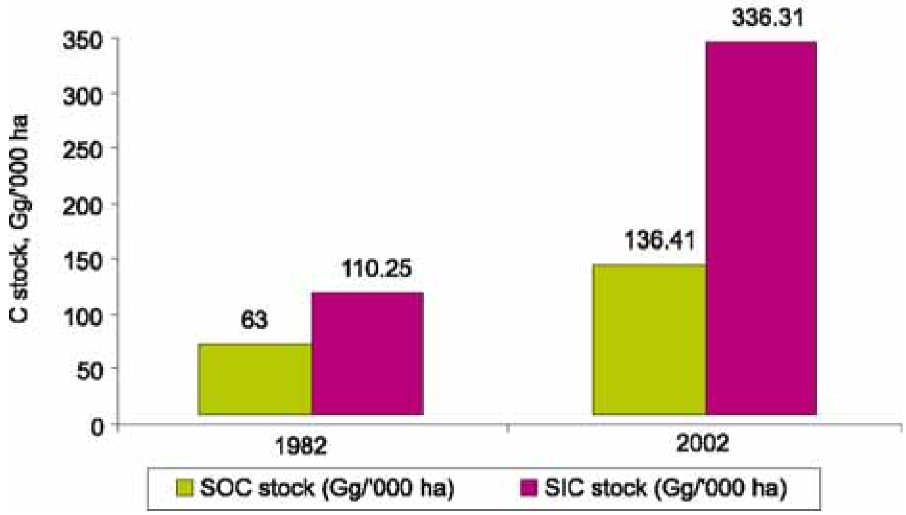


Figure 3.19. Organic and inorganic carbon stocks (0–150 cm soil depth) in Asra series soils.

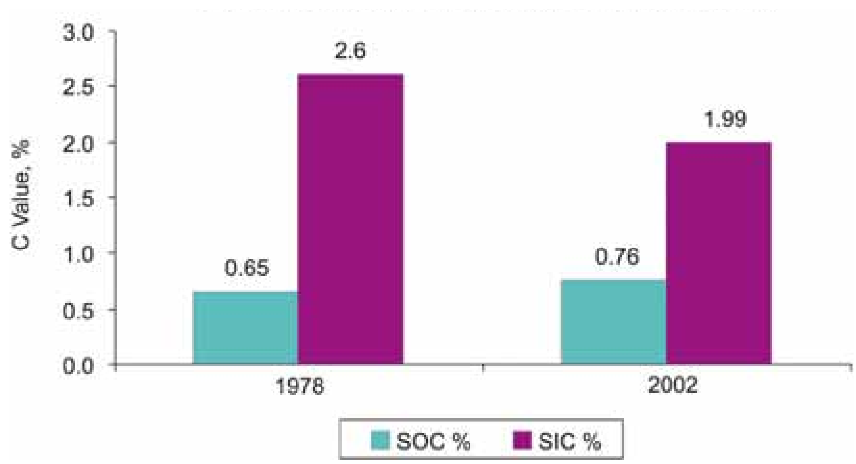


Figure 3.20. Carbon quasi-equilibrium values (0–30 cm soil depth) in Semla series soils.

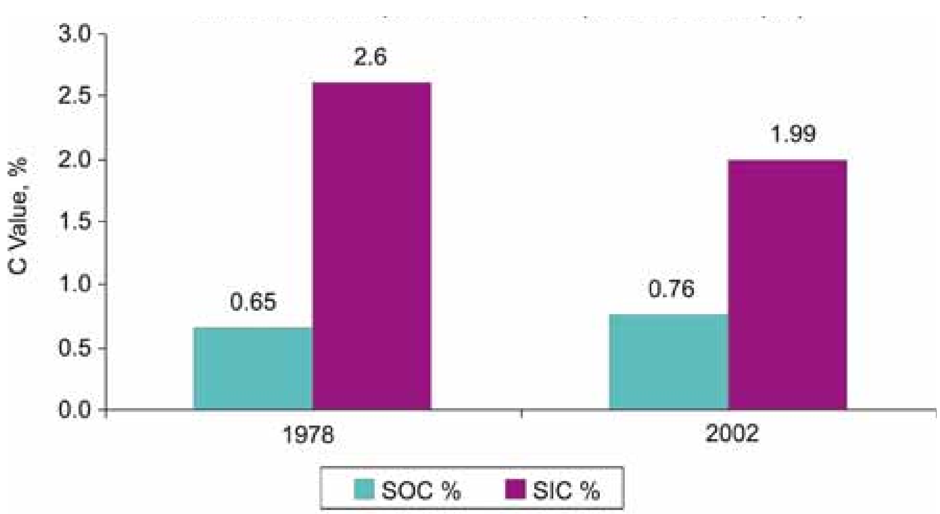


Figure 3.21. Organic and inorganic carbon stocks (0–150 cm soil depth) in Semla series soils.

3.17. Changes in carbon stock and QEV in semi-arid (dry) bioclimatic systems in black soils (P29 Semla series).

1978 Land use: Cotton, sorghum, wheat, sugarcane and chickpea	Quasi-equilibrium values	2002 Land use: Cotton/ Groundnut-wheat
0.65	SOC (0–30)	0.76
0.57	(0–150)	0.59
2.6	SIC (0–30)	1.99
2.66	(0–150)	2.06
3.31	TC (0–30)	2.75
3.23	(0–150)	2.65
	C Stock (Gg/‘000 ha)	
35.1	SOC (0–30)	31.7
158.17	(0–150)	132.8
140.39	SIC (0–30)	83.59
738.15	(0–150)	462.84
175.49	TC (0–30)	115.29
896.32	(0–150)	595.39
1.8	BD (0–30)	1.4
1.85	(0–150)	1.5

Teligi soils: These soils have reached a QEV of SOC of 1.03%, which is 132% more than that observed 28 years ago. The SIC values for QEV also increased from 0.7 to 1.31% (Figure 3.22). The SOC stock has nearly doubled (from 78.3 Gg/’000 ha to 152.2 Gg/’000 ha). The SIC stock has also increased by 41% during this period (Figure 3.23). Table 3.18 shows the changes in QEV and carbon stock during 1974 and 2002.

Table 3.18. Changes in carbon stock and QEV in semi-arid (dry) bioclimatic system in black soils (P43 Teligi series).

1974 Land use: Sorghum/Cotton	Quasi-equilibrium values	2002 Land use
0.444	SOC (0–30)	1.03
0.348	(0–150)	0.702
0.7219	SIC (0–30)	1.306
0.9536	(0–150)	1.649
1.1659	TC (0–30)	2.336
1.3016	(0–150)	2.351
	C Stock (Gg/’000 ha)	
19.97	SOC (0–30)	43.25
78.3	(0–150)	152.2
32.48	SIC (0–30)	54.78
214.56	(0–150)	302.43
52.45	TC (0–30)	98.03
292.86	(0–150)	454.63
NA*	BD (0–30)	1.41
NA*	(0–150)	1.43

*Assumed as 1.5 g/cc

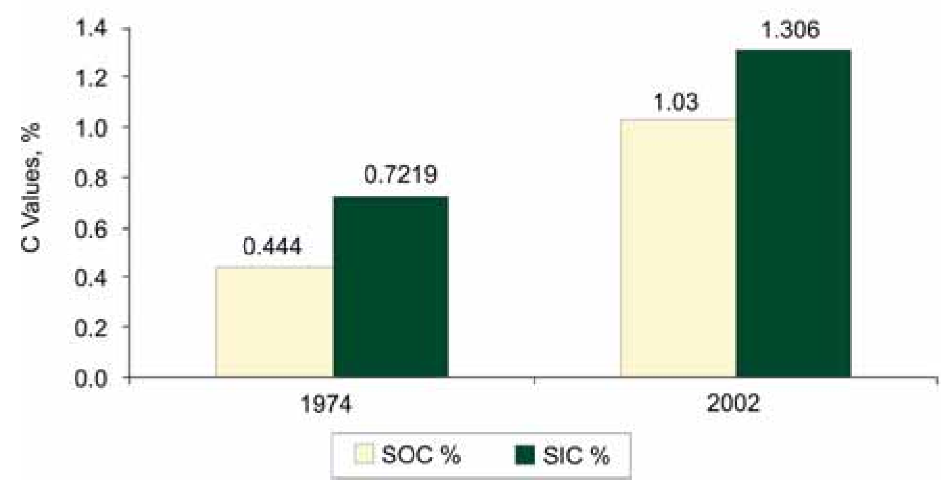


Figure 3.22. Carbon quasi-equilibrium values (0–30 cm soil depth) in Teligi series soils.

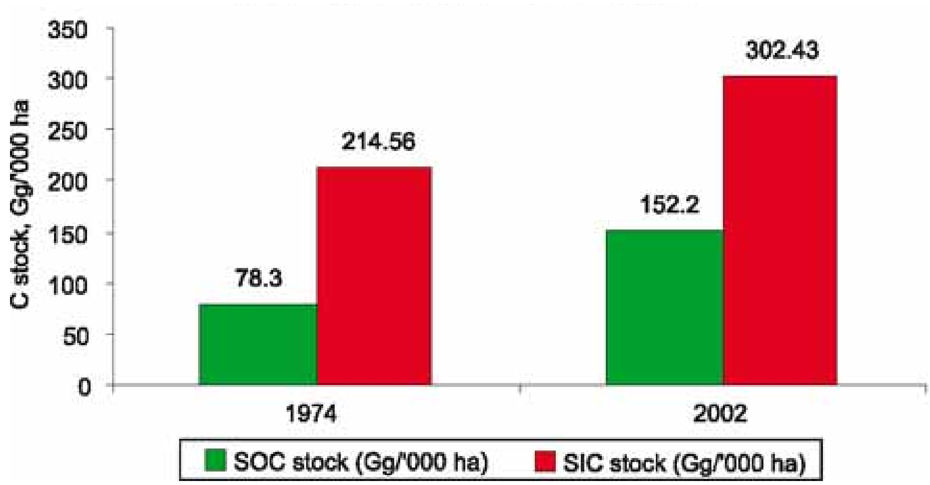


Figure 3.23. Organic and inorganic carbon stocks (0–150 cm soil depth) in Teligi series soils.

