Agropedology 2007, *17 (1)*, 1-15

Carbon sequestration in red and black soils of semi-arid tropical part of India :

I. Influence of morphological properties

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 Science, Bhopal-462038, India*

[4] *Central Research Institute for Dryland Agriculture, Hyderabad-500059, India*

Abstract : Colour, roots, coarse fragments, nodules, effervescence, and slickensides of red and black soils from different bioclimatic systems are described in relation to their organic and inorganic carbon content. Soils under high management (HM) are darker in colour and contain more soil organic carbon (SOC) than those under low management (LM). Higher concentration of roots in soils corresponds with low content of $CaCO_3$ as manifested by dilute HCl in the field.

Black soils under HM show slickensides at lower depth. With the decrease in mean annual rainfall (MAR), the depth of occurrence of slickensides appear at 60 cm in sub-humid (moist) to 30 cm in semi-arid (dry) bioclimate. Management interventions including irrigation in drier tracts push slickensides further down the depth. The formation of sodic Vertisols (Sodic Haplusterts) indicates poor organic carbon accumulation but a very high inorganic carbon sequestration in soils of the relatively dry bioclimatic system. Morphological properties used for grouping soils as per Soil Taxonomy thus can indicate the level of carbon sequestration in soils.

Additional keywords : *Bioclimate, morphological properties, organic carbon, inorganic carbon*

Introduction

The study on soil morphology provides a scope to know more about the external features and structures of soil body in a profile which may be the manifestations of pedogenic processes in soils. Generally these properties are colour, texture, structure, horizonation, consistence, mottles, roots, coarser fragments, other features such as concretions, depth and width of cracks, presence of slickensides and reaction with dilute HCl. Many morphological properties (Soil Division Staff, 2000) may be modified when the soils are put to use. The morphological features are often related to the physical, chemical and mineralogical properties of soils. It is likely that discussion on morphological properties will involve some physical and chemical parameters. This will in reality show the interaction of various soil forming factors that are finally manifested in some soil properties help to maintain the soil health by sequestering carbon.

Studies on forest soils (Alfisols) of Eastern India (Saikh *et al.* 1998) indicate that soil organic carbon (SOC) content sharply declined when they were put to cultivation. Reduction of SOC level is significant even within 5 to 15 years of cultivation. These authors have hypothesized that irrespective of the initial levels of OC the red soils exhibited a tendency to reach the quasi-equilibrium value of 1 to 2% SOC. Since such studies are limited to a specific geographical region, to develop a generalized view about carbon-carrying capacity of the soils, extrapolation of their results may not be advisable, because quality of soil substrate and its surface

Table 1. Benchmark spots and their site characteristics in sub-humid (moist) bioclimatic system

Serial No.	District/State	Series	System	MAR (mm)
BLACK SOILS				
1.	Jabalpur/Madhya Pradesh	Kheri	Agriculture(HM)/ *Paddy-Wheat*	1448
2.	Jabalpur/Madhya Pradesh	Kheri 1	Agriculture(LM)/*Soybean/Paddy-wheat*	1448
3.	Nagpur/Maharashtra	Boripani	Forest/ *(Teak)*	1279
4.	Bhopal/ Madhya Pradesh	Nabibagh	Agriculture(HM)/ *Soybean-Wheat*	1209
5.	Bhopal/ Madhya Pradesh	Nabibagh	Agriculture(FM) /*Soybean-Wheat*	1209
6.	Nagpur/Maharashtra	Panjri	Agriculture(HM) /*Cotton*	1127
RED SOILS				
1.	Dindori/ Madhya Pradesh	Dadarghugri	Agriculture(LM) /*Maize/Mustard*	1420
2.	Dindori/ Madhya Pradesh	Dadarghugri	Forest *(Teak)*	1420
3.	Umeria/ Madhya Pradesh	Karkeli	Forest *(Sal)*	1352
4.	Umeria/ Madhya Pradesh	Karkeli 1	Agriculure(LM) /*Minor millet/Sweet Potato*	1352

charge density (SCD) vary at places. An increase in SOC enhances the SCD of soils and also the ratio of internal/external exchange sites (Poonia and Niederbudde 1990).

