Land use and cropping effects on carbon in black soils of semi-arid tropical India

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Soil organic carbon (SOC) and rainfall are generally positively related, whereas a negative relationship between soil inorganic carbon (SIC) and rainfall with some exception is observed. Land use pattern in black soil region (BSR) of the semi-arid tropical (SAT) India, consists of 80% under agriculture, followed by forest, horticulture, wasteland and permanent fallow. For sustainable agriculture on these soils, there is a concern about their low OC status, which warrants fresh initiatives to enhance their OC status by suitable management interventions. In the BSR region, cotton, soybean and cereal-based systems dominate but it is not yet clear as to which cropping system in the SAT black soils is most suitable for higher OC sequestration. Many short-term experiments on cotton or cereal-based systems clearly suggest that cotton or cereal-based cropping systems including leguminous crops perform better in terms of SOC sequestration whereas soybean–legume combination do not add any substantial amount of OC. In sub-humid bioclimatic zones (1053–1209 mm mean annual rainfall), soybean is grown successfully with wheat or fallowing, and SOC concentration is maintained at 0.75% in the 0.30 m soil layer under integrated nutrient management. In view of enhancement and maintenance of OC in many short-term experiments conducted in various agro-climate zones of SAT, it is realized that OC accumulation in soils of the semi-arid ecosystem with suitable cropping and management practices could be substantial especially in cotton–pigeon pea rotation, and thus the discussed crop rotations in each major bio-climatic zone stand for wide acceptance by the SAT farmers.

Keywords: Land use and cropping systems, rainfall, soil carbon, Vertisol and associated soils.

Introduction

SOIL organic carbon (SOC) content is strongly affected by agricultural management[1]. Intensive cultivation without proper management practices has resulted in loss of SOC and nutrients[2]. Appropriate crop rotation can increase or at least maintain the quantity and quality of SOC. Land use and cropping systems influence soil fertility and related soil properties like bulk density, soil organic carbon, total nitrogen and total phosphorus[3]. Enhancement and maintenance of SOC is closely related with cropping systems, management practices and the climate (especially rainfall and temperature). Therefore, SOC changes over a period of time with land use and climate. Among other factors, climate directly or indirectly influences soil carbon content in a given agricultural production system[4].

Soil system attains a quasi-equilibrium stage after accumulation of dry matter and loss of SOC over time depending on land use systems[5]. 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 value (QEV). In this way, the SOC is stabilized to other new QEV of the changed situation in terms of new land use pattern, vegetation cover and management practices. The SOC tends to attain QEV with varying duration of 500–1000 years in a forest system[6,7], 30–50 years in agricultural systems after forest cutting[8], 5–15 years in agricultural systems after forest cutting[9] and 20–50 years under different agricultural systems with cotton for 20 years, with cotton and pigeon pea for 50 years and horticultural system (citrus) for 30 years[5].

Besides organic carbon, inorganic carbon sequestration was earlier addressed as a direct consequence for developing sub-surface sodicity, leading to chemical degradation of the black soils in the SAT[10,11], which would make soils unsuitable for agriculture. Through a carbon transfer process model, it has been suggested that SIC sequestration could be controlled by appropriate management interventions. Carbon sequestration in soils has been reported to be of two types: (i) inorganic C sequestration in the form of pedogenic $CaCO_3$ formation[11] which is considered to be a bane for agriculture, and (ii) organic C sequestration in the form of organic matter from various

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sources and often is a boon to farmers[12]. Knowledge and assessment of changes (positive or negative) in SOC status with time is necessary to evaluate the impact of different management practices[4].

Many reports on variation of SOC and SIC in Indian soils of the Indo-Gangetic Plains (IGP) and black soil regions (BSR) show increase in SOC content at different benchmark spots with concomitant increase in SIC[13]. Sahrawat *et al.*[14] showed that soil samples from sites under lowland rice–rice system had greater SOC sequestration capacity than those from soils under rice in rotation with upland crop or under other arable systems. For sustainable utilization of soil resources, SOC should be maintained at a threshold level, which is nearly 2% for dominant black and associated red soils in the SAT under forest and fallow lands[15], and 0.6% under agricultural crops[5]. Due to unique characteristics of black soils dominated by smectitic minerals, the potential of SOC storage in these soils has been reported to be 2–4% in India and Australia[16,17]. The global decline in SOC due to shifting cultivation, deforestation and intensive agriculture as part of the important land use system increased the level of atmospheric CO_2. The situation is of great concern in semi-arid tropics (SAT) due to long summer with very high temperature (45–48°C) and low amount of crop residues.