3.1.6.5 Changes in carbon stock and QEV in arid bioclimatic system in black soils

Sokhda soils represent arid bioclimatic system. During 1977, wheat, sugarcane and groundnut were cultivated on these soils. In 2002, it was cultivated for cotton/sunflower/linseed. These soils apparently stabilized in terms of SOC because QEV values did not change since 1977. As expected in arid bioclimatic system the SIC value has risen to a new QEV of 2.6%, which corresponds to 160% increase (Figure 3.24). Figure 3.25 shows the marginal decrease (18%) in the SOC stock and an increase in the SIC stock by 157%. Table 3.19 shows the changes in QEV and carbon stock.

Table 3.19. Changes in carbon stock and QEV in arid bioclimatic systems in black soils (P31 Sokhda soils).

1977 Land use: Cotton, wheat, sugarcane, groundnut	Quasi-equilibrium values	2002 Land use: Cotton-pearl millet/linseed
0.495	SOC (0–30)	0.5
0.5	(0–150)	0.4
0.997	SIC (0–30)	2.6
1.06	(0–150)	2.6
1.492	TC (0–30)	3.1
1.56	(0–150)	3
	C Stock (Gg/'000 ha)	
22.27	SOC (0–30)	21.01
112.5	(0–150)	92.65
44.86	SIC (0–30)	109.2
238.5	(0–150)	614.32
67.13	TC (0–30)	130.21
351	(0–150)	706.97
NA*	BD (0–30)	1.4
NA*	(0–150)	1.6

*Assumed as 1.5 g/cc

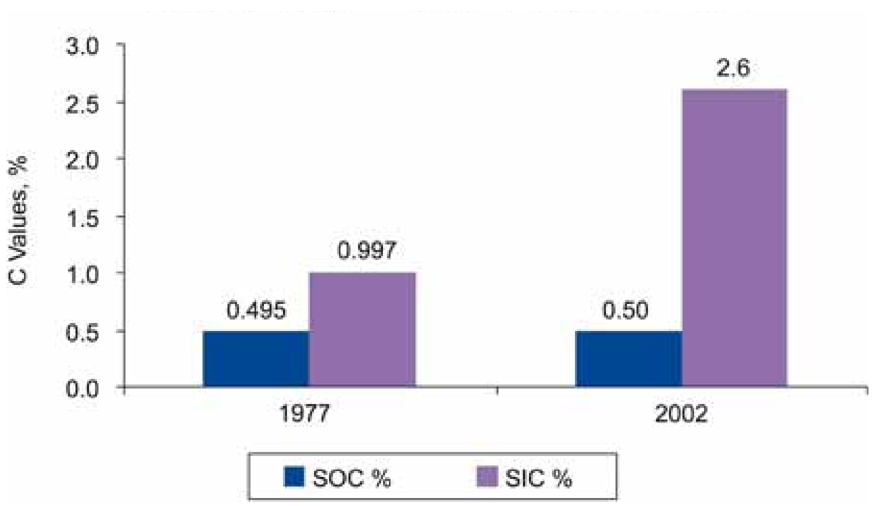


Figure 3.24. Carbon quasi-equilibrium values (0–30 cm soil depth) in Sokhda series soils.

3.1.6.6 Changes in carbon stock and QEV in semi-arid (moist) bioclimatic system in red soils

Vijaypura soils represent semi-arid (moist) bioclimatic system. The QEV of SOC remains almost similar (Figure 3.26). The SOC stock also does not show any perceptible change during the last 25 years (Figure 3.27). The soils were traditionally used for pigeonpea and groundnut along with some minor millets. Table 3.20 shows changes in QEV and carbon stock during 2002 and 1982. Vijaypura soils do not contain any $CaCO_3$.

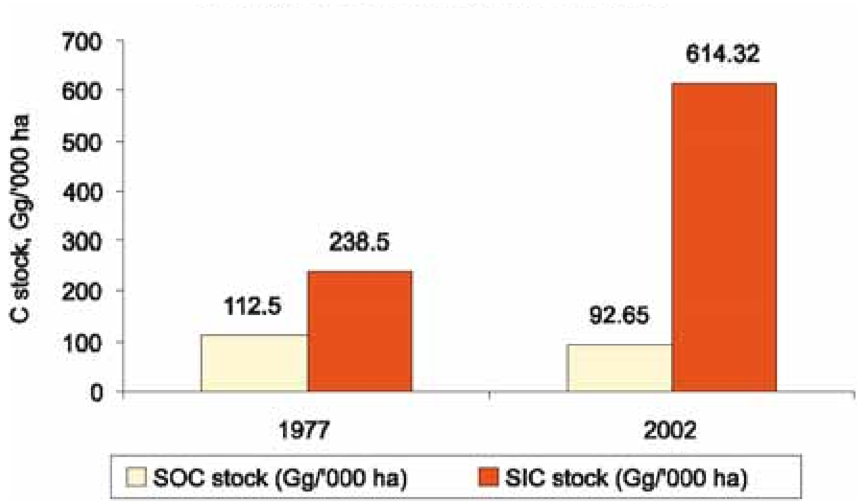


Figure 3.25. Organic and inorganic carbon stocks (0–150 cm soil depth) in Sokhda series soils.

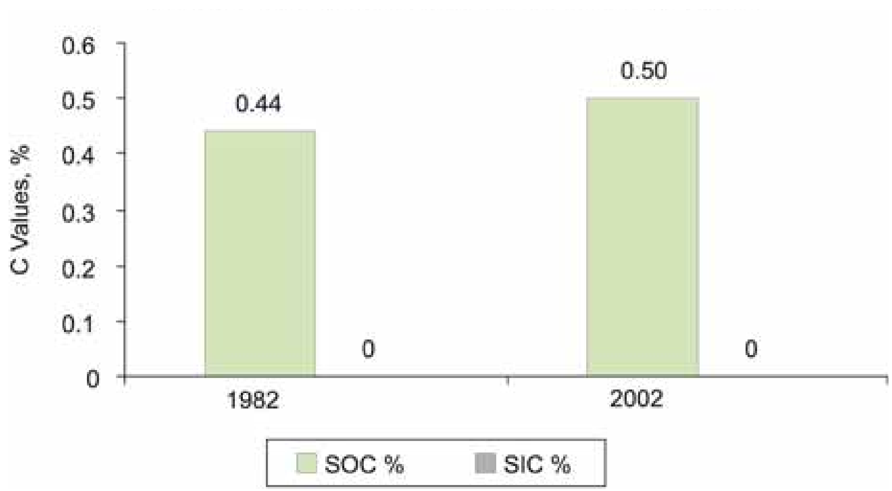


Figure 3.26. Carbon quasi-equilibrium values (0–30 cm soil depth) in Vijaypura series soils.

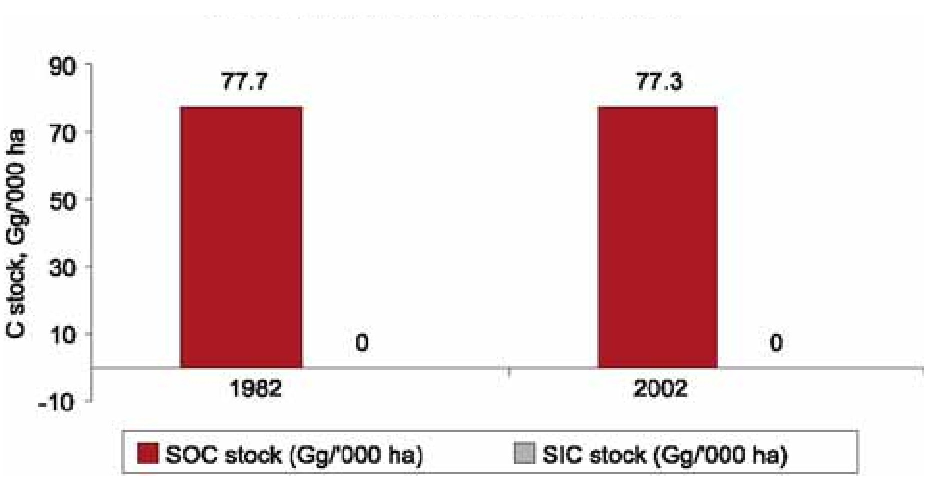


Figure 3.27. Organic and inorganic carbon stocks (0–150 cm soil depth) in Vijaypura series soils.

Table 3.20. Changes in carbon stock and QEV in semi-arid (moist) bioclimatic system in red soils (P17 Vijaypura series).

1982 Land use: Pigeonpea, beans, sorghum and groundnut	Quasi-equilibrium values	2002 Land use: Finger millet/ pigeonpea/groundnut
0.44	SOC (0–30)	0.50
0.37	(0–150)	0.38
0	SIC (0–30)	0
0	(0–150)	0
0.44	TC (0–30)	0.50
0.37	(0–150)	0.38
	C Stock (Gg/'000 ha)	
18.48	SOC (0–30)	21.4
77.7	(0–150)	77.3
0	SIC (0–30)	0
0	(0–150)	0
18.48	TC (0–30)	21.4
77.7	(0–150)	77.3
NA*	BD (0–30)	1.468
NA*	(0–150)	1.362

*Assumed as 1.4 g/cc

3.1.6.7 Changes in carbon stock and QEV in semi-arid (dry) bioclimatic system in red soils

Kaukuntla, Patancheru and Palathurai soils represent typical red soils in semi-arid (dry) bioclimatic system.

Kaukuntla soils: These soils are traditionally used for growing castor and pigeonpea, which remain unchanged for last 25 years. However, sorghum, ragi and groundnut were also grown during 1978 (Table 3.21). The QEV of SOC registers 125% increase from 0.32 to 0.72% during the last 25 years (Figure 3.28). This has affected the SOC stock of soils from 45.00 to 97.90 Gg/'000 ha (Figure 3.29). Table 3.21 shows the changes in QEV and carbon stock during 1978 and 2002. In the 1970s and the 1980s, most of the red soils was assumed as non-calcareous and therefore was not analyzed for $CaCO_3$ in the laboratory. The present study shows appreciable $CaCO_3$ in these soils.

