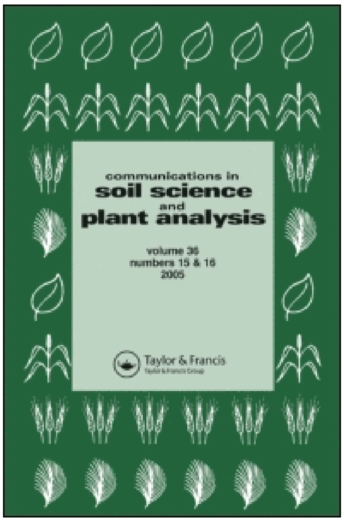

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Carbon Stocks in Different Soil Types under Diverse Rainfed Production Systems in Tropical India

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Carbon Stocks in Different Soil Types under Diverse Rainfed Production Systems in Tropical India

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Abstract: Soil carbon (C) pool plays a crucial role in the soil's quality, availability of plant nutrients, environmental functions, and global C cycle. Drylands generally have poor fertility and little organic matter and hence are candidates for C sequestration. Carbon storage in the soil profile not only improves fertility but also abates global warming. Several soils, production, and management factors influence C sequestration, and it is important to identify production and management factors that enhance C sequestrations in dryland soils. The objective of the present study was to examine C stocks at 21 sites under ongoing rainfed production systems and management regimes over the last 25 years on dominant soil types, covering a range of climatic conditions in India. Organic C stocks in the soil profiles across the country showed wide variations and followed the order Vertisols > Inceptisols > Alfisols > Aridisols. Inorganic C and total C stocks were larger in Vertisols than in other soil types. Soil organic C stocks decreased with depth in the profile, whereas inorganic C stocks increased with depth. Among the production systems, soybean-, maize-, and groundnut-based systems showed greater organic C stocks than other production systems. However, the greatest contribution of organic C to total C stock was under upland rice system. Organic C stocks in the surface layer of the soils increased with rainfall ($r = 0.59^*$), whereas inorganic C stocks in soils were found in the regions with less than 550 mm annual rainfall. Cation exchange capacity had better correlation with organic C stocks than clay content in soils. Results suggest that Indian dryland soils are low in organic C but have potential to sequester. Further potential of tropical soils to sequester more C in soil could be harnessed by

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identifying appropriate production systems and management practices for sustainable development and improved livelihoods in the tropics.

Keywords: Carbon sequestration, dryland cropping systems, India, inorganic carbon, organic carbon, total carbon stocks

INTRODUCTION

Agricultural soils are among the earth's largest terrestrial reservoirs of carbon (C) and hold potential for expanded C sequestration. Thus, they provide a potential way to reduce atmospheric concentration of carbon dioxide (CO_2) (Lal 2004). At the same time, this process provides other important benefits in terms of increased soil fertility and environmental quality. Because of low C in the dryland soils, there is good potential for C sequestration (Wani et al. 2003). Low soil organic matter (SOM) in tropical soils, particularly those under the influence of arid, semi-arid, and subhumid climates, is a major factor contributing to their poor productivity (Syers et al. 1996; Katyal, Rao, and Reddy 2001). Therefore, proper management of SOM is important for sustaining soil productivity and ensuring food security and protection of marginal lands (Scherr 1999). Because fertilizer input in dryland agriculture is low, mineralization of organic matter acts as a major source of plant nutrients. Maintaining or improving organic C levels in tropical soils is more difficult because of rapid oxidation of organic matter under prevailing high temperatures (Lal 1997; Lal, Follett, and Kimble 2003). However, maintaining or improving soil organic matter is a prerequisite to ensuring soil quality, productivity, and sustainability.

The C balance of terrestrial ecosystems can be changed markedly by the impact of human activities, including deforestation, biomass burning, and land-use change, which result in the release trace gases that enhance the greenhouse effect (Biolin 1981; Trabalka and Reichle 1986; IPCC 1990; Batjes 1996; Bhattacharya et al. 2000; Lorenz and Lal 2005). Routinely soil surveys conducted for estimating soil organic C (SOC) pool consider a depth of about 1 m. However, the subsoil C sequestrating may be achieved directly by selecting plants/cultivars with deeper and thicker root systems that are high in chemical recalcitrant compounds such as suberin and lignin (Wani et al. 2003; Lorenz and Lal 2005). Information on global regional the SOC pool is limited (Eswaran, Vanden Berg, and Reich 1993; Batjes 1996). Moreover, conclusions on the effects of land-use changes on soil C stocks are often hampered by the narrow global database available (Lorenz and Lal 2005). The size and dynamics of C pools in soils of the developing world are still poorly understood (Batjes 1996). In Indian soils, earlier studies on SOM content (Jenny and Raychaudhuri 1960) and its stocks (Gupta and Rao 1994) lacked wide sampling bases (Bhattacharya et al. 2001). In recent times, though the role of SOC (Bhattacharya et al. 2000) and inorganic C (Sahrawat 2003) have been highlighted in sequestering C in drylands, relatively little data are available on it. The objective of this study was to determine C stocks in a range of Indian soils under diverse climatic and crop production systems.