The level of SOC has always been a concern in the tropical soils and more so in the relatively dry areas[18]. Maintenance of soil quality in SAT, therefore, requires a concerted effort by the resource managers due to high temperature accompanied by low rainfall. In view of the projected increase of 0.5 m ha areas under SAT in the next 60 years and the reported[19] increase of SAT area in India by 8.45 m ha this will be more challenging to maintain the future soil health. Consolidated report on the influence of cropping systems dominated by a host of agricultural crops is lacking for areas at the sub-country level in BSR representing SAT areas covering 150.9 m ha (ref. 20). Keeping this in view, the present article brings all the datasets available on short-term experiments conducted in the SAT areas with various management interventions as a state of art information to highlight the influence of cropping systems on OC sequestration in SAT soils in general and specifically particular cropping systems that are capable of substantial accumulation of OC in SAT black soils even amidst inorganic C sequestration. Such cropping systems if identified may be recommended as a management protocol for its wide acceptance by the farmers.

Study area

The study area represents BSR of the country with five well pronounced bioclimatic systems such as arid (MAR < 550 mm), semi-arid (dry, 550–850 mm), semi-arid (moist, 850–1000 mm), sub-humid (dry, 1000–1200) and sub-humid (moist > 1200 mm)[15] (Figure 1). The study area covers the states of Rajasthan, Gujarat, Madhya Pradesh, Maharashtra, Andhra Pradesh, Karnataka, Tamil Nadu and a few other states. The general land use pattern shows 80% under agriculture followed by forest, horticulture, wasteland and permanent fallow (Figure 2). Black soils are present not only in the semi-arid tropics but also in arid and sub-humid regions and are generally associated with red soils. In Maharashtra and Madhya Pradesh, red soils occur on the hills and black soils in the valley whereas the scenario is opposite in Tamil Nadu. Some soils have been reported in juxtaposition in Tamil Nadu, Maharashtra and Andhra Pradesh. In India, BSR covers 76.4 m ha (ref. 21) and more than 60% of rainfed agriculture is practiced. The techniques of soil sampling and analytical protocols are described elsewhere[15].

Figure 1. Map showing the locations of benchmark spots in the semi-arid tropics (also see Table 1).

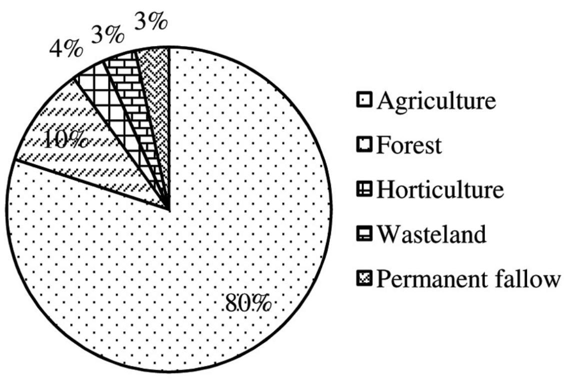

Figure 2. Relative proportions of areas under different types of land use in the study area under semi-arid tropics.

Carbon in SAT soils and climate

A positive relationship of SOC (%) with rainfall ($r = 0.58$) indicates that the soils become enriched with OC with increasing MAR[4,22,23]. The relation between SIC and rainfall is reverse with that of SOC as evidenced by the negative correlation with MAR ranging from 500 to 1500 mm (Figure 3).

