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Carbon sequestration in red and black soils of semi-arid tropical part of India : II. Influence of physical and chemical properties of soils

T. BHATTACHARYYA[1], P. CHANDRAN[1], S.K. RAY[1], D.K. PAL[1], M.V. VENUGOPALAN[1],
C. MANDAL[1], S.P. WANI[2], M.C. MANNA[3] AND V. RAMESH[4]

[1] *National Bureau of Soil Survey & Land Use Planning, Nagpur- 440010, India*
[2] *International Crop Research Institute for Semi-Arid Tropics, Hyderabad- 500059, India*
[3] *Indian Institute of Soil S2cience, Bhopal- 462038, India*
[4] *Central Research Institute for Dryland Agriculture, Hyderabad -500059, India*

Abstract : The physical and chemical properties of the associated red and black soils were related to the content of organic and inorganic form of carbon in soils. Soil organic carbon (SOC) is positively correlated with total clay but soil inorganic carbon (SIC) shows a negative correlation. SOC and bulk density (BD) are negatively correlated. The correlation between SIC and BD in various bioclimatic systems indicate a positive correlation. Direct and indirect relations between SOC, SIC, soil drainage, and BD were observed among 52 benchmark soils from the semi-arid tropics, India.

Additional keywords : *Soil parameters, soil degradation, subsoil sodicity.*

Introduction

The black and the associated red soils (Pal and Deshpande 1987; Pal *et al.* 1989; Bhattacharyya *et al.* 1993 1997, 1999) hold more moisture due to their characteristic physical and chemical properties, that are influenced primarily by smectitic and/or smectite-kaolin interstratified minerals contained in their different soil-size fractions. These soils are usually dominated by clay which commonly ranges between 40 to 60% but it may be as high as 80% especially for the black soils (Dudal 1965; Bhattacharyya *et al.* 2003b). Clay content of black soils is uniformly high to a depth of 50 cm (Dudal 1965). In general, surface soils show low amount of clay and it increases with depth (Butler and Hubble 1977). Although typical black soils (Vertisols) show high clay content in the subsurface, there are reports of Vertisols with sandy textured subsurface (Cocheme and Franquin 1967; Ray and Reddy 1997). In contrast, the red soils (Alfisols) show an increasing trend of clay down the depth followed by a decrease. The dominant mineral in clay fractions of the Vertisols is smectite (Pal and Deshpande 1987). It has been stated that Vertisols showing typical vertic properties can only be the function of smectite content in the cla (Bhattacharyya et al. 1997) with a minimum threshold valu of 20% (Shirsath *et al.* 2000). The presence of dominatin amount of clay fractions associated with smectite offer mor surface charge density (SCD) which is an important pre requisite of increasing SOC in soils (Poonia and Niederbudd 1990; Bhattacharyya *et al.* 2000, 2005).

Many morphological properties (Soil Surve Division Staff, 1995) may be modified when the soils are pu to use. The morphological features are often related wit the physical, chemical and mineralogical properties of soil It is likely that discussion on morphological properties wil involve some physical and chemical parameters. This will i reality show the interaction of various soil forming factor that are finally manifested in some soil properties maintain the soil health by sequestering carbon.

An important physical property which largel determines the stock of both organic and inorganic form o carbon is the bulk density (BD). The BD of Vertisols varie greatly because of their swelling and shrinking nature tha changes with moisture content. BD has been reported t vary from 1.0 to 2.0 Mg m-3 depending on the moisture content. BD usually tends to increase with depth, due to compression caused by overburden weight. It has been observed that a volume change of nearly 60% occurs when a dry Vertisol is saturated with water (Rao *et al.* 1978).

Due to relatively lower values of clay and/or extractable bases and exchangeable sodium percentage (ESP), the hydraulic conductivity (HC) of Vertisols show initial higher values in the surface horizons followed by reduction in the subsurface horizons. It has been reported that HC values decreased from 7.6 to 3.4 cm/hr for the first one hour to 0.4 cm/hr over 1 to 2 hr and further to 0.02 cm/hr after 144 hr when soils are saturated. It has also been reported that hydraulic conductivity gets impaired in Vertisols with increasing content of pedogenic $CaCO_3$ and concomitant development of ESP (Pal *et al.* 2000, 2003; Srivastava et al., 2002; Kadu *et al.* 2003). It, therefore, appears that soils sequestering more inorganic carbon will have highly impaired hydraulic conductivity.