MATERIALS AND METHODS

Study Locations, Climate, and Soil Characteristics

Soil samples were collected from 21 locations, representing a wide range of climatic conditions in tropical India, which were under long-term cultivation of dryland production systems (Figure 1). Climate varied from arid, semi-arid, to subhumid, with mean annual rainfall ranging from 412 mm to 1378 mm (Table 1) and maximum, minimum, and mean air temperature ranging from 27.8 °C to 42.4 °C, 16.4 °C to 26.7 °C, and 23.2 °C to 31.9 °C, respectively. Soils were alluvial, red, yellow, and black, and arid. Length of growing period varied widely from 60–90 days in the arid regions to 180–210 days in the subhumid regions. Among the soil types, Inceptisols/Entisols, Vertisols and Vertic subgroups, and Aridisols were neutral to alkaline in reaction, and Alfisols/Oxisols were acidic. Salinity was not a problem in most of the soils. Vertisols and associated soils and some Inceptisols were calcareous, whereas Alfisols/Oxisols were noncalcareous. Except at Ranchi (Alfisol) and Indore (Vertisol), the remaining 19 locations were low in organic C (Table 2).

Depthwise sampling of soils (0.15-m intervals up to 1.05 m deep) was undertaken at 21 locations as depicted in Figure 1. At each location, sampling was done based on several dugout pits, and finally a composite sample was made for each horizon. The Walkley and Black (1934) method was used to estimate SOC, and calcium carbonate ($CaCO_3$) content in soils was determined by standard acid–base titration method (Jackson 1973). Bulk density of each horizon was determined by weight by volume. The size of C stock in each profile was calculated following the method described by Batjes (1996). It involved calculation of organic C by multiplying OC content (g C g^{-1} soil), bulk density (Mg m^{-3}) of each layer, and thickness of this layer (m) for each horizon (0–0.15 m, 0.30 m, 0.45 m, 0.60 m, 0.75 m, 0.90 m, and 1.05 m). For the determination of carbonate (CO_3) carbon stock (inorganic), the calculation was made using 12% of C values in $CaCO_3$ using a similar procedure. Summation of C in all the horizons was taken as C stock for the individual profile, and summation of soil inorganic and organic C stocks was taken as total C stock and expressed on a per hectare basis. This information is relevant in terms of comparing the soil C stocks among soil

Figure 1. Soil sampling sites.

types, production systems, and climate, and accordingly suitable management practices could be identified for better C sequestration in dryland soils.

RESULTS AND DISCUSSION

Stocks in Relation to Soil Type

Organic, inorganic, and total C stocks varied between and within soil types (Table 3). Vertisols and associated soils contained greater C stocks, followed by Inceptisols < Alfisols < Aridisols (Figure 2). In general, SOC content was greater than inorganic C content in Alfisols and Aridisols,

Table 1. Details of location, climate, soil type, rainfall, and production systems

Order	Production system and state	Agroecological region	Climate	Soil type	Mean annual rainfall (mm)	Length of growing period (days)
	Inceptisols					
1	Varanasi (rice) Uttar Pradesh	9.2	Subhumid	Alluvial deep Inceptisols	1080	150–180
2	Faizabad (rice) Uttar Pradesh	9.2	Subhumid	Alluvial deep Inceptisols	1057	150–180
3	Agra (Pearl millet) Uttar Pradesh	4.1	Semi-arid	Alluvial deep Inceptisols	665	90–120
4	Ballowal Saunkri (maize) Punjab	9.1	Semi-arid	Alluvial deep Inceptisols	1000	120–150
5	Rakh-Dhiansar (maize) Jammu and Kashmir	14.2	Semi-arid	Alluvial deep Inceptisols	1180	150–210
6	Jhansi (rabi-sorghum) Uttar Pradesh	4.4	Semi-arid	Alluvial deep Inceptisols	1017	120
	Alfisols/Oxisols					
7	Phulbani (rice) Orissa	12.1	Subhumid	Red/yellow deep Alfisols	1378	180–210
8	Ranchi (rice) Jharkhand	12.3	Subhumid	Red shallow Alfisols	1299	150–180
9	Anantapur (groundnut) Andhra Pradesh	3.0	Arid	Red shallow Alfisols	590	90–120
10	Bangalore (finger millet) Karnataka	8.2	Semi-arid	Red deep Alfisols	926	120–150
	Vertisols/Vertic group					
11	Rajkot (groundnut) Gujarat	2.4	Arid	Black deep Vertisols	615	60–90
12	Indore (soybean) Madhya Pradesh	5.1	Semi-Arid	Black deep Vertisols	944	120

Table 1. Continued

Order	Production system and state	Agroecological region	Climate	Soil type	Mean annual rainfall (mm)	Length of growing period (days)
13	Rewa (soybean) Madhya Pradesh	10.3	Subhumid	Black medium deep Vertisols	590	150
14	Akola (cotton) Maharashtra	6.3	Semi-Arid	Black medium deep Vertic/Vertisols	825	120–150
15	Kovilpatti (cotton) Tamil Nadu	8.1	Semi-Arid	Black deep Vertisols	743	120
16	Bellary (rabi-sorghum) Karnataka	3.0	Semi-Arid	Black deep Vertisols	500	90–120
17	Bijapur (rabi-sorghum) Karnataka	3.0	Semi-Arid	Black medium deep Vertisols	680	90–120
18	Solapur (rabi-sorghum) Maharashtra	6.1	Semi-Arid	Black medium deep Vertic/Vertisols	723	90–120
19	Arjia (maize) Rajasthan	4.2	Semi-Arid	Black shallow deep Vertisols	656	90–120
	Aridisols					
20	Hisar (pearl millet) Haryana	2.3	Arid	Alluvial deep Aridisols	412	60–90
21	Sardar Krishinagar (pearl millet) Gujarat	2.3	Arid	Desert deep Aridisols	550	60–90