Soil carbon and cropping systems

The SOC generally decreases sharply with soil depth in each of the selected land use types (Table 1). In general, SOC varies from 0.30% to 1.05% in the 0–30 cm layer and the soil surface layer is enriched with OC. In BSR, agricultural systems are mainly divided into three major dominant cropping patterns, viz. cotton, soybean and cereal-based systems. Among all bench mark spots, 7 agricultural systems are cotton-based (Typic Haplusterts-4, Sodic Haplusterts-2 and Leptic Haplusterts-1) followed by soybean (Typic Haplusterts-4) (Figure 4). Interestingly most of the soils belong to Typic Haplusterts of the sub-humid (moist) to semi-arid (dry) bioclimatic zone. The cereal-based cropping systems (paddy-3, sorghum-3) were found in six benchmark spots covering all types of soils like Typic Haplusterts, Sodic Haplusterts, Vertic

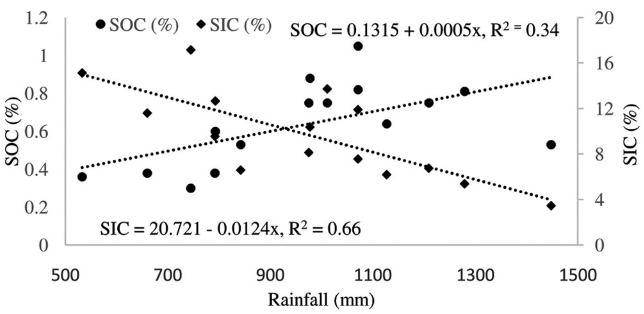

Figure 3. Distribution of soil organic carbon (SOC) in first 30 cm depth and soil inorganic carbon (SIC) in first 150 cm of depth in different benchmark spots showing the retention with mean annual rainfall.

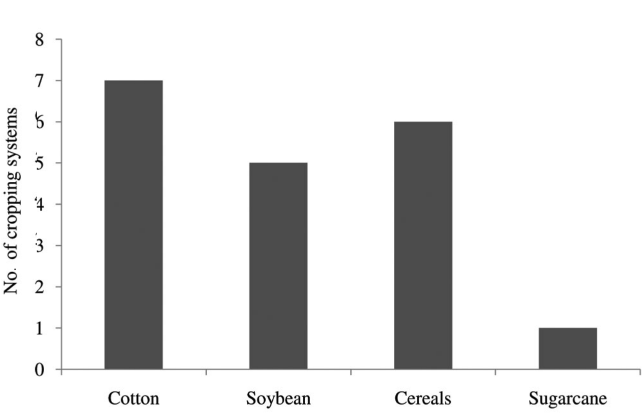

Figure 4. Distribution of cropping systems in black soil region.

Haplustepts, Udic Haplustepts and Gypsic Haplustepts. Sugarcane-based cropping systems were found in one benchmark spot. Ideally, the black soils are grown for cotton which however in recent years are utilized for growing other crops specially soybean.

Cotton-based cultivation is predominant in BSR. Usually cotton along with legume crops (pigeon pea, chickpea) and cereals (wheat, sorghum and pearl millet) are common practice though oilseed crop (groundnut) is also grown (Figure 5 *a*). Cotton–legume systems perform well in terms of SOC sequestration throughout the sub-humid to arid bioclimatic zones in comparison to other cropping practices. An amount of 0.70% SOC in the top 30 cm layer in BSR soil is considered as the threshold level for good agricultural practice. In view of this threshold value, the suggested cropping practice in BSR could be cotton–legume combination or cash-crop cotton alone that can maintain threshold limit of SOC[20].

Soybean-based agricultural practices are the second best after cotton in BSR. Soybean–wheat or sometimes soybean–gram and soybean–chickpea are the options for the farmers. No significant effect of legume (chickpea) in terms of SOC sequestration was found in soybean-based cropping systems (Figure 5 *b*). On an average, all combinations of cropping systems show similar potential to sequester SOC depending on bio-climatic systems.

In paddy-based cropping systems, two practices such as paddy–wheat and paddy–paddy have been observed. As expected paddy–paddy systems sequester more SOC compared to paddy–upland crop-based cropping systems (Figure 5 *c*)[14].