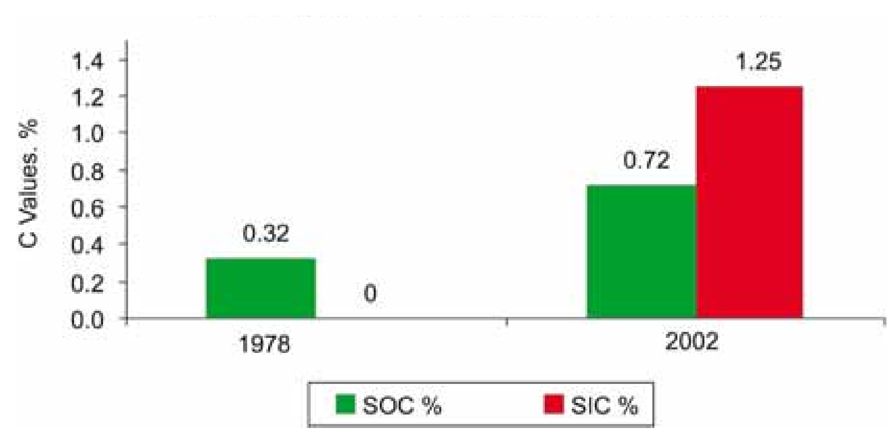


Figure 3.28. Carbon quasi-equilibrium values (0–30 cm soil depth) in Kaukuntla soils.

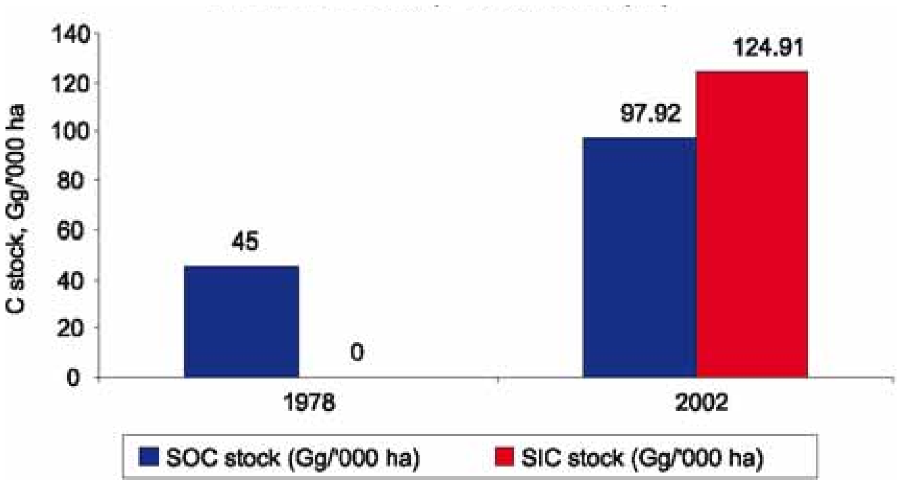


Figure 3.29. Organic and inorganic carbon stocks (0–150 cm soil depth) in Kaukuntla series soils.

Table 3.21. Changes in carbon stock and QEV in semi-arid (dry) bioclimatic system in red soils (P34 Kaukuntla soils).

1978 Land use: Sorghum, ragi, groundnut, pigeonpea, castor	Quasi-equilibrium values	2002 Land use: Castor, pigeonpea
0.32	SOC (0–30)	0.72
0.2	(0–150)	0.384
0	SIC (0–30)	1.25
0	(0–150)	0.49
0.32	TC (0–30)	0.72
0.2	(0–150)	0.384
	C Stock (Gg/'000 ha)	
14.4	SOC (0–30)	32.4
45	(0–150)	97.92
0	SIC (0–30)	566.44
0	(0–150)	124.9
14.4	TC (0–30)	598.84
45	(0–150)	222.52
NA*	BD (0–30)	1.5
NA*	(0–150)	1.5

*Assumed as 1.4 g/cc

Patancheru soils: Patancheru soils were utilized to grow sorghum and pulses during 1978 to 1993. These were kept under permanent fallow for about 8–9 years. Three sets of data (1978, 1993 and 2002) show a gradual increase of QEV of SOC by 46% from 1978 to 1993. However, keeping the soils under permanent fallow has brought about 150% change in SOC QEV from 1993 to 2002 (Figure 3.30). Figure 3.31 shows changes in SOC stock from 83.25 Gg/'000 ha to 166.77 Gg/'000 ha. Table 3.22 gives the SOC and SIC changes in Patancheru soils.

Table 3.22. Changes in carbon stock and QEV in semi-arid (dry) bioclimatic system in red soils (P41 Patancheru soils).

Land use: Sorghum+Pulses			Land use: Permanent Fallow *Typic Rhodustalf*
1978	1993	Quasi-equilibrium values	2002
0.39	0.569	SOC (0–30)	1.42
0.37	0.305	(0–150)	0.654
0	0	SIC (0–30)	0.553
0	0	(0–150)	0.4533
0.39	0.569	TC (0–30)	1.42
0.37	0.3	(0–150)	0.654
		C Stock (Gg/'000 ha)	
17.55	25.61	SOC (0–30)	68.16
83.25	68.63	(0–150)	166.77
0	0	SIC (0–30)	26.53
0	0	(0–150)	117.54
17.55	25.61	TC (0–30)	68.16
83.25	68.63	(0–150)	166.77
NA*		BD (0–30)	1.5
NA*		(0–150)	1.5

*Assumed as 1.5 g/cc

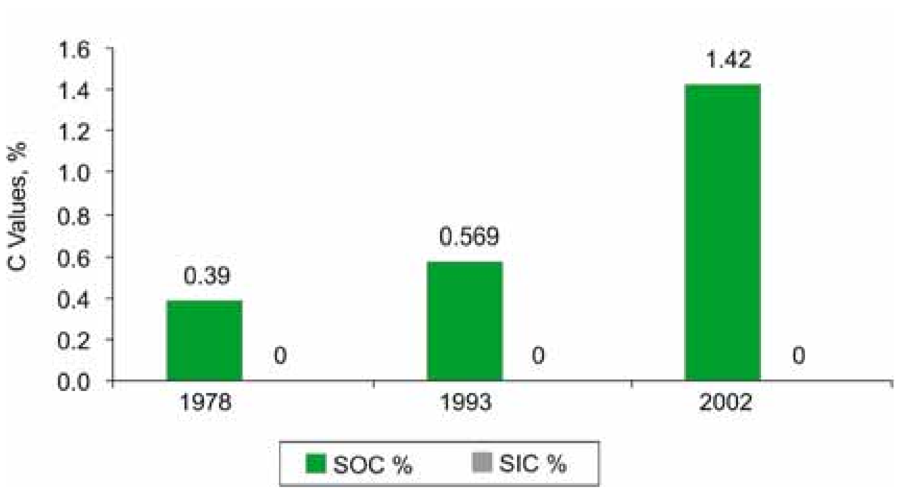


Figure 3.30. Carbon quasi-equilibrium values (0–30 cm soil depth) in Patancheru soils.

Palathurai soils: Palathurai soils were used for cultivating sorghum and horse gram during 1982. These are now used for horse gram and vegetables. The QEV of SOC remains almost unchanged during the last 25 years (Figure 3.32). This is also reflected in a marginal increase in SOC stock at 0–30 cm soil depth (Figure 3.33). Table 3.23 shows the SOC and SIC changes in Palathurai soils.

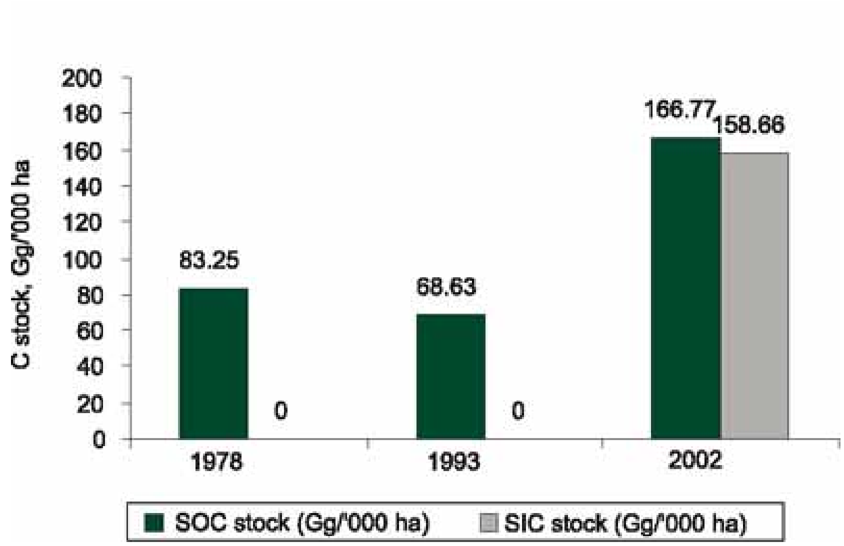


Figure 3.31. Organic and inorganic carbon stocks (0–150 cm soil depth) in Patancheru soils.

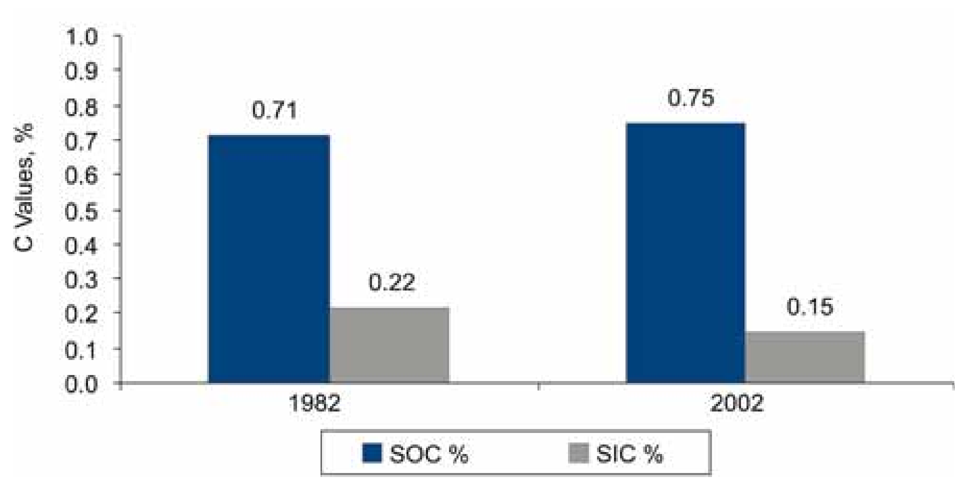


Figure 3.32. Carbon quasi-equilibrium values (0–30 cm soil depth) in Palathurai soils.