Table 2. Physical-chemical properties of surface (0–15 cm) soils

Location	pH (1:2)	EC (dsm^{-1})	$CaCO_3$ (%)	OC ($g\,kg^{-1}$)	Particle size (%)			CEC [C mol (+) kg^{-1}]
					Sand	Silt	Clay	
Inceptisols								
Varanasi	6.7	0.27	5.60	3.7	56	14	30	9
Faizabad	8.3	0.19	0.94	5.2	32	38	30	22
Agra	8.1	0.34	0.50	3.2	52	14	34	20
Ballowal-Sauntri	7.8	0.12	3.16	5.2	65	17	18	10
Rakh-Dhiansar	7.1	0.11	2.85	5.6	80	80	12	7
Jhansi	7.2	0.24	8.90	4.8	50	14	36	26
Alfisols/Oxisols								
Phulbani	5.2	0.07	0.38	2.4	67	14	19	9
Ranchi	6.1	0.04	1.19	6.2	61	18	21	19
Anantapur	6.5	0.03	0.98	1.9	70	6	24	11
Bangalore	5.7	0.05	0.20	2.2	75	1	25	8
Vertisols/Vertic groups								
Rajkot	8.0	0.12	5.82	5.0	19	14	67	27
Indore	7.9	0.27	4.65	6.8	3	32	65	55
Rewa	7.6	0.08	0.68	2.3	30	23	47	21
Akola	8.2	0.13	19.20	2.5	18	20	62	61
Kovilpatti	8.0	0.32	9.70	4.2	32	6	62	62
Bellary	8.2	0.21	14.50	3.0	21	16	63	29
Bijapur	8.5	0.24	20.80	3.7	31	12	57	33
Solapur	8.0	0.08	3.70	3.1	13	12	75	37
Arjia	8.1	0.14	2.15	4.7	51	16	33	27
Aridisols								
Hisar	7.5	0.25	0.50	1.9	66	14	20	13
SK Nagar	8.2	0.06	1.34	2.3	85	4	11	7

and inorganic C was larger than organic C in Vertisols and Inceptisols. The SOC stocks ranged from 26.69 to 59.71 $Mg\,ha^{-1}$ with a mean of 43.74 $Mg\,ha^{-1}$ in Inceptisols, from 23.28 to 49.83 $Mg\,ha^{-1}$ with a mean of 30.82 $Mg\,ha^{-1}$ in Alfisols, from 28.60 to 95.90 $Mg\,ha^{-1}$ with a mean of 46.38 $Mg\,ha^{-1}$ in Vertisols, and from 20.10 to 27.36 $Mg\,ha^{-1}$ with a mean of 23.73 $Mg\,ha^{-1}$ in Aridisols. The stabilizing effect of clay particles on SOM decreased in the sequence allophone > amorphous minerals > smectite > illite > kaolinite (Van Breemen and Feijtel 1990). In our study, Vertisols with smectite as dominant mineral had larger organic C stocks than illitic Inceptisols and kaolinitic Alfisols.

Similarly, soil inorganic carbon (SIC) content varied widely among the soil types. Vertisols contained more inorganic C followed by Inceptisols, Alfisols, and Aridisols. The SIC stocks ranged from 22.30 to 135.11 $Mg\,ha^{-1}$ (mean 69.08 $Mg\,ha^{-1}$) in Inceptisols, from 8.81 to

Table 3. Organic, inorganic, and total carbon stocks in tropical soils of India

Soil location	Production system	Carbon stocks ($Mg\,ha^{-1}$)		
		Organic	Inorganic	Total
Inceptisols				
Varanasi	Rice	32.54	112.36	144.90
Faizabad	Rice	29.81	22.30	52.11
Agra	Pearl millet	26.69	26.76	63.45
Ballowal-Sauntri	Maize	56.73	72.21	128.94
Rakh-Dhiansar	Maize	59.71	45.75	105.46
Jhansi	Rabi sorghum	56.97	135.11	192.08
Alfisols/Oxisols				
Phulbani	Rice	23.28	8.81	32.10
Ranchi	Rice	49.83	23.35	73.18
Anantapur	Groundnut	25.41	57.02	82.43
Bangalore	Finger millet	24.75	17.88	42.63
Vertisols/Vertic groups				
Rajkot	Groundnut	58.02	154.77	212.79
Indore	Soybean	95.90	88.33	184.24
Rewa	Soybean	28.71	16.03	44.74
Akola	Cotton	28.60	367.63	396.23
Kovilpatti	Cotton	48.20	183.05	231.26
Bellary	Rabi sorghum	34.67	298.53	333.20
Bijapur	Rabi sorghum	36.60	326.06	362.67
Solapur	Rabi sorghum	49.73	106.70	156.42
Arjia	Maize	36.93	62.07	99.01
Aridisols				
Hisar	Pearl millet	20.10	14.27	34.38
SK Nagar	Pearl millet	27.36	20.50	47.86