A huge data base on the physical and chemical properties of black and associated red soils are available in relation to their organic and inorganic carbon sequestration. In view of the above, nearly 52 pedons were selected from SAT, India to study the influence of physical and chemical properties on carbon sequestration in Vertisols and their associated soils.

Materials and Methods

Materials

The soils and their other details have been explained earlier (Bhattacharya et al., 2007, this issue).

Methods

The particle size distribution was determined by the international pipette method after the removal of cementing agents (Jackson, 1979). Sand (2000-50 μm), silt (50-2 μm), total clay (<2 μm) and fine clay (<0.2 μm) fractions were separated according to the procedure of Jackson (1979). Bulk density was determined by field moist method using core samples (diameter 50 mm) of known volume (100 ml) ((McIntyre 1974; Klute 1986).

The water dispersible clay was determined by taking 10 g of soil and then shaking on an end to end shaker for 8 hours. Suspension aliquots were drawn by following the international pipette method (USDA 1972). Hydraulic conductivity (HC) was measured by taking 200 g of soil, uniformly tapped and saturated overnight. It was measured by taking an hourly observation till three constant observations were obtained. It was measured in cm/hr (Richard 1954). The soil organic carbon (SOC) was determined by the modified Walkley and Black rapid titration procedure (Walkley and Black 1934; Jackson 1973). For soil inorganic carbon (SIC), $CaCO_3$ content value was used. The $CaCO_3$ content in soils was determined by standard acid-base titration method (Jackson 1973).

Results and Discussion

Particle-size distribution in soils vis-à-vis carbon sequestration

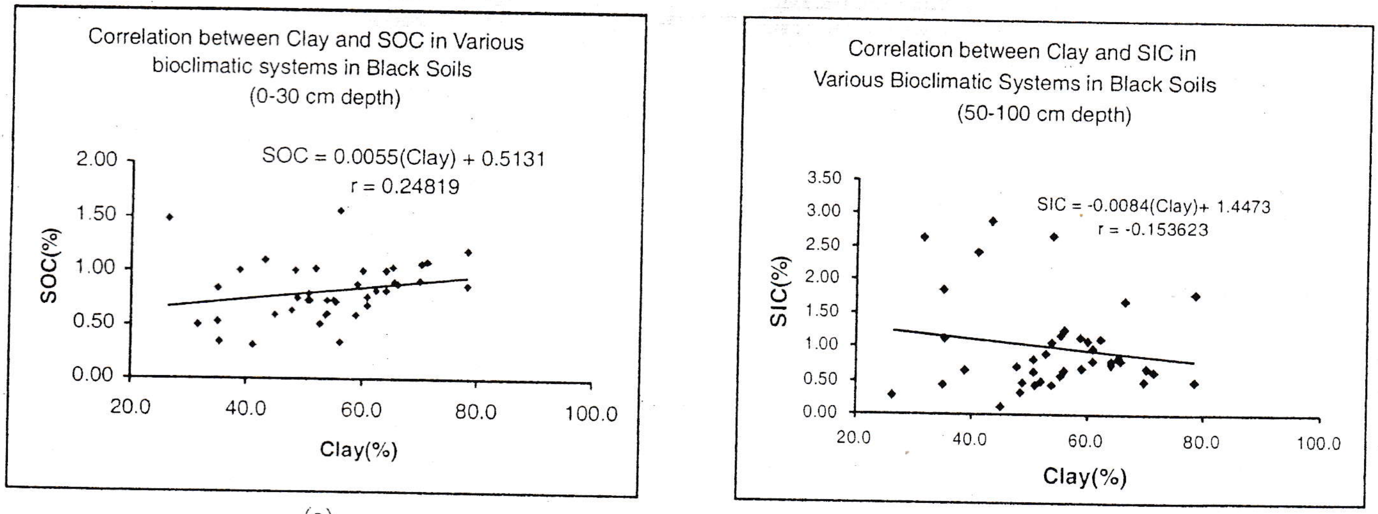
The soils of the present study are Vertisols and their intergrades. Logically the sand, silt and clay content should be within the range to qualify them as Vertisols (Soil Survey Staff 1999). However, depending on geological formation and the bioclimatic regions the content of sand, silt and clay vary as shown in table 1. The clay contents vary between a low of 30% in arid system to as high as 82% in sub-humid (dry) and 79% in semi-arid (dry) system.