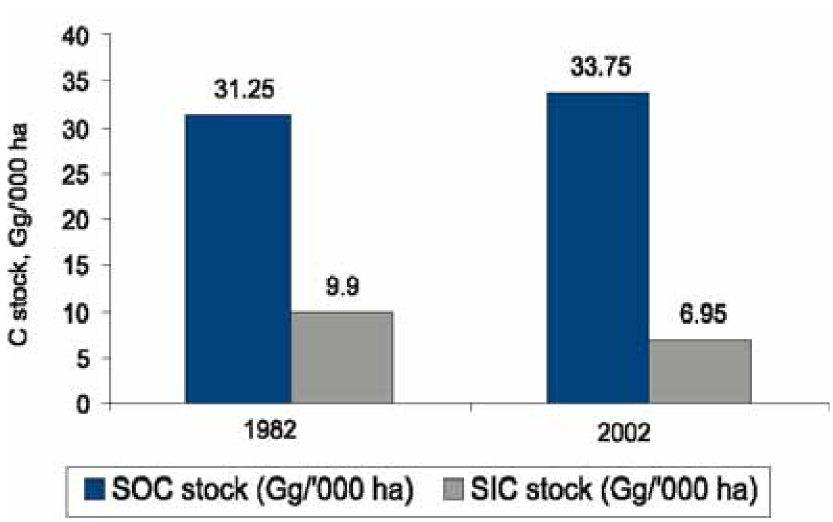


Figure 3.33. Organic and inorganic carbon stocks (0–150 cm soil depth) in Palathurai soils.

Table 3.23. Changes in carbon stock and QEV in semi-arid (dry) bioclimatic system in red soils (P22 Palathurai series).

1982 Land use: Sorghum/Horse gram	Quasi-equilibrium values	2002 Land use: Horse gram/Vegetables
0.71	SOC (0–30)	0.75
—	(0–150)	0.42
0.22	SIC (0–30)	0.15
—	(0–150)	1.08
0.93	TC (0–30)	0.9
1.74	(0–150)	1.32
	C Stock (Gg/'000 ha)	
31.9 5	SOC (0–30)	33.75
—	(0–150)	94.46
9.9	SIC (0–30)	6.95
—	(0–150)	245.72
—	TC (0–30)	40.7
—	(0–150)	340.18

Note: BD taken as 1.5 g/cc

4. General Discussion

This chapter explains various reasons for carbon changes in soils. Most importantly it clarifies the reasons why C stock per unit area [say Pg/(million ha)] should be considered as an effective parameter to find out the best systems for C sequestration. It explains the fact that C stock vis-à-vis BD values should be considered simultaneously for identifying systems for C sequestration. Recognition of BD value as an important parameter, takes care of soil particle size separates, porosity, ESP and hydraulic conductivity since these parameters are highly correlated with the BD (Bhattacharyya et al. 2006c).

4.1 Changes in carbon level

Current arid and semi-arid environment prevailing in central and southern peninsular India is ascribed to the global warming phenomenon (Eswaran and Evan den Berg 1992), which is the causative factor for low SOC level in the shrink-swell soils of India (Velayutham et al. 2000; Bhattacharyya et al. 2000; Bhattacharyya, Pal, Velayutham, Chandran and Mandal 2001). It was opined that in view of large extent and characteristic properties of soils, the arid and semi-arid tracts offer a better scope for carbon sequestration. Effective carbon management can help not only in building of the SOC stock to a level of 10.5 Pg from their existing level of 2.9 Pg stock but will also help to reduce the SIC stock to the tune of 1.9 Pg much to the benefit of growing plants in terms of better physical and chemical environment of soils (Bhattacharyya et al. 2000). In the present scenario of changing climatic environment such as rising of temperature and shrinking of annual rainfall in the semi-arid and arid tract of the country, it will continue to remain as a potential threat for the tropical soils of the Indian subcontinent (Jenny and Raychaudhuri 1960; Sombroek et al. 1993). It, therefore, seems that arid climate will continue to remain as a bane for Indian agriculture, because this will cause soil degradation in terms of depletion of SOC, formation of pedogenic $CaCO_3$ with the concomitant development of sodicity and salinity (Balpande et al. 1996; Pal et al. 2000; Vaidya and Pal 2002). To combat such situation, the restoration of SOC balance and efforts to enlarge the soil carbon pool by appropriate management technique so as to sustain the soil health of semi-arid and arid bioclimatic system has to be the major perspective in maintaining productivity of soils of SAT, India (Bhattacharyya et al. 2000; Bhattacharyya, Pal, Velayutham, Chandran and Mandal 2001; Goswami et al. 2000; Velayutham et al. 2000).

It is interesting to note that ten BM spots comprising six under black soils and four under red soils show an increase in the SOC content in almost all the cases over a period of 25–30 years. The increase in OC in these soils could be ascribed to the following factors:

(A) Soil related factors

1. Good substrate quality: Barring few, the shrink-swell soils contain high amount of clay, fine clay and silt. These are considered as the main substrate for OC sequestration. Besides quantity, these substrates are dominated by smectitic minerals possessing very high surface area, which enhances the degree of carbon sequestration (Bhattacharyya et al. 2006b, 2006c).
2. Presence of soil modifiers: Natural modifiers such as zeolites in soils can maintain the pedo-environment for more carbon sequestration. The modifiers were present in the shrink-swell soils in Maharashtra (Bhattacharyya et al. 1993, 1999; Bhattacharya, Pal, Srivastava and Velayutham 2001). Zeolites and/or gypsum may be identified in soils with more than 100% base saturation. These base-rich zeolites can continuously supply bases and maintain depleted base status in red soils formed in Deccan basalt. The natural modifiers can even stabilize the bad effect of increased quantity of $CaCO_3$ in black soils and thus can help in making these degraded black soils resilient (Bhattacharyya et al. 2006c).

(B) Other Factors

Improved methods of management using good quality irrigation water, high-yielding varieties, and recommended dose of fertilizers (NPK and manures) help in sequestering more OC in soils. Our observation indicates that appropriate crop rotation with intercropping preferably with a leguminous crop, broad based furrow (BBF) and green manuring (sunhemp, *Sesbania* spp.) helped in increasing the level of SOC. Conversely monocropping (cotton) and exhaustive farming practice (soybean-wheat/gram) deplete SOC level. Earlier it was reported that for Vertisols in Patancheru more OC was sequestered resulting in higher stock of OC up to 120 cm soil depth with sorghum/pigeonpea system and improved soil water, and nutrient management options as compared to sorghum sole system (Wani et al. 2003).

4.2 Technique for identifying systems

In view of the findings, it seems appropriate to find out techniques for identifying some systems for carbon sequestration. The present study has identified 22 systems showing relatively high amount of SOC. It may be mentioned that while identifying such systems lower amount of SIC was taken into consideration.

On the basis of % of SOC, 14 systems were earlier identified as viable for OC sequestration in soils (Bhattacharyya et al. 2006c). The present study based on SOC stock per unit area [Pg/(million ha)] permits us to identify finally 22 systems with varied bioclimatic systems and cropping patterns (Figs. 3.3 to 3.10).

A closer look at the soil parameters of these 22 systems indicate the following minimum and maximum threshold limit of SOC, SIC and BD under two distinct conditions.

Condition 1: Minimum threshold limit of SOC

The minimum threshold limit of SOC is 0.63% at 0–30 cm soil depth, which is associated with a maximum threshold value of BD 1.6 g/cc. The values of SOC and BD were obtained, since they correspond to approximately 10 Pg SOC stock in India at 0–30 cm soil depth (Bhattacharyya et al. 2000). This minimum SOC and maximum BD values correspond to an average value of 1.19% SIC. It may be cautioned that the minimum threshold value of SOC are often associated with increase in SIC and decrease in hydraulic conductivity due to compaction and thus effecting high BD values.

Condition 2: Maximum threshold limit of SOC

The maximum threshold limit of SOC is 2.42%, which corresponds to a minimum threshold limit of BD 1.22 g/cc containing $CaCO_3$ (SIC). This is the highest SOC obtained in forest ecosystem under luxurious vegetation of teak (*Tectona grandis)*. The high value of SOC makes the soil more porous, soft and lighter in weight effecting lower value of BD. Tables 4.1 to 4.5 detail SOC, SIC, BD and SOC stock per unit area for the 20 identified systems for carbon sequestration and increased productivity in the SAT environments. Figure 4.1 depicts the conditions for identifying OC sequestration systems. Figures 4.2 to 4.23 shows typical landscapes and soil profiles of the selected systems.

The maximum threshold value of SOC was found in shrink-swell soils under forest. Similar observations were made earlier (Bhattacharyya and Pal 1998; Naitam and Bhattacharyya 2004). Judging by qualitatively and quantitatively similar substrate, the present observation provides a scope of reaching a maximum threshold limit of SOC equilibrium (Naitam and Bhattacharyya 2004).

Table 4.1. Selected soil parameters for identifying systems for carbon sequestration (0–30 cm) in sub-humid (moist) bioclimatic system.

Sl. No.	Pedon No. (Soils)	Soil Series	Land use (Crops)	BD (g/cc)	SOC (%)	SIC (%)	SOC stock [Pg/(million ha)]
1.	P5 (Black)	Nabibagh	Agriculture (HM) (soybean-wheat)	1.30	0.75	0.66	0.029
2.	P15 (Black)	Boripani	Forest (teak) (*Tectona grandis*)	1.35	0.810	0.48	0.032
3.	P24 (Red)	Dadarghugri	Forest (teak)	1.22	2.42	0.00	0.078
4.	P25 (Red)	Karkeli	Forest (sal) (*Shorea robusta*)	1.73	1.09	0.00	0.056

Table 4.2. Selected soil parameters for identifying systems for carbon sequestration (0–30 cm) in sub-humid (dry) bioclimatic system.

Sl. No.	Pedon No. (Soils)	Soil Series	Land use (Crops)	BD (g/cc)	SOC (%)	SIC (%)	SOC stock [Pg/(million ha)]
1.	P1 (Black)	Linga	Horticulture (*Citrus spp.*)	1.50	0.75	0.762	0.0340
2.	P3 (Black)	Linga	Agriculture (FM) (soybean-wheat/ chickpea)	1.40	0.86	0.870	0.036
3.	P8 (Black)	Sarol	Agriculture (FM) (soybean-wheat)	1.40	0.76	0.780	0.032
4.	P48 (Black)	Nipani	Agriculture (FM) (cotton+pigeonpea)	1.57	0.82	3.04*	0.039

* High SIC value due to the parent material (limestone) and hence not considered while fixing SIC threshold value.

Table 4.3. Selected soil parameters for identifying systems for carbon sequestration (0–30 cm) in sub-humid (moist) bioclimatic system.