57.02 $Mg\,ha^{-1}$ (mean 26.76 $Mg\,ha^{-1}$) in Alfisols, from 16.03 to 367.63 $Mg\,ha^{-1}$ (mean 178.13 $Mg\,ha^{-1}$) in Vertisols, and from 14.27 to 20.50 $Mg\,ha^{-1}$ (mean 17.39 $Mg\,ha^{-1}$) in Aridisols. In most of the cases, surface soil storage of organic C was greater than deeper layers, whereas the reverse was the trend in the case of SIC. Total carbon stocks (TCS) ranged from 52.11 to 192.08 $Mg\,ha^{-1}$ (mean 112.82 $Mg\,ha^{-1}$) in Inceptisols, from 32.10 to 82.43 $Mg\,ha^{-1}$ (mean of 57.58 $Mg\,ha^{-1}$) in Alfisols, from 44.74 to 396.23 $Mg\,ha^{-1}$ (mean of 224.51 $Mg\,ha^{-1}$) for Vertisols, and from 34.38 to 47.86 $Mg\,ha^{-1}$ (mean of 41.12 $Mg\,ha^{-1}$) in Aridisols. Total C stock was also greater in Vertisols, followed by Inceptisols, Alfisols, and Aridisols.

Soil C content mostly depends on, climate, soil type, and land use (Dalal and Mayer 1986). Wani et al. (2003) reported increased C sequestration in Vertisols with pigeonpea-based systems with improved

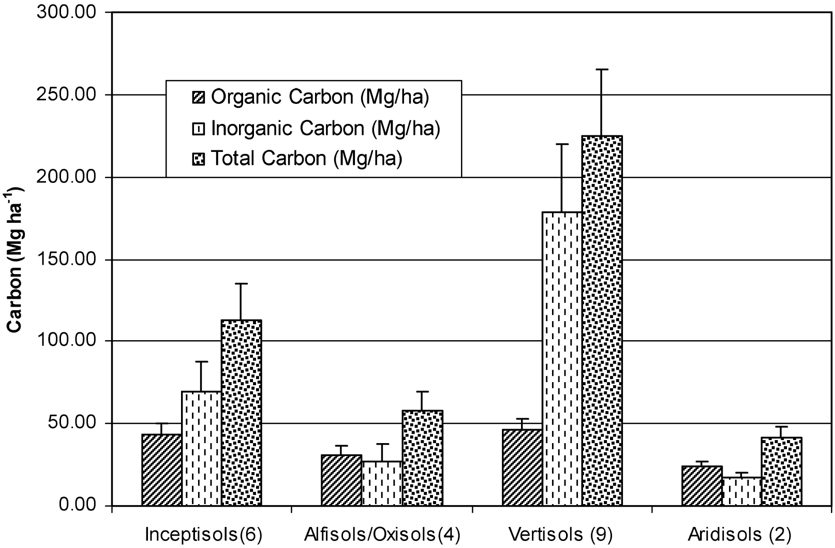


Figure 2. Carbon stocks in different soil types under diverse rainfed production systems.

management options (32 kg OC ha^{-1} y^{-1}) as compared to sorghum-based systems with farmer's management. The C concentrations reported from the Indian tropics are less than those reported by Dalal and Mayer (1986), Dalal (1989), Murphy et al. (2002), and Young et al. (2005). Significantly lower levels of organic C in these soils are attributed to high rates of oxidation of SOM resulting from high temperature in tropics and frequent cultivation (Dalal and Chan 2001; Wani et al. 2003). Young et al. (2005) reported that Vertisols with high clay content showed greater carbon stocks than other soils. Sahrawat (2003) stated that calcium carbonate is a common mineral in soils of the dry regions of the world, stretching from subhumid to arid zones, as soils of this region are calcareous in nature. According to an estimate by the National Bureau of Soil Survey and Land Use Planning, Nagpur, India, calcareous soils occupy about 230 million ha and constitute 69% of the total geographical area of India. It was further stated that SIC pool consists of primary inorganic carbonates or lithogenic inorganic carbonates and secondary inorganic carbonates. The reaction of atmospheric CO_2 with water (H_2O) and calcium (Ca^{2+}) in the upper horizons of the soil, leaching into the subsoil, and subsequent reprecipitation results in formation of secondary carbonates and the sequestration of atmospheric CO_2. This was the reason why deeper layers showed more inorganic C than surface soils in most profiles (Sahrawat 2003).