The seat of charge in soil mostly lies in clays and fine silt fractions. Therefore, both the physical and chemical activities of soils are expected to be controlled by clay (both total and fine clay) and silt with the contribution of former being more. The major emphasis being the sequestration of carbon in soils, it seems prudent to find the relation between organic carbon (SOC) and inorganic carbon in soils (SIC) with the reactive components namely fine clay (<0.2μ), clay (<2 μm), and clay+silt (<50 μ). SOC is positively correlated with these reactive components while SIC shows a negative correlation. For brevity the relation between SOC and SIC with clay is shown (Fig. 1a,b). When the relation with SOC and three different combination of substrate was compared (0-30 cm depth of soils) highest correlation was found in SOC vs fine clay (<0.2μ) (Table 2) followed by SOC vs total

Table 1. Range of sand, silt and clay in Black and Red soils in different bioclimatic systems

Bioclimate	pH (1:2 water)	Sand (2-0.05 mm)	Silt (0.05-0.002 mm)	Clay (<0.002 mm)
Black Soils				
Sub-humid (moist)	7.1 - 8.1	0.3 - 16.8	31.0 - 46	47 - 68
Sub-humid (dry)	7.4 - 8.0	0.2 - 6.4	22.6 - 44.0	49 - 82
Semi-arid (moist)	7.8 - 8.2	0.8 - 5.6	26 - 36	60 - 73
Semi-arid (dry)	7.8 - 9.2	0.5 - 34	17 - 44	41 - 79
Arid	7.9 - 9.7	4 - 28	26 - 40	30 - 69
Red Soils				
Sub-humid (moist)	5.1 - 5.6	6 - 10	37 - 40	40 - 55
		49 - 80	12-30	8-33
Semi-arid (moist)	4.4 - 7.4	50 - 62	7 - 20	27 - 65
Semi-arid (dry)	5.2 - 8.1	35 - 76	4 - 19	14 - 53

[1] Basalt; [2] Sandstone; [3] Granite-gneiss



(a) (b)

Fig. 1. Correlation between soil organic carbon (SOC) and soil inorganic carbon (SIC) with clay as the reactive components in black soils of SAT (a) SOC (0-30 cm depth) (b) SIC (50-100 cm depth).

clay (<2 μm). This might be due to higher surface area and charges of fine clay than clay and silt. Recently such high correlation values have been reported while comparing SOC sequestration and clay content in Mollisols of Madhya Pradesh (Bhattacharyya *et al.* 2005, 2006). Table 2 shows the correlation coefficient values of CaCO3 (SIC) and different fractions of soils as substrate. Generally a negative correlation indicates that perhaps more amount of clay, and silt will effect a reduction in SIC. Interestingly most of the shrink-swell soils have high clay and silt and these soils are calcareous (Pal *et al.* 2000; Srivastava et al. 2002). Since this information is in contrast with the earlier statement. It seems that SIC accumulation in these soils is not as intimately linked with substrate as observed in case of SOC.