Sl. No.	Pedon No. (Soils)	Soil Series	Land use (Crops)	BD (g/cc)	SOC (%)	SIC (%)	SOC stock [Pg/(million ha)]
1.	P12 (Black)	Asra	Agriculture (HM) (cotton+pigeonpea/ soybean-chickpea)	1.50	0.92	0.64	0.041
2.	P18 (Red)	Vijaypura-1	Agriculture (HM) (finger millet)	1.52	0.81	0.00	0.037
3.	P42(Black)	Bhatumbra	Agriculture (FM) (sorghum+pigeonpea/black gram-chickpea)	1.36	0.88	1.12	0.036

Table 4.4. Selected soil parameters for identifying systems for carbon sequestration (0–30 cm) in semi-arid (dry) bioclimatic system.

Sl. No.	Pedon No. (Soils)	Soil Series	Land use (Crops)	BD (g/cc)	SOC (%)	SIC (%)	SOC stock [Pg/(million ha)]
1.	P13 (Black)	Paral	Agriculture (LM) (cotton+pigeonpea/ sorghum)	1.60	0.63	1.19	0.0302
2.	P29 (Black)	Semla	Agriculture (cotton/groundnut -wheat)	1.40	0.756	1.99	0.032
3.	P37(Red)	Hayatnagar	Agriculture (HM) (sorghum-castor)	1.51	0.93	0.00	0.042
4.	P38(Red)	Hayatnagar	Agriculture (LM) (sorghum-castor)	1.526	0.96	0.00	0.044
5.	P39(Black)	Kasireddipalli	Agriculture (HM) (soybean+pigeonpea)	1.60	0.76	0.53	0.036
6.	P41(Red)	Patancheru	Permanent Fallow (grassland)	1.60	1.42	0.00	0.068
7.	P43(Black)	Teligi	Agriculture (LM) (paddy-paddy)	1.40	1.03	1.39	0.043
8.	P44(Black)	Teligi-1	Agriculture (HM) (paddy-paddy)	1.56	0.80	0.96	0.037
9.	P47(Black)	Kalwan	Agriculture (HM) (sugarcane/sorghum-wheat/chickpea)	1.40	0.90	0.37	0.038

Table 4.5. Selected soil parameters for identifying systems for carbon sequestration (0–30 cm) in arid bioclimatic system.

Sl. No.	Pedon No. (Soils)	Soil Series	Land use (Crops)	BD (g/cc)	SOC (%)	SIC (%)	SOC stock [Pg/(million ha)]
1.	P51(Black)	Nimone	Agriculture (HM) (cotton-wheat/chickpea)	1.39	0.76	1.71	0.0320
2.	P52(Black)	Nimone	Agriculture (FM) (sugarcane/soybean-wheat/chickpea)	1.31	0.76	2.64	0.0300

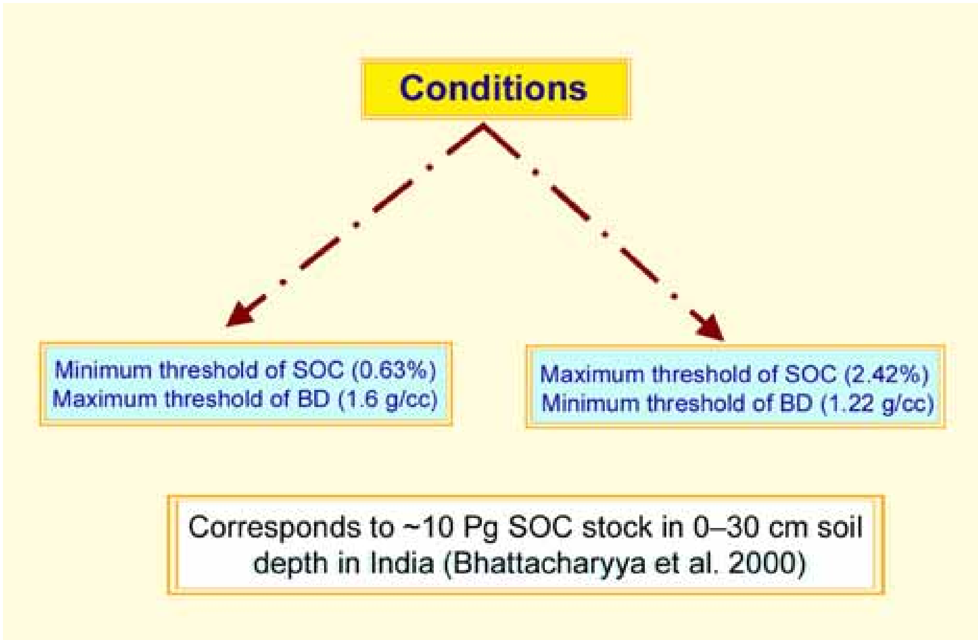


Figure 4.1. Conditions for identifying systems for organic carbon sequestration in soils of SAT, India.

Identified System 1 (P5)

Sub-Humid (Moist) — Black Soils

Cropping pattern, yield and management level in P5 (Nabibagh, Madhya Pradesh)

Sl. No.	Attribute	Description
1	Production system	Double cropping of soybean-wheat under irrigated conditions with 1–2 months fallow (summer).Yield range: Soybean 1900–2230 kg/ha and Wheat - 3380–3940 kg/ha.
2	Management level	• Improved varieties • Organic manures: 3–4 tonnes/ha per year • Fertilizer: Soybean – 25:60:20 and wheat – 120:60:40 • Pesticide, weedicide; Pesticides: Endosulphan and Lindane. • Residues: Burnt • Soil conservation measures: None • Sowing time: Soybean – 1st week of July, wheat – last week of November • Seed rate: Soybean 80 kg/ha, wheat 100–120 kg/ha

(a) BM spot No. 3 at Indian Institute of Soil Science, Research farm, Bhopal, Madhya Pradesh.

*(b) Typical Nabibagh soil series under agricultural system with high management practice having soybean-wheat crop rotation (*Typic Haplusterts*).*

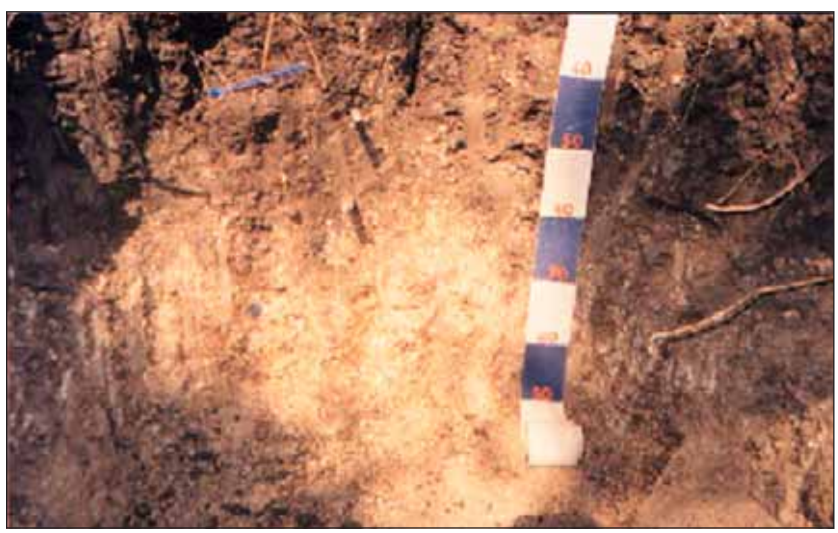
Figure 4.2. Landscape, land use and soils in BM spot 3 (Nabibagh, Bhopal).

Identified System 2 (P15)

Sub-Humid (Moist) | Black Soils

(a) Site for Boripani with dominantly teak forest.

(b) Typical Boripani soil profile (Vertic Haplustepts).



(c) Closer view of the soil profile.

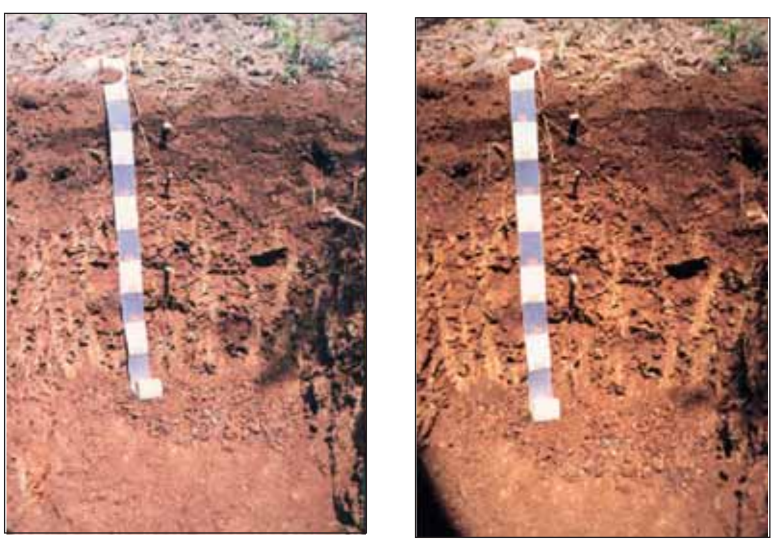
Figure 4.3. Landscape, land use and soils in BM spot 7 (Boripani, Nagpur).

Identified System 3 (P24)

Sub-Humid (Moist)

Red Soils

(a) Dadarghugri (Dindori, Madhya Pradesh) soil-site under forest system [Teak (Tectona grandis)*].*



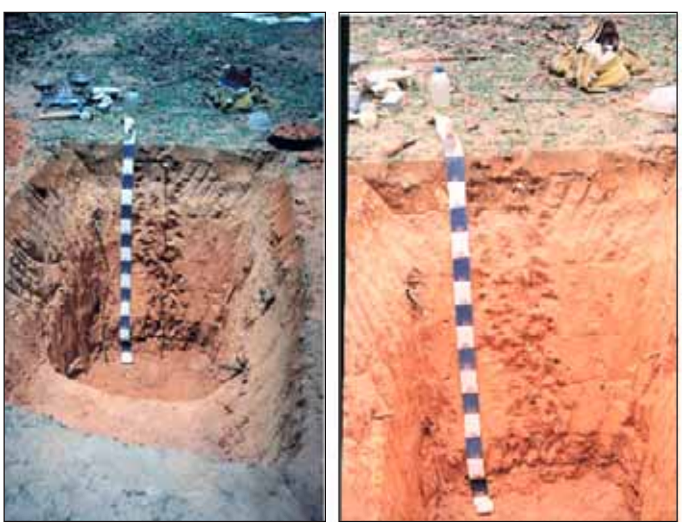
*(b) Typical soil profile of Dadarghugri soil (*Typic Haplustalfs*).*

Figure 4.4. Landscape, land use and soils of BM spot 11.