In semi-arid region, sorghum-based cropping systems are the most common cropping system (Figure 5 *d*). Sorghum with leguminous crops (pigeon pea, blackgram, greengram, chickpea, etc.) or two-year rotation of sorghum with cotton is found. Though sorghum–legume combination sequesters good amount of SOC (0.88%) in semi-arid (moist), but the same combination failed to improve SOC sequestration in semi-arid (dry) region. Similarly, in semi-arid (dry) bioclimate, crop rotation of sorghum and cotton in 2-year interval also did not sequester a good amount of SOC (0.38%). In the same bioclimatic region, different management practices caused changes in SOC and SIC level (Table 2). Cotton was the major crop on Asra black soils, and it did not sequester OC. When it was occasionally double cropped with pigeon pea, SOC and SIC values were 0.75% and 1.12%, but when legume was introduced in rotation, SIC decreased to 1.05% and SOC did not change. However, inclusion of green manuring with sun hemp (*Sasanian* sp.) in the system increased SOC level (0.92%) and reduced the SIC (0.64%). In Nimone black soils, the cropping practice was cotton or sugarcane. In sugarcane and cotton systems SOC did not change although SIC was higher in the former. It seems that irrigation with poor quality water might have added additional HCO_3^- to contribute to

Table 1. Distribution of organic and inorganic carbon in soils of drier bioclimatic systems in India

Bio-climatic systems	Soil series	MAR (mm)	Soil taxonomy	State	Land use	Soil carbon (%)	Depth (cm)			
							0–30	0–50	0–100	0–150
Sub-humid (moist)	Kheri	1448	Typic Haplusterts	Madhya Pradesh	Agriculture	SOC	0.53	0.46	0.43	0.44
					(paddy–wheat) (HM)	SIC	3.67	3.62	3.36	3.45
	Boropani	1279	Vertic Haplustepts	Maharashtra	Forest (teak)	SOC	0.81	0.76	–	–
						SIC	4.00	4.48		
	Nabibagh	1209	Typic Haplusterts	Madhya Pradesh	Agriculture	SOC	0.75	0.71	0.66	0.63
					(soybean–wheat) (HM)	SIC	5.50	5.60	5.39	5.38
	Panjri	1127	Typic Haplusterts	Maharashtra	Agriculture	SOC	0.64	0.60	0.54	0.48
					(cotton) (HM)	SIC	5.37	5.78	6.48	6.74
Sub-humid (dry)	Nipani	1071	Typic Haplusterts	Andhra Pradesh	Agriculture	SOC	0.82	0.70	0.55	0.47
					(cotton + pigeon pea) (FM)	SIC	25.30	25.22	25.04	25.01
	Pangidi	1071	Typic Haplusterts	Andhra Pradesh	Agriculture	SOC	1.05	1.03	0.94	–
					(cotton + pigeon pea) (FM)	SIC	6.33	6.35	6.54	