Bulk density of soils vis-à-vis carbon sequestration

It has been observed that SOC and SIC vary depending on rainfall and the atmospheric temperature (Jenny and

Table 2. Correlation coefficient between SOC and SIC and different fractions of black soils (0-30 cm soil depth)

Bioclimatic system	r values	
	With SOC	With SIC
Fine clay (<0.2 μm)		
Sub-humid (moist)	0.29	-0.41
Sub-humid (dry)	0.14	-0.87*
Semi-arid (moist)	0.60	-0.98*
Semi-arid (dry)	-0.04	0.27
Arid	0.94*	-0.66
Total clay (<2 μ m)		
Sub-humid (moist)	0.64	-0.05
Sub-humid (dry)	0.20	-0.86*
Semi-arid (moist)	0.62	-0.93*
Semi-arid (dry)	-0.11	0.43
Arid	0.85	-0.74
Total clay (<2 μm) + Silt (0.2 - 2 μ m)		
Sub-humid (moist)	0.55	0.65
Sub-humid (dry)	-0.47	-0.86*
Semi-arid (moist)	-0.02	-0.36
Semi-arid (dry)	-0.21	0.39
Arid	0.87	-0.58

* Significant at 5% level.

Raychaudhuri 1960; Bhattacharyya *et al.* 2000; Pal *et al.* 2000). Since SOC and SIC influence BD, therefore, BD is supposed to change in different bioclimatic systems. BD decreases from sub-humid, moist (SH,m) to sub-humid, dry (SH,d) system. In the drier tract (semi-arid,dry, and Arid) the values remain 1.5 Mg dm-3. BD of the black soils decreases as SOC content increases in first 30 cm depth of soil. For red soils, BD is low in the SH(m) bioclimatic system. These soils are rich in organic matter and are under forest. These landscapes at the upper riches support Mollisols (Bhattacharyya et al. 2006) which are in association with red (Alfisols) and black soils (Vertisols) (Bhattacharyya *et al.* 2005). In general, BD increases in soils in the drier tract of SAT (Table 3). For SIC this relation is reverse for the black soils. This observation finds support from the fact that SOC makes the soils lighter and SIC heavier. Red soils are, by and large, noncalcareous.

If $CaCO_3$ content is expected to increase the BD, then the coarser fragments in black soils, present primarily as Ca-concretions (and responsible for high $CaCO_3$ content), should also increase the BD of soils. Interestingly, a negative correlation is found between coarse fragments and BD in SH (m), SH(d) and SA (d) climate with SA (m) and soils of arid climates are however the exceptions. Increase in relative proportion of coarse fragments increase the pore space effecting decrease in BD values (Fig. 2). This is in sharp contrast with earlier observations made with $CaCO_3$ content and BD values. $CaCO_3$, as cementing agent, helps in binding soil particles and causes a greater cohesion between soil particles. This leads to greater compaction that increases BD values. It seems, therefore, that the $CaCO_3$ present as powdery lime and $CaCO_3$ present as calcium concretions will have opposite effect on BD of the soils. Interestingly both the form of $CaCO_3$ (lime and *conca*) will increase the inorganic carbon concentration in soils. Irrespective of the physical form of $CaCO_3$ its content will, however, decide high or low degree of SIC stock. The range of BD, SOC, SIC and coarse fragments are shown in table 3. Tables 4 and 5 show the correlation between SOC and SIC with BD.

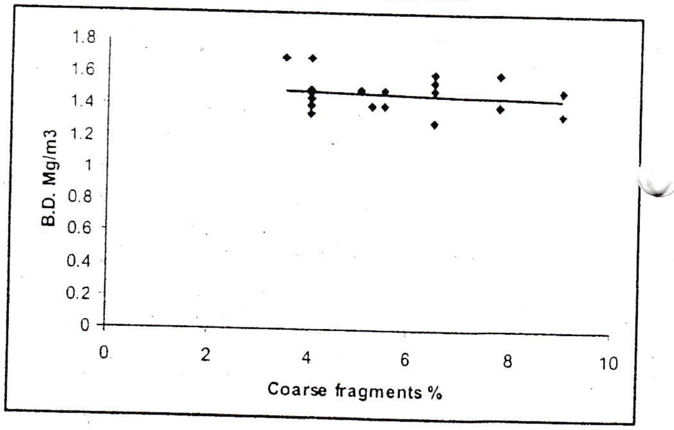


Fig. 2. Correlation between coarse fragments & bulk density (0-30 cm) in various bioclimatic systems.