Stocks in Relation to Production System

Carbon stocks varied with production system and showed significant interaction with soil type. Organic, inorganic, and total C stocks under each production are presented in Figure 3. Soybean-based production system (62.31 Mg C ha^{-1}) showed the most organic C stocks, followed by maize-based (47.57 Mg ha^{-1}) and groundnut-based (41.71 Mg ha^{-1}) systems. Pearl millet– and finger millet–based systems showed lower organic C stocks. On the other hand, cotton system (275.3 Mg ha^{-1}) and post-rainy (rabi) sorghum production system (243.7 Mg ha^{-1}), primarily on Vertisols and associated soils, showed the most SIC, whereas the SIC was the least in soils under lowland rice systems (18.15 Mg ha^{-1}). Highest TCSs were found under the cotton-based based production system, followed by rabi sorghum–based and pearl millet–based system. However, percentage contribution of organic C to TCS was most under the rice-based system, whereas the greatest inorganic C contribution to total C was observed under the cotton-based system (Figure 4). On a regional scale, above- and belowground biomass production is probably the major determinant of the relative distribution of SOC with depth (Jobbagy and Jackson 2000). Aboveground organic matter has probably only limited effects on SOM levels compared to belowground organic matter, as has been demonstrated by long-term residue management studies (Clapp et al. 2000; Reicosky et al. 2002). The dominant role of root C in soil was also indicated by greater relative contribution of root vs. shoot tissue to the SOC pool (Rasse, Rumpel, and Dignac 2004). Root-to-shoot ratio of corn varied from 0.21 to 0.25; that of soybean was 0.23 and that of barley was 0.50 (Allmaroas, Linden, and Clapp 2004;

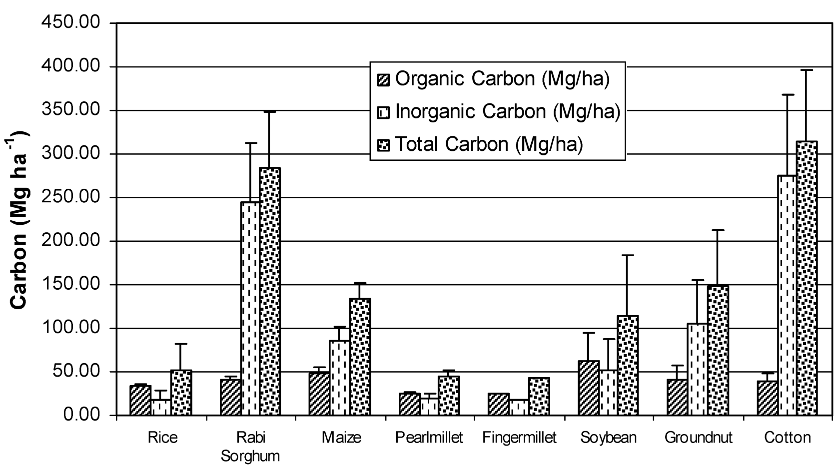


Figure 3. Carbon stocks in soils under diverse rainfed production systems.

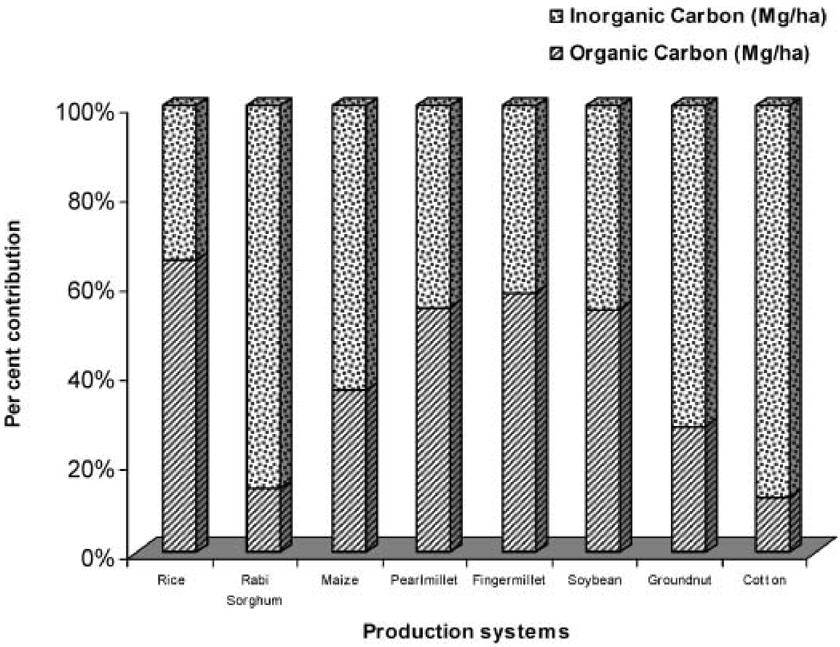
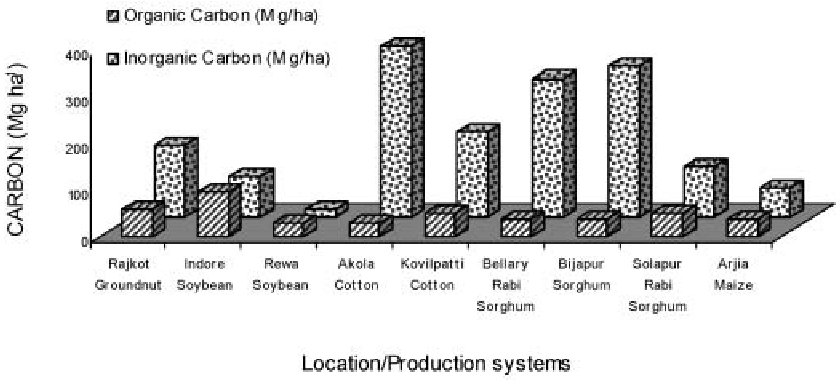


Figure 4. Contribution of organic and inorganic pools to total carbon stocks in soils under diverse rainfed production systems.