	Sarol	1053	Typic Haplusterts	Madhya Pradesh	Agriculture	SOC	0.54	0.48	0.43	0.37
					(soybean–wheat) (HM)	SIC	6.13	6.28	6.16	6.19
					Agri-horticulture	SOC	0.73	0.64	0.59	0.48
					(soybean–chickpea in mango orchard) (HM)	SIC	5.53	5.62	6.02	6.40
	Linga	1011	Typic Haplusterts	Maharashtra	Agriculture	SOC	0.83	0.74	0.61	0.52
					(soybean–gram/wheat) (FM)	SIC	6.23	5.85	5.80	5.73
					Horticulture (citrus)	SOC	0.75	0.71	0.64	0.54
					(HM)	SIC	6.35	6.40	6.83	7.56
Semi-arid (moist)	Bhatumbra	977	Udic Haplusterts	Karnataka	Agriculture (sorghum +	SOC	0.88	0.87	0.82	–
					pigeon pea/blackgram–chickpea) (FM)	SIC	9.72	9.86	10.10	
	Asra	975	Typic Haplusterts	Maharashtra	Agriculture (cotton/green	SOC	0.75	0.70	0.65	0.58
					gram + pigeon pea) (FM)	SIC	9.35	9.63	10.53	11.90
Semi-arid (dry)	Jhalipura	842	Typic Haplusterts	Rajasthan	Agriculture (paddy–wheat)	SOC	0.53	0.45	0.36	0.30
					(FM)	SIC	9.14	13.19	13.48	13.72
	Paral	793	Sodic Haplusterts	Maharashtra	Agriculture (cotton +	SOC	0.60	0.57	0.53	0.45
					pigeon pea/sorghum) (HM)	SIC	9.91	10.01	10.17	10.38
	Jajapur	792	Vertic Haplustepts	Andhra Pradesh	Agriculture (sorghum/	SOC	0.38	0.35	0.30	0.27
					pigeon pea + greengram) (FM)	SIC	3.44	4.03	6.04	8.13
	Kasireddipalli	764	Sodic Haplusterts	Andhra Pradesh	Agriculture (soybean–	SOC	0.76	0.62	0.53	0.51
					pigeon pea) (HM)	SIC	4.38	5.07	5.69	6.59
	Konheri	745	Vertic Haplustepts	Maharashtra	Agriculture (pigeon pea/	SOC	0.30	0.30	0.27	0.26
					sunflower–sorghum) (FM)	SIC	8.97	9.41	10.00	12.66
	Kalwan	742	Typic Haplusterts	Maharashtra	Agriculture (sugarcane/	SOC	0.90	0.82	0.61	0.46
					sorghum–wheat/chickpea) (FM)	SIC	3.10	3.48	7.25	9.56
	Kovilpatti	660	Gypsic Haplusterts	Tamil Nadu	Agriculture (sorghum/cotton	SOC	0.38	0.37	0.34	–
					2 year rotation) (org)	SIC	4.85	5.50	7.90	
					Wasteland	SOC	0.47	0.48	0.44	–
						SIC	6.69	9.53	9.84	
	Semla	635	Typic Haplusterts	Gujarat	Agriculture (cotton/	SOC	0.76	0.73	0.65	0.59
					groundnut–wheat) (org)	SIC	16.61	17.33	16.59	17.15
	Teligi	632	Sodic Haplusterts	Karnataka	Agriculture (paddy–	SOC	0.80	0.70	0.60	0.53
					paddy) (HM)	SIC	8.00	8.71	9.72	11.60
Arid	Sokhda	533	Leptic Haplusterts	Gujarat	Agriculture (cotton–pearl	SOC	0.36	0.34	0.30	–
					millet) (FM)	SIC	20.16	20.65	20.29	
	Nimone	520	Sodic Haplusterts	Maharashtra	Agriculture (Cotton–wheat/	SOC	0.79	0.73	0.66	0.59
					chickpea) (HM)	SIC	14.27	14.63	14.71	15.14