The dominant soils in the semi-arid tropics (SAT) are black soils (Vertisols and their intergrades, with some inclusions of Entisols of the hills) and associated red soils. These soils are dominated by smectites (Bhattacharyya et al. 1993; Pal and Deshpande, 1987a,b; Pal *et al.* 1989, 2000). Presence of smectite mineral also increases the SCD of soils which offer greater scope for carbon sequestration (Bhattacharyya et al., 2005, 2006). Black soils, therefore, may reach a higher quasi-equilibrium value (>2%) compared to red soils dominated by kaolins with low SCD.

Bhattacharyya and Pal (1998) reported 2-5% of SOC of black soils in the surface soils from Madhya Pradesh. Recently, Dalal and Conter (2000) and Naitam and Bhattacharyya (2004) have also indicated the scope of sequestering higher SOC content in the shrink-swell soils of Australia and India, respectively. To find out the sufficient and deficient zones for SOC in different agro-ecoregions of India, Velayutham *et al.* (2000) adopted the lower limit of the quasi-equilibrium value of 1%. In view of higher SCD of the dominant soils of the SAT, considering a quasi-equilibrium value of 2% of SOC in the first 30 cm depth of soils, the potential SOC stock is worked out as 10.5 Pg for an area of 116.4 m ha. This value is more than 3 times of the existing SOC stock of SAT (Bhattacharyya et al. 2000), suggesting that the SAT area of Indian subcontinent could be fruitfully prioritized for carbon sequestration.

Keeping in view of these points a project was undertaken to identify systems for carbon sequestration and increased productivity in semi-arid tropical environments with the black soils and the associated red soils. The present paper is the first in the series which finds relation between carbon sequestration in soils with their selected morphological properties.

Materials and Methods

Study area

The study area was chosen in the SAT (AESRs 5.1, 5.2, 6.1, 6.2, 6.3, 7.2, 8.1, 8.2) 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 m ha area in India. During the selection of the soil-sites, the specific bioclimatic systems viz sub-humid (moist) (>1100 mm mean annual rainfall, MAR), sub-humid (dry) (1100-1000 mm MAR), semi-arid (moist) (1000-850 mm MAR), semi-arid (dry) (850-550 mm MAR), arid (<550 mm MAR) were identified.

For the present study, a total of 28 Benchmark (BM) spots were selected which included 52 pedon sites

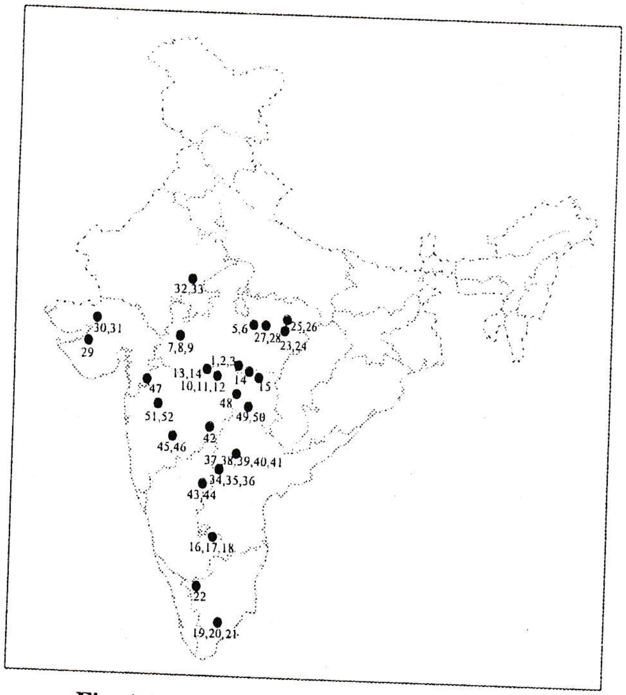

Fig. 1. Benchmark spots in the study area.