It seems therefore that organic carbon sequestration in soils will decrease the BD (Table 3); and this SOC built-up may be more pronounced in the higher rainfall area. Inorganic carbon sequestration, through the formation of powdery lime will increase BD; with time this powdery lime will form $CaCO_3$ nodules to decrease BD.

Table 3. Bulk density, soil organic carbon (SOC) and soil inorganic carbon content (SIC) under different bioclimatic systems

	BD Mg/m3		Carbon		Coarse Fragments v/v	
	0-30 cm	50-100 cm1	SOC (0-30 cm) (%)	SIC (50-100 cm) (%)	0-30 cm	50-100 cm
Black Soils						
SH (m)	1.40	1.50	0.7	0.6	4	4
SH (d)	1.39	1.42	0.9	0.8	5	5
SA (m)	1.50	1.53	0.9	1.1	3	3
SA (d)	1.50	1.55	0.8	1.2	6	5
A	1.35	1.58	0.6	2.4	9	9
Red Soils						
SH (m)	1.47	1.47	2.1	nil	nil	nil
SA (m)	1.70	1.55	1.0	nil	nil	nil
SA (d)	1.50	1.60	1.0	0.1	nil	nil

Soil drainage vis-à-vis carbon sequestration

Hydraulic conductivity (HC) measures the drainage of the Vertisols. At the beginning of the wet season these soils show good drainage due to the presence of cracks. With the passage of time drainage is impeded especially in the subsurface horizons due to compaction. It has been found that soils showing better drainage (high HC) contain more SOC (Fig. 3). This is because organic matter (SOC) increases soil drainage which is reflected by high HC. It has been reported that organic matter can dissolute native $CaCO_3$ and decrease the soil pH (Bhattacharyya et al. 2000, 2004; Bhattacharyya and Pal 2003) which in turn decreases the ESP and increase the HC of soils (Balpande *et al.* 1996).

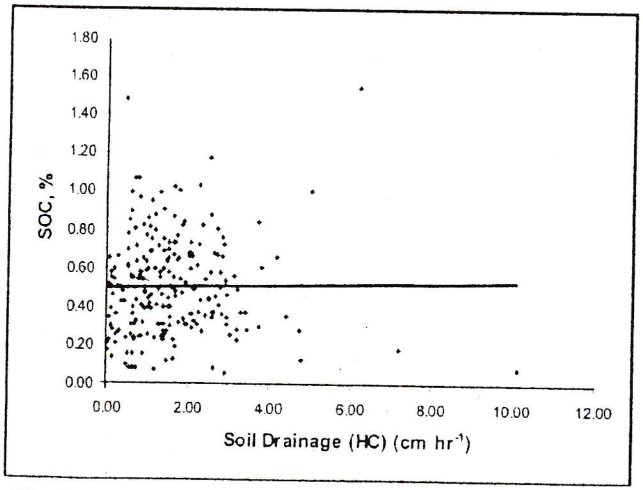


Fig. 3. Relation between soil drainage and SOC in various bioclimatic systems in black soils.

Soil drainage is improved with the decrease in $CaCO_3$ (SIC) content in SH(m), SH(d) and SA(m) bioclimatic systems (Fig. 4). However, a reverse trend was observed in the drier bioclimatic systems viz. SA(d) and arid (Figs. 5 and 6). Earlier Pal *et al.* (2000) reported two different sources of $CaCO_3$ (SIC) in these soils namely pedogenic carbonates (PC) and non-pedogenic carbonates (NPC). In the wetter bioclimatic system the contribution of NPC towards SIC is less than the drier tracts (Pal *et al.* 2000; Srivastava et al. 2002). An improved drainage condition is possible due to the reduction in ESP in soils (Fig. 7). Again reduction in ESP occurs when $CaCO_3$ is dissolved either as the precipitated Ca ions from $CaCO_3$ or are replenished by natural modifiers like gypsum or zeolites (Pal *et al.* 2006). In the wetter bioclimates, $CaCO_3$ present as powdery lime, is dissolved due to decrease in pH effected by the increase in SOC. This happens by C-transfer model (Bhattacharyya et al. 2004).