Identified System 4 (P25)

Sub-Humid (Moist) **Red Soils**

(a) Karkeli soil-site, Karkelitolla, Bandhavgarh (in Umeria district, Madhya Pradesh) under forest (Sal, Shorea, robusta).



(b) Very deep redsoil profile of Karkeli series showing deep red subsurface horizon (Typic Haplustalfs).

(c) Typical termite mound in the Karkeli forest site.

Figure 4.5. Landscape, land use and soils of BM spot 12 forest.

Identified System 5 (P1)

Sub-Humid (Dry)   Black Soils

(b) *Horticultural system under high management with Linga soil.*

(a) Exact management practice in a 10-year old horticulture farm on Linga soils.

(c) Site selection for profile examination and sample collection.

*(d) Very deep black soil profile of Linga series (*Typic Haplusterts*).*

Figure 4.6. Landscape, land use and soils of Pedon P1 in BM spot (Linga, Nagpur).

Identified System 6 (P3)

Sub-Humid (Dry) **Black Soils**

(a) The original BM spot of Linga series under horticulture system (Citrus) under LM practice, (pedon No. 2). Previous soil sample collection from this site was during 1982.

(b) Very dark shrink-swell soil profile (P2) of Linga series.

Figure 4.7. Landscape, land use and soils of Pedon No. 2 in BM spot Linga, Nagpur.

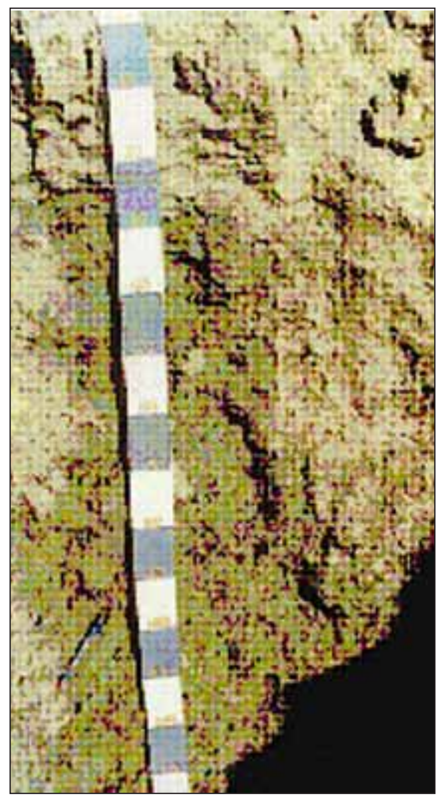
Identified System 7 (P8)

Sub-Humid (Dry) — Black Soils

Cropping pattern, yield and management level in P8 (Sarol, Madhya Pradesh)

S. No.	Attribute	Description
1	Production system	Extensive, irrigated (supplemental life saving) soybean- wheat system. Yield: Soybean – 800–1000 kg/ha, wheat – 2000–2200 kg/ha. Crop-livestock farming system.
2	Management level	• Improved seeds of soybean and wheat • Manures: FYM @ 2 tonnes/ha per year • Chemical fertilizer: 25:60:0 for soybean 60:60:0 for wheat • Poor plant stand • Insecticides: Occasional • Sowing time: Soybean in last week of June, wheat in first week of December • Seed rate: Soybean 80 kg/ha, wheat 80–100 kg/ha

(a) Very deep black soil of Sarol series under agricultural system (farmers' management) with soybean - wheat crop rotation.



*(b) Soil profile Sarol soil series (*Typic Haplusterts*).*

Figure 4.8. Landscape, land use and soils in BM spot 4 (Sarol, Indore).

Identified System 8 (P48)

Sub-Humid (Dry) **Black Soils**

Cropping pattern, yield and management level in P48 (Nipani, Andhra Pradesh)

S. No.	Attribute	Description
1	Production system	Rainfed (monsoon) and irrigated (summer) crop of cotton: Pigeonpea (8:1 for 3 year)- maize/sorghum system and occasional summer vegetables (irrigated). Crop – livestock farming system (1–5 months fallow). Yield range: 2000–3000 kg/ha of cotton + 100–150 kg pigeonpea/ha, 4000–5000 kg/ha maize/sorghum
2	Management level	• Improved seeds • Manures: FYM (4 trolley/ha once in 3 years) • Fertilizer: 110:80:80 kg/ha per crop • Pesticides: Frequently • Soil conservation measures: Nil, • Residue management techniques: Nil • Sowing time: Cotton, pigeonpea, maize, sorghum - last week of Jun to 1st week of July • Seed rate: Cotton 3 kg/ha, pigeonpea 2 kg/ha (as intercrop), sorghum 12–15 kg/ha, maize 20 kg/ha

(a) Typical BM spot at Nipani, Adilabad, Andhra Pradesh under agricultural system (farmers' management) with cotton-pigeonpea cropping system.

(b) More than 0.5 cm polygonal cracks on the surface of Nipani soil.

(c) Typical Nipani benchmark soil profile (Vertic Haplustepts).

Figure 4.9. Landscape, land use and soils in BM spot 26 (Nipani, Adilabad, A.P.).

Identified System 9 (P12)

Semi-Arid (Moist) **Black Soils**

*(a) Sunhemp (*Crotalaria juncea*) as a common green manuring crop in Asra soil under agriculture system with high management (cotton + pigeonpea / soybean – chickpea).*

(b) Pedon site for Asra soil under agricultural system (high management).

(c) Typical black soil profile of Asra series showing cracks and slickensides.

Figure 4.10. Landscape, land use and soils in BM spot 5 (Asra, Amravati).

Identified System 10 (P18)

Semi-Arid (Moist) — Red Soils

Cropping pattern, yield and management level in P8 (Vijaypura, Karnataka)

S. No.	Attribute	Description
1	Production system	Rainfed groundnut- groundnut finger millet (3 year rotation) cropped during *kharif* with 8–9 month fallow (winter and summer).Yield range: Finger millet - 2000 kg, groundnut 700–1100 kg
2	Management level	• Improved varieties • Optimum plant stand • Manures: FYM @10 tonnes /ha for finger millet • Chemical fertilizer: 25:50:25 for groundnut, 25:40:25 for finger millet. • Weedicides: Occasional. Insecticides: Occasional • Conservation measure: Levelling. • Sowing time: Finger millet – first fortnight of June, groundnut – second fortnight of May • Seed rate: Finger millet – 6–8 kg/ha, groundnut – 80–100 kg/ha

(a) Benchmark site of Vijaypura series under agricultural system (high management) with finger millet as the dominant crop.

(b) Ragi (finger millet) staple food of benchmark spot No. 8, collection of horizontal soil sample. Typical red soil profile of Vijaypura series (Typic Haplustalfs), *a closer view of soil profile*

Figure 4.11. Landscape, land use and soils in BM spot 8 (Vijaypura (HM), Bangalore).

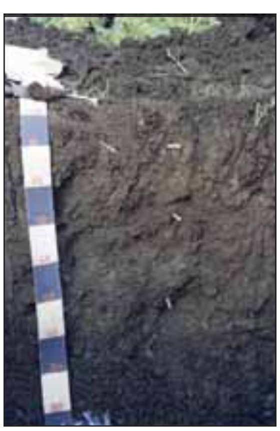
Identified System 11 (P42)

Semi-Arid (Moist) — Black Soils

Cropping pattern, yield and management level in P42 (Bhatumbra, Karnataka)

S. No.	Attribute	Description
1	Production system	Irrigated (canal) multiple cropping of black gram (*kharif*) – chickpea (*rabi*) – sorghum + pigeonpea (intercropping) (2-year rotation) with 3–5 months fallow. Crop based farming system. Yield range: black gram – 1000 kg/ha, chickpea- 600–700 kg/ha, sorghum – 1000 kg (as intercrop) and pigeonpea 600–700 kg/ha as intercrop
2	Management level	• Improved seeds • Chemical fertilizer, pesticides or organic manures: Nil (although manures and fertilizers were regularly applied till 6–7 years ago) • Conservation or residue management: Nil • Insecticides • Sowing time: Black gram/sorghum/pigeonpea – first week of July, chickpea – first fortnight of November • Seed rate: Black gram 18–20 kg/ha, chickpea 60–70 kg/ha, sorghum 6–8 kg/ha, pigeonpea (as intercrop) 4-5 kg/ha

(a) Benchmark spot at Bhatumbra, Bidar, Karnataka under agricultural system (Farmers' Management) with sorghum + pigeonpea/black gram-chickpea crop rotation.



*(b) Typical Bhatumbra profile (*Typic Haplusterts*). Seepage water at 110 cm depth.*

(c) Closer view of the profile.

Figure 4.12. Landscape, land use and soils in BM spot 22 (Bhatumbra, Bidar, Karnataka).

Identified System 12 (P13)

Semi-Arid (Dry) — Black Soils

Cropping pattern, yield and management level in P13 (Paral, Maharashtra)

S. No.	Attribute	Description
1	Production system	Rainfed intercropping system of cotton (8R) +sorghum (2R) + pigeonpea (1R), crop livestock farming system, 5–6 months of fallow period (summer). Yield range: Cotton (hybrid) 200–250 kg/ha, sorghum 150–200 kg/ha and pigeonpea 50 kg/ha.
2	Management level	• Improved varieties of cash crop only • Organic manure: Nil • Fertilizer: 40–60 kg N/ha and 30–40 kg P_2O_5/ha with no ammendments • Conservation measures: Nil • Insecticides: Regular • Sowing time: 26^{th} met week • Seed rate: Cotton 1 kg/ha, sorghum 3–5 kg/ha, pigeonpea (as intercrop) 2–2.5 kg/ha

(a) Site for Paral soil under agricultural system (LM) with cotton + pigeonpea/sorghum).

(b) Typical degraded black soil of Paral soil (Sodic Haplusterts).

Figure 4.13. Landscape, land use and soils in BM spot 6 (Paral, Akola).

Identified System 13 (P29)

Semi-Arid (Dry)

Black Soils

Cropping pattern, yield and management level in P29 (Semla, Gujarat).