Bolinder, Angers, and Dubuc 1997). Besides root biomass, its composition also has greater impact on C sequestration. In general, leafy plants decompose faster than the woody plants, and leaves decompose faster than roots (Wang et al. 2004). The second most abundant compounds after proteins are lignins, which largely contribute to terrestrial biomass residues. These compounds exhibit a greater resistance to microbial degradation as compared to celluloses (Martin and Haider 1986). Suberin is mostly found in root tissues and is a major contributor to soil organic matter (Nierop, Haafs, and Verstraten 2003). Among dryland crops, lignin percentages are as follows: sorghum plant litter (4%), soybean (8%), maize roots (10%), millets (9–13%), rice (11–13%), and legumes like alfalfa (6–16%) (Scheffer 2002; Fernandez, Mahieu, and Cadisch 2003; Bilbro et al. 1991; Devevre and Horwath 2000; Clement, Ladha, and Chalifour 1998). Corn roots contain a wide range of fatty acids beside carbohydrates, lignin, lipids, and alkyl-aromatics (Gregorich et al. 1996).

For each soil type, the effect of particular production system was also examined. For Vertisols and associated soils, cotton and sorghum systems showed larger SIC stocks (Figure 5), whereas soybean and groundnut systems showed more SOC. Legume-based systems on

(a)



(b)

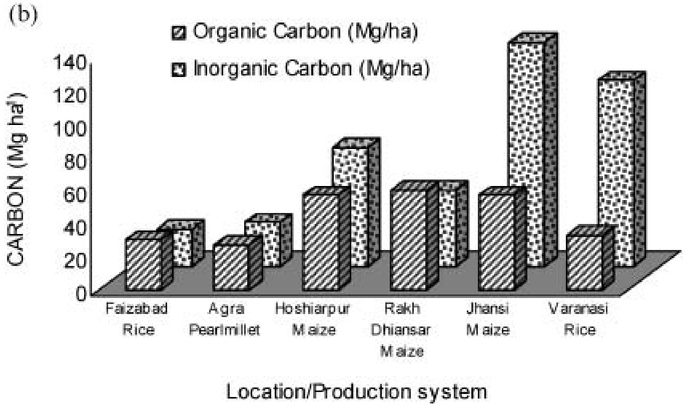


Figure 5. Distribution of carbon stock in (a) Vertisols and associated soils and (b) Inceptisols/Entisols under diverse rainfed production systems.

Vertisols showed more SOC than cereal-based systems in the tropics (Wani et al. 1995, 2003). In Inceptisols, maize-based systems showed more inorganic as well as organic C content. In Alfisols, rice-based system (Ranchi and Phulbani) showed relatively more organic C content, whereas groundnut-based (Anantapur) system showed more inorganic C (Figure 6). This could be due to larger carbonate deposits found in the deeper layers of the profile, frequent addition of gypsum to groundnut crop, and differences in rainfall, parent base material, and other management practices adapted at these locations. Under Aridisols, the pearl millet–based system at SK Nagar showed more total carbon than in Hisar.

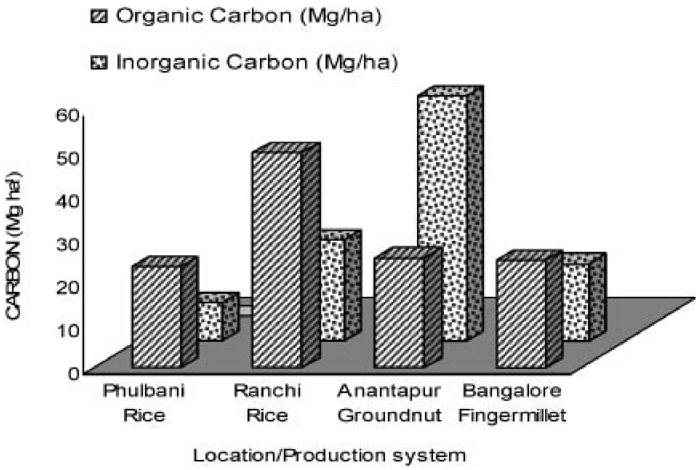


Figure 6a. Distribution of carbon stocks in Alfisols/Oxisols under diverse rainfed production systems.

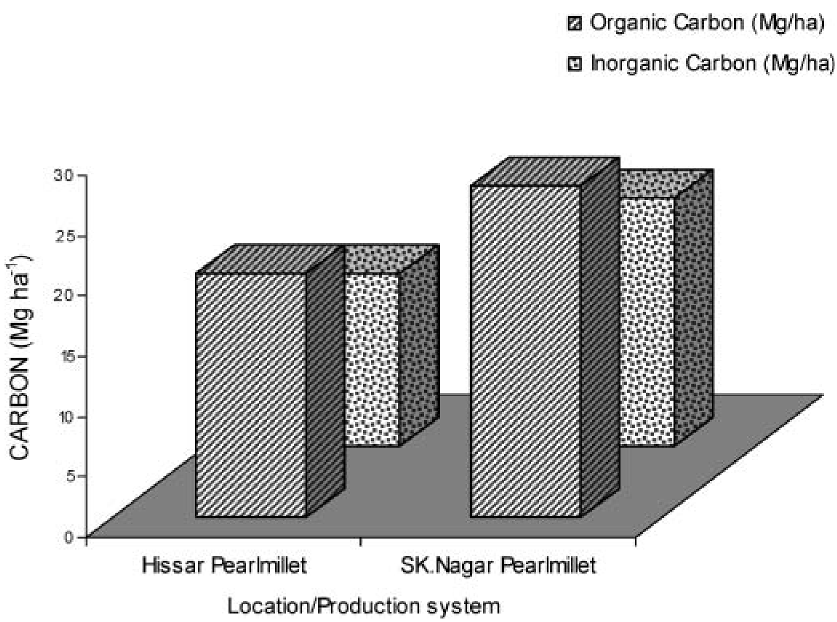


Figure 6b. Distribution of carbon stocks in Aridisols under pearl millet production system.