Increase in SIC, interestingly, improves the drainage condition of the soils of SA(d) and arid bioclimatic systems (Figs. 5 and 6). Improvement of drainage is caused by more pore (macro) spaces which is again controlled by coarser fractions (<2 mm and >2mm) of the soils. Interestingly soils in the drier bioclimatic systems contain more sand (Table 1) and coarser fragments (Table 3); the latter is mostly in the form of calcium carbonate nodules.

This observation thus brings forth a fact that it is the form (quality) of $CaCO_3$ (SIC) which will dictate the

Table 4. Correlation between SOC vs BD in first 30 cm depth of black soil in SAT, India

Bioclimate (MAR)	Regression Equation	Correlation Coefficient (r)	No. of samples
Subhumid moist (>1100 mm)	BD = - 1.0 (SOC) + 2.12	- 0.54	5
Subhumid dry (1100-1000 mm)	BD = -0.4074(SOC) + 1.8519	- 0.55	4
Semi-arid moist (1000-850 mm)	BD = -0.3874(SOC) + 1.7757	- 0.48	9
Semi-arid dry (850-550 mm)	BD = -0.0281(SOC) + 1.496	- 0.050	16
Arid (<550 mm)	BD = -0.35(SOC) + 1.635	- 0.7182	4
All bioclimatic systems	BD = -0.0499(SOC) + 1.508	- 0.0866	38

Table 5. Correlation between SIC vs BD in first 50-100 cm depth of black soil in SAT, India

Bioclimate (MAR)	Regression Equation	Correlation Coefficient (r)	No. of samples
Subhumid moist (>1100 mm)	BD = 0.0449(SIC) + 1.4383	+0.1568	4
Subhumid dry (1100-1000 mm)	BD = 0.2295(SIC) + 1.2425	+0.3569	6
Semi-arid moist (1000-850 mm)	BD = -0.0601(SIC) + 1.5483	- 0.1220	4
Semi-arid dry (850-550 mm)	BD = -0.0992(SIC) + 1.6255	- 0.3160	16
Arid (<550 mm)	BD = 0.2204(SIC) + 0.9803	0.5521	4
All bioclimatic systems	BD = 0.0261(SIC) + 1.4507	0.1393	34

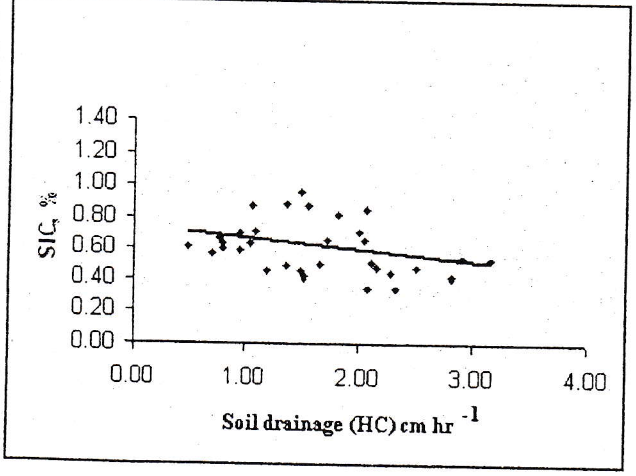


Fig. 4. Relation between soil drainage and SIC in black soils of sub-humid moist bioclimate.

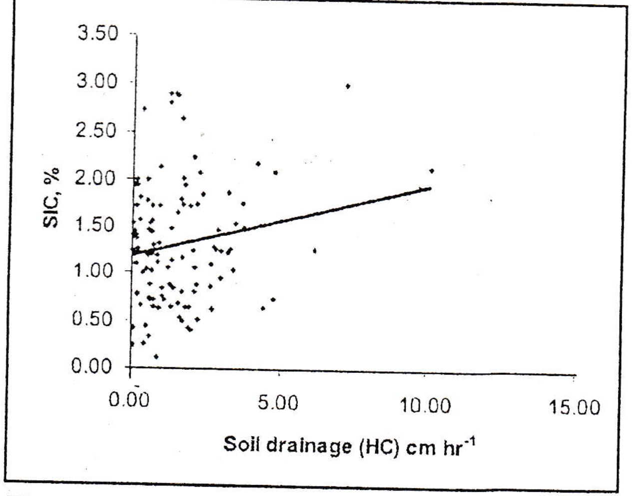


Fig. 5. Relation between soil drainage and SIC in black soils of semi-arid bioclimate