S. No.	Attribute	Description
1	Production system	Irrigated, predominantly *kharif* based, cotton-groundnut (wheat after groundnut to limited extent) 2 year rotation with 4–8 months fallow period.Yield range: 2000–3500 kg/ha groundnut, 2000–3000 kg/ha of cotton and 3000–3500 kg/ha of wheat. Crop livestock farming system.
2	Management level	• Improved seeds • Organics: 30 cartloads/ha • Chemical fertilizer: 40–45 kg/ha/year N, 60 kg P_2O_5/ha/year as DAP and Urea for cotton-groundnut rotation, 80 kg/ha/year N and 40 kg/ha/year P_2O_5 for wheat • Insecticides: Frequent (10–12 sprays in cotton) • Residue management: Poor • Conservation measures: Ridge furrows, bunding, etc, adopted • Sowing time: Cotton and groundnut – first week of July, wheat (after groundnut) – last week of November • Seed rate: Cotton – 8 kg/ha, groundnut – 100 kg/ha, wheat – 80–100 kg/ha

(a) Benchmark spot at Semla, Rajkot Gujarat under agricultural system with cototn/groundnut-wheat crop rotation.

(b) Wide cracks are common in Semla soils.

(c) Typical profile of Semla soil.

(d) Closer view of the profile.

Figure 4.14. Landscape, land use and soils in BM spot 14 (Semla, Rajkot).

Identified System 14 (P37)

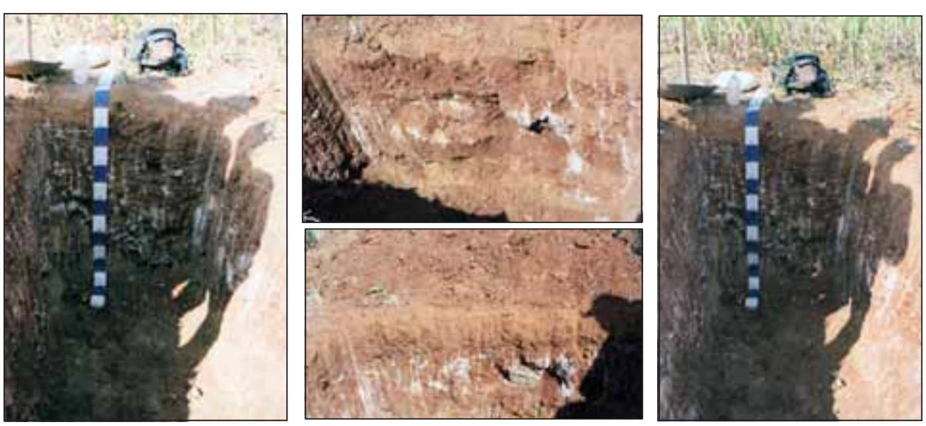
Semi-Arid (Dry) | Red Soils

Cropping pattern, yield and management level in P37 (Hayatnagar, Andhra Pradesh)

S. No.	Attribute	Description
1 of	Production system	Rainfed *kharif* sorghum-castor (2 year rotation) with 5–8 months fallow period (including summer). Yield range: Castor – 975–1263 q/ha, sorghum – 1220–1450 kg/ha.
2	Management level	• Improved varieties/hybrid (Aruna for castor and CSH 5, 6 or 9 for sorghum), • Chemical fertilizers: 60 kg/ha N + 30 kg/ha P_2O_5 + green manure (*Glyricidia*) • Insecticides: Limited (to shoot fly control) • Residue management: Sorghum stover @ 2 t/ha and *Glyricidia* loppings @ 2 times fresh wt/ha • Soil conservation measures: Bunding • Sowing time: Castor and sorghum – first week of July • Seed rate: Castor 12–15 kg/ha, sorghum 8–10 kg/ha

(a) Benchmark spot at Hayatnagar, Hyderabad.

(b) Benchmark spot at Hayatnagar, Rangareddy, A.P. under agricultural system (high management) with sorghum-castor cropping system.



*(c) Typical Hayatnagar profile (*Typic Rhodustalfs*).*

Figure 4.15. Landscape, land use and soils in BM spot 19 (Hayatnagar-HM, Rangareddy, A.P.).

Identified System 15 (P38)

Semi-Arid (Dry) **Red Soils**

(a) Benchmark spot at Hyderabad and the participants.

(b) Benchmark spot at Hayatnagar, Rangareddy, Andhra Pradesh under agricultural system (Low Management) with sorghum-castor crop rotation.

*(c) Typical Hayatnagar profile (*Typic Rhodustalfs*).*

Figure 4.16. Landscape, land use and soils in BM spot 19 (Hayatnagar-HM, Rangareddy, A.P.).

Identified System 16 (P39)

Semi-Arid (Dry)

Black Soils

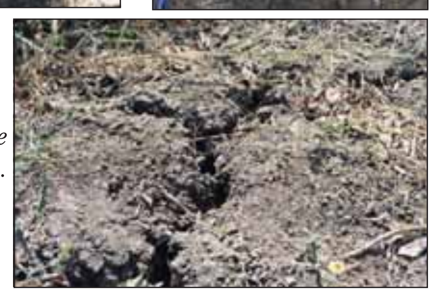
Cropping pattern, yield and management level in P59 (Kasireddipalli, Andhra Pradesh)

S. No.	Attribute	Description
1	Production system	Rainfed *kharif* intercropping system with 6–7 months fallow. Soybean + pigeonpea 4:1 intercropping system.Yield range: Soybean – 469–2068 kg/ha and pigeonpea – 589–1452 kg/ha.
2	Management level	• Improved varieties (PK432 soybean and Asha-pigeonpea) • 250kg SSP/ha per year (40 kg P_2O_5/ha) • Green manuring with Glyricidia loppings. • Insecticides: Occasional • Weedicide: Basalin @ 2 L/ha. • Broad bed (1.05 m) ridge and furrow (0.50 m) land management system.

(a) Benchmark spot at Kasireddipalli, Medak, Andhra Pradesh under agricultural system (high management) with soybean and pigeonpea crop rotation.

(b) Closer view of the profile.

*(c) Typical Kasireddipalli soil profile (*Sodic Haplusterts*).*



(d) Wide polygonal cracks at the benchmark spot.

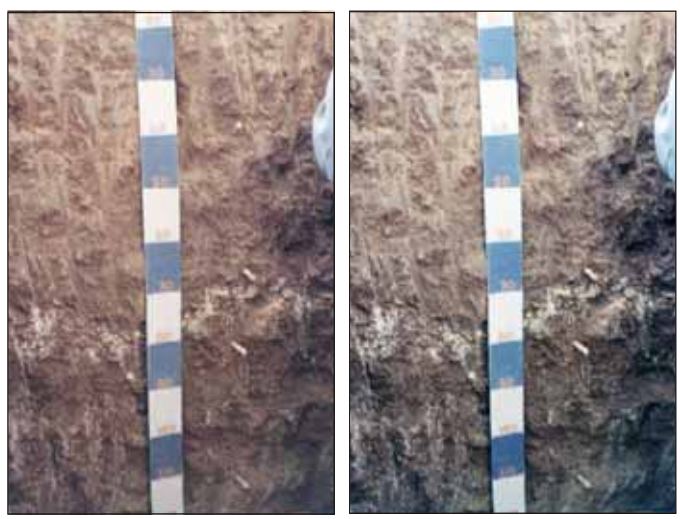
Figure 4.17. Landscape, land use and soils in benchmark spot 20 (Kasireddipalli, HM, Ramchandrapuram, Medak, A.P.).

Identified System 17 (P41)

Semi-Arid (Dry) — Red Soils

(a) Spot at Patancheru, ICRISAT Medak, Andhra Pradesh, with permanent fallow under grass vegetation 7 to 10 years.

(b) Earthworm casts bigger than 4 cm are common in Patancheru soils.



(c) Closer view of the profile.

(d) Typical Patancheru soil profile (Typic Rhodustalfs).

Figure 4.18. Landscape, land use and soils in BM spot 21 (Patancheru, ICRISAT Original, Medak, A.P.)

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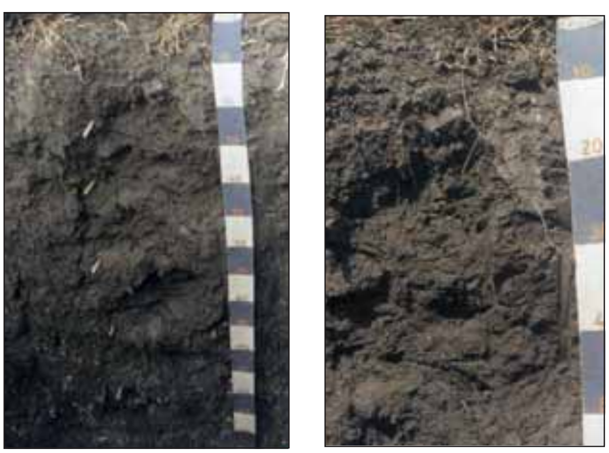
Identified System 18 (P43)

Semi-Arid (Dry) — Black Soils

Cropping pattern, yield and management level in P43 (Teligi, Karnataka)

S. No.	Attribute	Description
1 with	Production system	Mono cropping of rice, lowland transplanted (single crop/year) 7–8 months fallow period. Yield range: 1880–3190 kg/ha
2	Management level	• Improved varieties (Sona Masuri) Integrated Pest Management • Weed control: Manual • Fertilizers: 150:75:75 • Manures: Nil • Residues of paddy: Turned down. • Soil conservation measures: Field bunding • Sowing time: July

(a) Benchmark spot Teligi at Siruguppa, Bellary, Karnataka under agricultural system (Low Management), wheat, paddy-paddy crop rotation.



(b) Typical Teligi soil profile (Sodic Haplusterts).

(c) Closer view of the profile.

Figure 4.19. Landscape, land use and soils in BM spot 23 (Teligi, Siruguppa, Bellary, Karnataka).