Carbon Stocks in Relation to Rainfall and Temperature

In general, SOC stocks increased as the mean annual rainfall increased (Figure 7). Significant correlation ($p < 0.05$) was obtained between SOC stock and mean annual rainfall ($r = 0.59^{*}$; Figure 8). On the other hand, SIC stocks decreased with the increase in mean annual rainfall from 156.40 Mg ha^{-1} (<550 mm) to 25.97 Mg ha^{-1} (>1100 mm). As the SIC stocks were more dominant than SOC, TCS decreased with increase in mean annual rainfall from 183.79 Mg ha^{-1} in the arid environment (<550 mm) to 70.24 Mg ha^{-1} in subhumid regions (>1100 mm). As all the locations are under dryland conditions and belong to similar temperature regimes, air temperature showed nonsignificant negative correlation with organic C stocks (Figure 9). However, cation exchange capacity (CEC) showed significant positive correlation ($r = 0.81^{**}$), whereas clay content in soil showed nonsignificant positive correlation with organic C stocks (Figure 10). This indirectly indicates the type of clay mineral with larger surface area is largely responsible for greater C sequestration.

It has been postulated that aridity in the climate is responsible for the formation of pedogenic calcium carbonate, and this is a reverse process to the enhancement in soil organic C. Thus, increase in C sequestration via SOC enhancement in the soil would induce dissolution of native calcium carbonate, and the leaching of SIC would also result in C sequestration (Sahrawat 2003). In the present scenario of differing

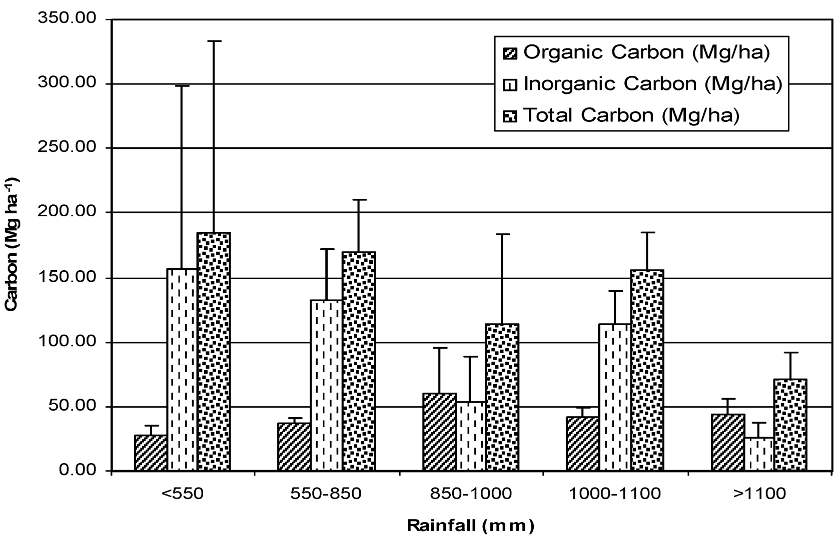


Figure 7. Carbon stocks in soils under diverse rainfed production systems in relation to rainfall.

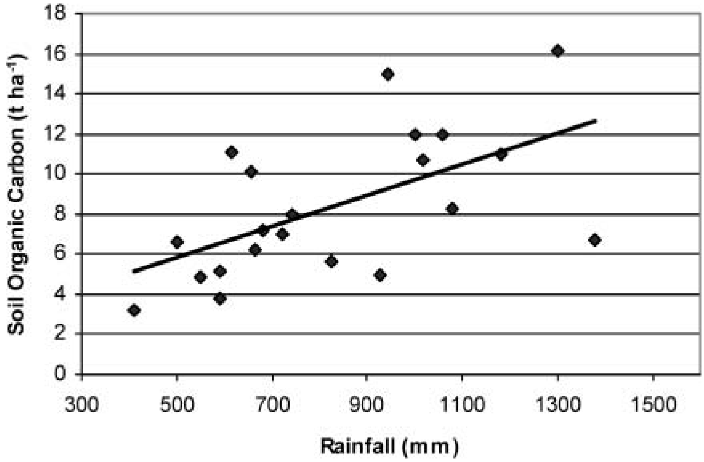


Figure 8. Relationship between mean annual rainfall (mm) and soil organic carbon in surface layer (0–15 cm) under rainfed conditions (OC stock = 1.91 + 0.008x; r = 59*).

climatic parameters such as temperature and annual rainfall in some areas of the country, it will continue to remain a potential threat for C sequestration in tropical soils of the Indian subcontinent. Therefore, the arid climate will continue to remain as a bane for Indian agriculture because this will cause soil degradation in terms of depletion of organic C and formation of pedogenic $CaCO_3$ with the concomitant development of sodicity and/or salinity (Eswaran, Vanden Berg, and Reich 1993; Bhattacharya et al. 2000).