physical soil conditions (viz. drainage) of these soils. Loose powdery lime in the soils of the wetter bioclimate will be subject to dissolution due to increase in SOC and decrease in soil pH as described earlier. This will effect reduction in ESP to enhance drainage. However, in drier regions the formation of more amount of $CaCO_3$ nodules due to rapid formation of powdery lime will cause higher subsoil sodicity that impairs the hydraulic properties. Thus, total amount of $CaCO_3$ can not be used as an indicator for soil drainage, without the knowledge of

Discussion

The soil properties viz. organic and inorganic carbon contents are directly governed by climate (Fig. 8). Relatively dry climate (aridity and semi-aridity) causes more calcium carbonate to form. High temperature in these climatic systems causes more organic carbon from soils to oxidize. In

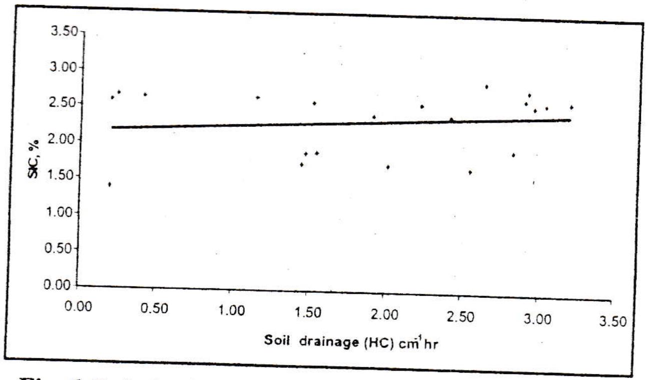


Fig. 6. Relation between soil drainage and SIC in black soils of Arid bioclimate.

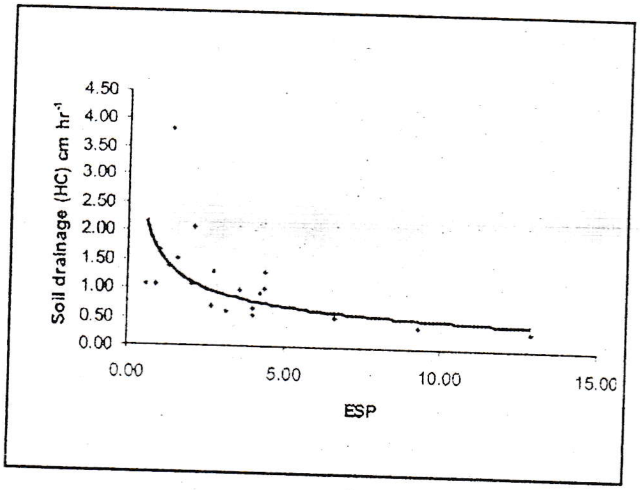


Fig. 7. Relation between ESP and soil drainage in black soils of Arid bioclimate.

and less organic carbon. The soil properties are influenced indirectly by the climatic adversity as depicted in figure 8. Under natural conditions formation of secondary carbonates will influence soil properties viz. exchangeable sodium, pH, BD, soil porosity, soil drainage and cause low SOC sequestration. It may be pointed out that many soils (in arid and semi-arid climates) show higher SOC and low SIC sequestration during the course of the present investigation. This shows the influence of management interventions in controlling soil properties to affect high SOC and low SIC sequestration.

Conclusions

Physical and chemical properties of the associated red and black soils are related to the carbon sequestration. The reactive components in soils in the form of clay and silt control the sequestration of organic form of carbon. Inorgani carbon is apparently not related with these soils particle Bulk density indicates the content of organic and inorgani form of carbon. The study shows that it is the quality (CaCO3, rather than its content, will dictate soil drainage.. seems soil drainage and BD are important soil propertie which can be linked with the sequestration of SOC and SI particularly in shrink-swell soils.