HM, High management; FM, Farmers' management; Org, Organic farming; paddy (*Oryza sativa*); wheat (*Triticum aestivum*); soybean (*Glycine max*); sunflower (*Helianthus annuus*); sugarcane (*Saccharum officinarum*); sorghum (*Sorghum vulgare*); pigeon pea (*Cajanus cajan*); chickpea (*Cicer arietinum*); pearl millet (*Pennisetum glaucum*); cotton (*Gossypium hirsutum*); blackgram (*Phaseolus aureus*), greengram (*Vigna radiata*). –, Means the soils are shallow (source: Bhattacharyya *et al.*[20]).

Table 2. Relationship between management practices and soil carbon level

Bio-climatic systems	Soil series	Management practices	Soil carbon SOC (0–30 cm) (%)	Soil carbon SIC (0–150 cm) (%)
Cotton system				
Semi-arid (moist)	Asra	Occasional double cropping (cotton–pigeon pea)	0.75	1.12
		Legume always part of rotation	0.75	1.05
		2-year rotation of cotton + pigeon pea–sorghum–chickpea	0.92	0.64
		Green manuring (sunhemp/*Sesbania*)		
Semi-arid (dry)	Paral	Cotton + pigeon pea (sorghum as 3rd intercrop)	0.63	1.19
		Cotton + pigeon pea (green gram as 3rd intercrop)	0.60	1.43
		FYM, fertilizers, seed rate: high		
Semi-arid (dry)	Kovilpatti	2-year rotation of cotton–sorghum	0.38	0.58
		N : P : K = 40 : 20 : 20		
		No FYM		
		Alternate row intercropping of cotton + black gram/maize/sorghum	0.43	0.85
		Manure: FYM@10–12 t ha^{-1} + sheep manure @ 10–12 t ha^{-1}		
		N : P = 90 : 110		
		Black gram residue in the field		
Arid	Sokhda	Cotton + green gram-pearl millet	0.36	2.42
		FYM: 30 cartloads ha^{-1}		
		Green gram as manure		
		2-year rotation of cotton–sesame	0.50	2.60
		N : P : K = adequate		
Cotton/sugarcane system				
Arid	Nimone	Cotton + pigeon pea	0.76	1.71
		Sorghum fodder and *Sesbania* (green manure) in regular rotation		
		FYM and fertilizer: recommended dose (80 : 40 : 40)		
		Water requirement – 1000 to 1200 mm ha^{-1}		
		Sugarcane–wheat/sorghum	0.76	2.64
		N : P = high dose		
		FYM: nil		
		Irrigation: 30 nos per year		
		Water requirement: 2500 to 3000 mm ha^{-1}		
Soybean system				
Sub-humid (moist)	Nabibagh	Soybean–wheat	0.75	0.65
		Seed rate: high		
		Fertilizer: balanced		
		FYM: 3–4 t ha^{-1} (annual)		
		Soybean–wheat	0.65	0.50
		Seed rate: low		
		Fertilizer: low		
Sub-humid (dry)	Sarol	Soybean–wheat	0.54	0.74
		Seed rate: recommended		
		Fertilizer: balanced		
		Weed control: chemical		
		Mechanized cultivation		
		Soybean–wheat/fallow	0.76	0.78
		FYM: regular		
Semi-arid (dry)	Kasireddypalli	Soybean + pigeon pea (4 : 1)	0.76	0.53
		Fertilizers: 40 kg P_2O_5 ha^{-1}		
		Manure: *Glyricidia* as green manure		
		Broad bed furrow (1.05/0.5 m)		
		Kharif fallow–rabi (chickpea–sugarcane) – 2-year rotation	0.48	0.73
		Manure – 10 t ha^{-1} alternate year		
Cereals system				
Semi-arid (dry)	Jhalipura	Soybean–wheat	0.44	0.45
		FYM: 6–8 cartloads ha^{-1} (annual)		
		Fertilizer: N – 150 kg ha^{-1} and P_2O_5 – 120 kg ha^{-1}		
		Paddy–wheat	0.53	1.09
		Fertilizer: N – 230–260 kg ha^{-1} and P_2O_5 – 140 kg ha^{-1}		
		Burning wheat/paddy stubble		
Semi-arid (dry)	Teligi	Monocrop (paddy)	1.03	1.31
		Canal irrigation		
		Monocrop (paddy)	0.80	0.96
		Input: high		

Source: Bhattacharyya *et al.*[20].