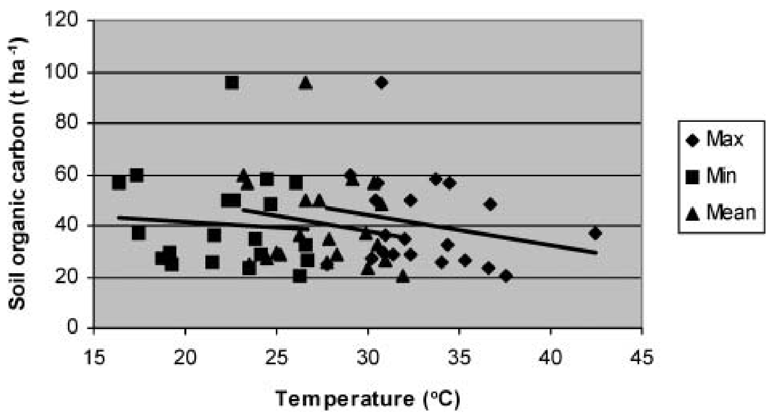


Figure 9. Relationships among maximum, minimum, and mean temperature (°C) and soil organic carbon in surface layer (0–15 cm) under rainfed conditions (r_{max} = -0.22^{NS}, r_{min}= -0.07^{NS}, r_{mean} = -0.18^{NS}).

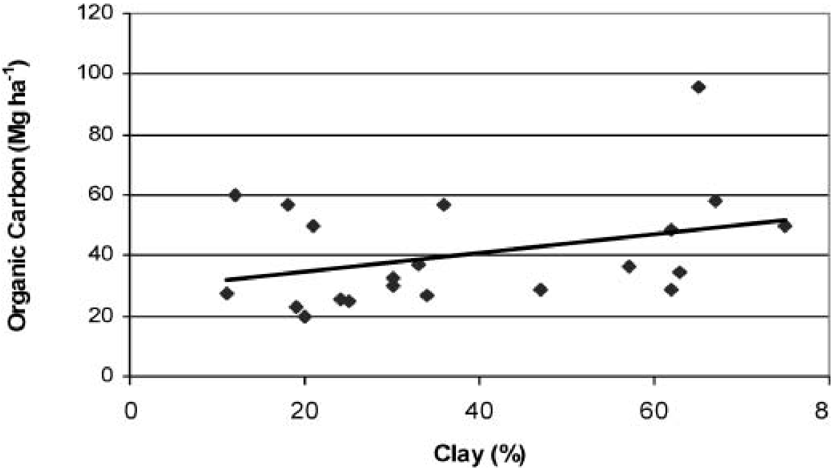


Figure 10a. Relationship between clay and organic carbon stocks in soils (r = 0.35[NS]).

CONCLUSIONS

Vertisols and associated soils had relatively greater SOC stocks than other soil types, whereas soils of regions with less rainfall showed larger inorganic C content than soils of regions with more rainfall. Amount of rainfall was significantly related with amounts of organic C stocks in the soils, and legume-based production systems showed more organic C sequestration. As soils of India are very low in organic C, its depletion

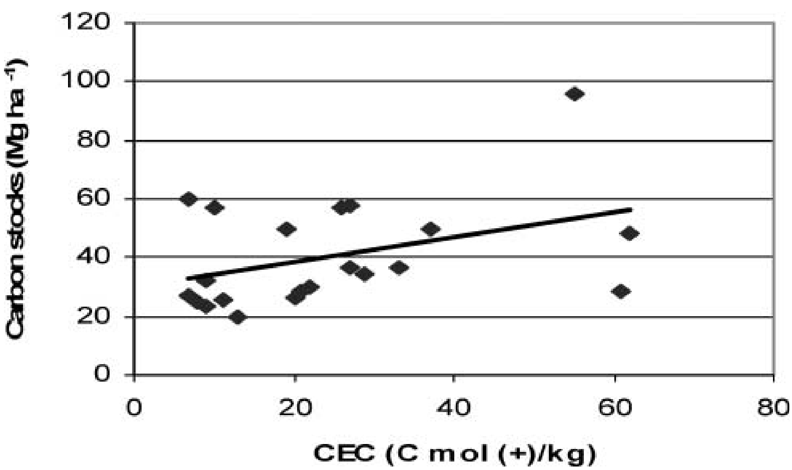


Figure 10b. Relationship between CEC and orbanic carbon stocks in soils (r = 0.81**).

occurs at a rapid rate because of continuous cultivation and exposure of the subsoil organic matter. However, long-term manure experiments under rainfed conditions showed marginal improvements in organic C levels with regular additions of organic manures. Most of the dryland farmers are not in a position to add manure or crop residue regularly without their own cattle. Therefore, alternative measures like minimum tillage, green manuring, cover cropping, green leaf manuring like gliricidia, compositing the farm waste, vermicomposting the farm and household waste, and including legumes in the system may have potential for improving C stocks in Indian soils. This could have long-term consequences in sustaining natural resources.

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