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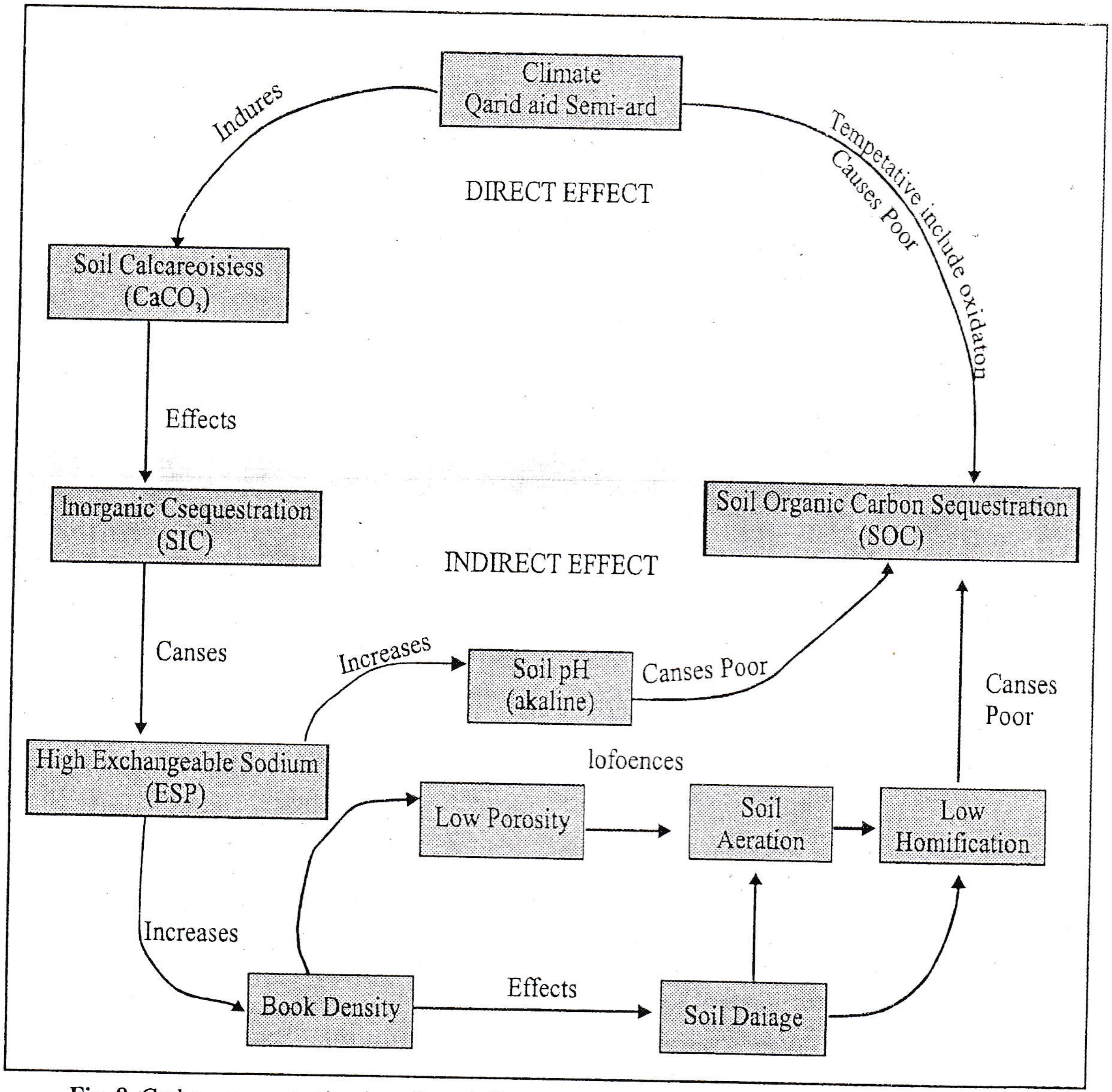

Fig. 8. Carbon sequestration in soils as influenced by soil properties under natural conditions.

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