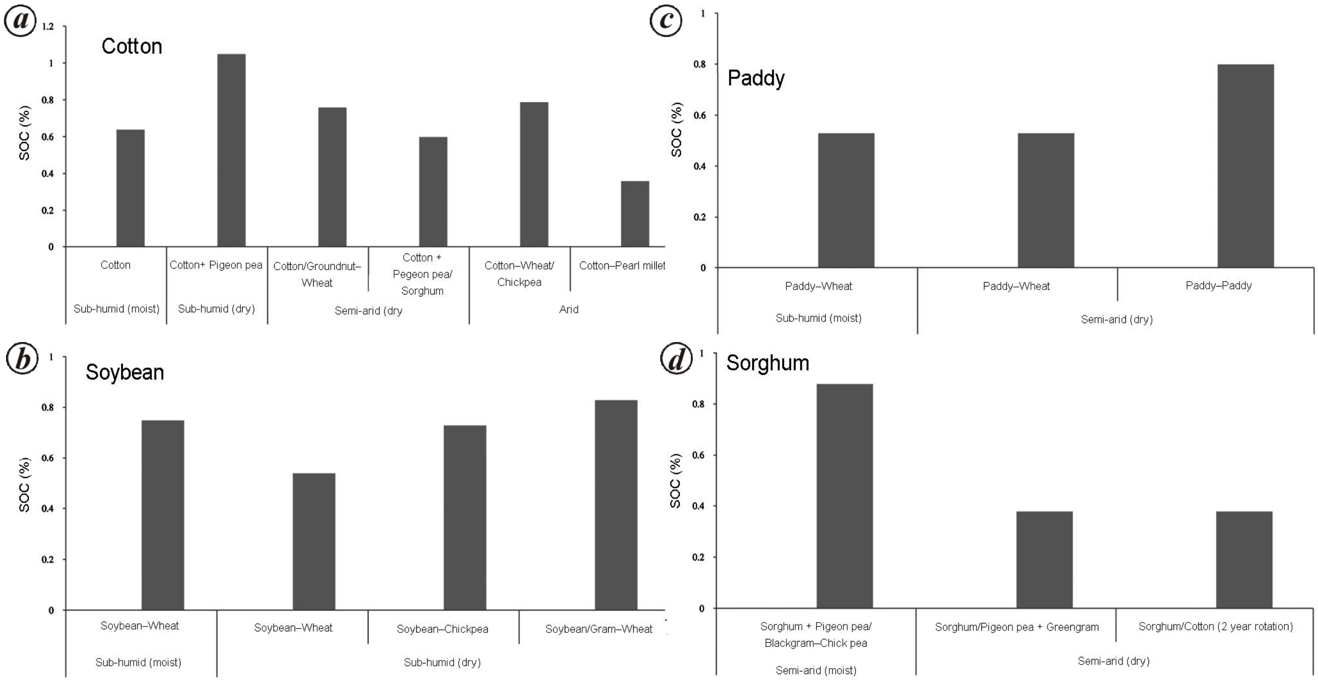

Figure 5. Soil organic carbon stored in first 30 cm depth of soils in different cropping systems in the semi-arid tropics. Source: Bhattacharyya *et al.*[20].

Table 3. Suggested management practices in different cropping systems in three dominant bioclimatic systems in the semi-arid tropics

Bio-climate systems	Cropping systems	Range of MAR (mm)	Management practices followed	Remarks*
Sub-humid	Soybean	1053–1209	Soybean–wheat/fallow Balanced fertilizer FYM	In different bioclimatic areas within given range of MAR for particular suitable cropping systems if suggested management practices should follow properly, soil health in terms of SOC and SIC will be maintained.
Semi-arid	Cotton	660–975	2-year rotation of cotton + pigeon pea–sorghum–chickpea Green manure	
	Paddy	632	Paddy Irrigation Balanced input	
Arid	Cotton	520–533	Cotton + pigeon pea Irrigation Balanced fertilizer and FYM Green manure	

*Minimum threshold of SOC stock for identifying systems in SAT was estimated as 0.03 Pg/m ha (source: Bhattacharyya *et al.*[20]).

SIC. High level of HCO_3^- in irrigation water is common in semi-arid tropics[24].

The influence of dry bioclimatic system on the accumulation of more SIC as $CaCO_3$ in black soils is evidenced. The average value of SIC shows an increasing trend in soil: arid > semi-arid (moist) > semi-arid (dry) > sub-humid (moist) > sub-humid (dry). In BSR, 80% of the land is under agriculture. So, to maintain soil health in terms of the threshold SOC value, proper cropping systems are suggested (Table 3). Studies showed that continuous rotation of cereal–cereal (paddy–wheat) or continuous monocropping of cotton or sorghum decreased SOC. Depending on the soil type and rainfall pattern in the SAT areas, cotton/cereals–legume combination (intercrop or rotation) with proper management interventions appear to be a good management protocol, which could be recommended to farmers for maintaining the threshold limit of SOC.

General observations

SOC stocks show decreasing trend from sub-humid (moist) to arid climate. Though bioclimate directly influences SOC and SIC levels in soils, appropriate cropping systems along with proper management practices can restore and sequester OC in soils. Cotton, soybean and cereals like sorghum, paddy are the common agricultural practices in the SAT areas. Among cereals, paddy–paddy system with irrigation seems to be more beneficial for higher amount of SOC sequestration. In case of cotton, continuous monocropping with the crop can reduce SOC, while crop rotation with legume can increase or maintain SOC. Soybean–wheat or soybean–fallow is a good practice in sub-humid region to restore SOC. The return of crop residues, application of farm yard manure, green manure and balanced fertilizers can increase the SOC content. A package of combined management practices with proper cropping systems is recommended for improvement of soil health (Table 3). In sub-humid bioclimatic zones, soybean–wheat/fallow cropping systems with balanced fertilizers are recommended whereas in semi-arid or arid bioclimates, cotton with pigeon pea or chickpea with balanced nutrient and supplemental irrigation are also recommended in arid bioclimate to maintain threshold limit of SOC in soil.

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