Identified System 19 (P44)

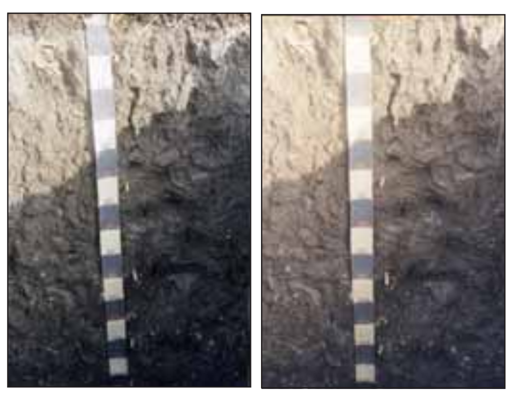
Semi-Arid (Dry) — Black Soils

Cropping pattern, yield and management level in P44 (Teligi, Karnataka)

S. No.	Attribute	Description
1	Production system	Mono cropping of rice lowland transplanted (single crop/year) with 7–8 months fallow period. Yield range: 6000–7000 kg/ha
2	Management level	• Improved varieties (Sona Masuri) • Integrated pest management • Weed control: Manual • Fertilizers: 200–250 kg N/ha, 75 kg P_2O_5/ha and 75 kg K_2O/ha • Organic manures: Not applied. • Residues of paddy turned down. • Soil conservation measures: Field bunding • Sowing time: (transplanting) – July

(a) Benchmark spot at Siruguppa, Teligi, Bellary, Karnataka under agricultural system (High Management) with paddy-paddy crop rotation.

(b) Wide, polygonal cracks on the surface of Teligi soils.



*(c) Typical Teligi soil profile (*Sodic Haplusterts*).*

(d) Closer view of the profile showing slickensides.

Figure 4.20. Landscape, land use and soils in BM spot 23 (Teligi, HM Siruguppa, Bellary, Karnataka).

Identified System 20 (P47)

Semi-Arid (Dry) — Black Soils

Cropping pattern, yield and management level in P47 (Kalwan, Maharashtra)

S. No.	Attribute	Description
1	Production system	Multiple cropping of maize-sugarcane/wheat/onion irrigated (well) with 1–2 months fallow period. Yield range: Maize- 4000–5000 kg/ha, Onion- 250–300 q/ha, Wheat- 3500–4000 kg/ha and Sugarcane- 1000–1225 q/ha.
2	Management level	• Use of improved seeds/planting material • Organic manures • Pesticides • Soil conservation measures: ridge furrow and bunding, drip irrigation • Chemical fertilizers: Sugarcane 250 kg N/ha, 50 kg P_2O_5/ha; wheat- 100 kg N/ha and 20 kg P_2O_5/ha. Other crops not available • Sowing time: Maize – last week of June, sugarcane – July–August, wheat/onion – last week of November • Seed rate: Maize 20 kg/ha, sugarcane 30–35 thousand setts/ha, wheat 100 kg/ha

(a) Benchmark site at Kalwan, Nasik, Maharashtra under agricultural system (farmers' management) with sugarcane/sorghum-wheat-chickpea/onion).

(b) Benchmark soil profile at Kalwan (Typic Haplusterts).

Figure 4.21. Landscape, land use and soils in BM spot 25 (Kalwan, Nashik, Maharashtra).

Identified System 21 (P51)

Semi-Arid (Dry) — Black Soils

Cropping pattern, yield and management level in P51 (Nimone, Maharashtra)

S. No.	Attribute	Description
1	Production system	Irrigated, double cropping system of cotton (summer irrigated Mar-Oct)- chickpea/wheat (in *rabi*) with less than 1 month fallow period. Rotation of sorghum (R)- fallow or green manure with Dhaincha (once in 3–4 years). Yield range: Cotton – 1800–2000 kg/ha, wheat – 4500 kg/ha and sorghum (rainfed)- 12 kg/ha.
2	Management level	• Improved varieties/hybrids • Optimum plant stand • Chemical fertilizers: Recommended (cotton 100:50:50, wheat 100:50:50 and sorghum 50:0:0), • Manures: Adequate FYM (10 cart loads/ha in 4 year) • Green manuring: Occasional • Soil conservation measures: Leveling and field bunding. • Sowing time: Cotton – first fortnight of April • Seed rate: 2.45–3 kg/ha

Figure 4.22. Landscape, land use, soils and level of management in agricultural system.

Identified System 22 (P44)

Semi-Arid (Dry) — Black Soils

Cropping pattern, yield and management level in P44 (Nimone, Maharashtra)

S. No.	Attribute	Description
1	Production system	Irrigated soybean based, ie, sugarcane-soybean/sorghum/wheat with extended sugarcane ratooning and 2–3 months fallow period at the end of each cycle. Yield range: Sugarcane (main)-1500 kg/ha, (ratoon)-750–900 q/ha. Crop-livestock-garden farming system with improved cattle breed.
2	Management level	• Improved varieties • Drip irrigation • Optimum plant stand • Chemical fertilizers: Recommended (but no K), sugarcane – 240–300 kg N, 150–170 kg P_2O_5/ha. • FYM: Nil • Ridge furrow planting • Weedicide and insecticide: Occasional • Crop residues: Burnt or used for feed and housing • Sowing time: Sugarcane – (no fixed time), soybean and sorghum- 1st week of July, wheat – end of Nov. • Seed rate: Sugarcane- 35–40 thousand setts/ha, soybean 80 kg/ha, sorghum 15 kg/ha, wheat 80–100 kg/ha

(a) Land use at Nimone site (Sugarcane)

*(b) Soil profile at Nimone (*Typic Haplusterts*).*

Figure 4.23. Landscape, land use, soils and level of management in agricultural system.

Summary and conclusions

5.1 Summary

On the basis of Walkley Black Carbon, the SOC stock was estimated at various depths of soil. The soils studied in 28 BM spots were generally calcareous and contain $CaCO_3$ with the exception of Dadarghugri, Karkeli and Vijaypura soils. The stock of inorganic form of carbon present in soil (SIC) was estimated. The sum of SOC and SIC stocks gives the TC stock. The calculation of carbon stock requires information on %SOC, %SIC, BD, depth of soil and the areal extent of each soil series. The SOC, SIC and TC stocks were estimated at 0–30, 0–50, 0–100 and 0–150 cm soil depths following standard methods for forty black soils and twelve red soils.

Out of 150.9 million ha area of the country indicated as the potential area for carbon sequestration (Pal et al. 2000; Bhattacharyya et al. 2000), the present study covers 21.63 million ha covering 14% of the priority area of India and 28 BM spots represented by 52 soil pedons. Out of 52 pedons, 40 pedons are represented by black soils and cover 15.29 million ha. The remaining 12 pedons are represented by red soils covering 6.34 million ha. The SOC, SIC and TC stocks are expressed in Pg/(million ha) for easy comparison of carbon status in soils under different bioclimatic systems.

As mentioned earlier, total 28 BM sites were studied. Of this, 10 spots were common to the 180 BM spots which were reported earlier (Lal et al. 1994). The data generated through the present study and those reported earlier during the 1980s were compared to the changes in the QEV of SIC and SOC stocks. This indicates that 10 BM spots comprising six under black soils and four under red soils show an increase in SOC content to reach a new QEV in terms of SOC, over a period of 25–30 years. This was possible due to good substrate, qualitatively and quantitatively, characteristic soil modifiers such as zeolites and gypsum supported by improved method of management, adopting HYV, irrigation and proper dose of fertilizers and manures. Incorporating legumes in crop rotation, adopting the BBF system and addition of green manure have helped the soils to attain higher level of QEV in terms of SOC.

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. The number of identified systems comprising agriculture, horticulture, forest and fallow lands represent sub-humid (moist), sub-humid (dry), semi-arid (moist), semi-arid (dry) and arid bioclimatic systems were 4, 4, 3, 9 and 2, respectively. The selection process indicates a minimum threshold limit of SOC 0.63 with a corresponding maximum threshold value of BD (1.6 g/cc). Conversely the maximum threshold limit of SOC (2.42%) corresponds to a minimum threshold limit of BD (1.22 g/cc) at 0–30 cm soil depth.

5.2 Conclusions

The present investigation on 28 BM spots in the Indian SAT leads to following conclusions:

1. The systematic studies and documentation of soil parameters vis-à-vis the management interventions helped us to identify 22 systems comprising forest (2 nos.), fallow (1 no.), horticulture (2 nos.) and agriculture (17 nos.)
2. The minimum and maximum threshold limits of SOC for the selection of viable system are 0.63 and 2.42%, respectively, which corresponds to maximum and minimum BD values of 1.60 and 1.22 g/cc, respectively.

3. The level of management adopted in the shrink-swell soils for the last 25–30 years helped these soils to reach a higher QEV in terms of SOC. This indicates that these shrink-swell soils respond to controlled management level and are not depleted in SOC. This might have been possible through the consistent efforts of agricultural institutes under the able guidance of the Indian Council of Agricultural Research (ICAR) and various state agricultural universities and other agencies. The participation of ICRISAT might have also helped to maintain increased SOC levels for soils of SAT, India, during the last 2 decades or so.
4. The higher QEV of SOC (2.42%) observed in forest soils (shrink-swell soils) indicates the scope of these soils under agriculture to further increase the QEV. Consistent efforts to increase the SOC in shrink-swell soils may be, therefore, highly probable as suggested by the present investigation.

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About NBSS&LUP

The National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, a premier Institute of the Indian Council of Agricultural Research (ICAR), was set up in the year 1976 with the objective to prepare soil resource maps at state and district level and to provide research inputs in soil resource mapping, and its applications, land evaluation, land use planning, land resource management, and database management using GIS for optimising land use on different kinds of soils in the country. The Bureau has been engaged in carrying out agro-ecological and soil degradation mapping at the country, state and district level for qualitative assessment and monitoring the soil health towards viable land use planning. The research activities have resulted in identifying the soil potentials and problems, and the various applications of the soil surveys with the ultimate objective of sustainable agricultural development. The Bureau has the mandate to correlate and classify soils of the country and maintain a National Register of all the established soil series. The Institute is also imparting in-service training to staff of the soil survey agencies in the area of soil survey and land evaluation, soil survey interpretations for land use planning. The Bureau in collaboration with Dr.Panjabrao Deshmukh Krishi Vidyapeeth, Akola is running post-graduate, teaching and research programme in land resource management, leading to M.Sc. & Ph.D. degrees. Recently the Bureau has been actively engaged in the research work under National Agricultural Technology Project (NATP).

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The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is a nonprofit, non-political organization that does innovative agricultural research and capacity building for sustainable development with a wide array of partners across the globe. ICRISAT's mission is to help empower 600 million poor people to overcome hunger, poverty and a degraded environment in the dry tropics through better agriculture. ICRISAT belongs to the Alliance of Future Harvest Centers of the Consultative Group on International Agricultural Research (CGIAR).

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