Table 2. Benchmark spots and their site characteristics in sub-humid (dry) bioclimatic system

Serial No.	District/State	Series	System	MAR (mm)
BLACK SOILS				
1.	Adilabad/Andhra Pradesh	Nipani	Agriculture(FM)/*Cotton+Pigeonpea*	1071
2.	Adilabad/Andhra Pradesh	Pangidi	Agriculture(FM1)/*Cotton+Pigeonpea*	1071
3.	Adilabad/Andhra Pradesh	Pangidi 1	Agriculture(ITDA)/*Soybean*	1071
4.	Indore/ Madhya Pradesh	Sarol	Agriculture(HM)/*Soybean-Wheat*	1053
5.	Indore/ Madhya Pradesh	Sarol	Agriculture(FM)/*Soybean-Wheat*	1053
6.	Indore/ Madhya Pradesh	Sarol	Agri-horticulture(HM)/*Soybean-Gram in mango orchard*	1053
7.	Nagpur/Maharashtra	Linga	Horticulture(HM)/*Citrus*	1011
8.	Nagpur/Maharashtra	Linga	Horticulture(LM)/*Citrus*	1011
9.	Nagpur/Maharashtra	Linga	Agriculture(FM)/*Soybean-Gram/Wheat*	1011

(Bhattacharyya *et al.* 2004). The BM spots were selected as each soil covers extensive area in the landscape and the monitoring the benchmark sites would be easier. Besides, the BM soils were chosen in such a way that their substrate quality remained similar. Therefore, the study area and the soil series representing Vertisols and the vertic intergrades of other soils were selected. Some associated black soils under sparse forest were chosen as control. In addition to this, some red soils from both cultivated and forest (as control) systems were selected for the study (Fig. 1). These controls have been taken to compare the substrate quality *vis-à-vis* carbon storage capacity of black soils with the red soils.

A total of 5 systems viz. agriculture (24 BM spots), horticulture (1 BM spot), forest (3 BM spots), wasteland and permanent fallow (1 BM spot) were selected. The BM spots alongwith location and dominant cropping system are given in tables 1 to 5. The soil series were selected in such a way that in an agricultural system under a particular cropping pattern, two representative pedons (under the same soil series), representing low or farmers' management (LM or FM) and high management (HM) were studied. The level of management describing high and low is indicated in table 6.

Methods

The profiles were examined following standard methods (Soil Survey Division Staff, 1995). The concept of bioclimatic system was adopted from Bhattacharjee *et al.* (1982). The soils were classified following Soil Taxonomy (Soil Survey Staff, 2003). The morphological properties have been described by standard procedures (AIS&LUS, 1970; Soil Survey Division Staff 1995; Soil Survey Staff 1999, 2003). The SOC was determined following the method of Walkley and Black (1934). The soil inorganic carbon (SIC) was calculated as 12 percent of $CaCO_3$. The $CaCO_3$ in soils was determined following acid-base titration (Jackson 1973).

Table 3. Benchmark spots and their site characteristics in semi-arid (moist) bioclimatic system

Serial No.	District/State	Series	System	MAR (mm)
BLACK SOILS				
1.	Bidar/Karnataka	Bhatumbra	Agriculture(FM)/*Sorghum+Pigeonpea/ Blackgram-Chick pea*	977
2.	Amravati/Maharashtra	Asra	Agriculture(FM)/*Cotton/Green gram+Pigeonpea*	975
3.	Amravati/Maharashtra	Asra	Agriculture(FM)/*Soybean+Pigeonpea*	975
4.	Amravati/Maharashtra	Asra	Agriculture(HM)/*Cotton+Pigeonpea/Soybean-Gram*	975
RED SOILS				
1.	Bangalore/Karnataka	Vijaypura	Agriculture(FM)/*Finger millets*	924
2.	Bangalore/Karnataka	Vijaypura 1	Agriculture/*Finger millet/Pigeonpea/ Red gram/Groundnut*	924
3.	Bangalore/Karnataka	Vijaypura 1	Agriculture(HM)/*Finger millet*	924

Results and Discussion

The discussion on various morphological properties has been presented for all the pedons on the basis of bioclimatic systems for the black soils and red soils separately.

Soil Colour vis-à-vis SOC and SIC

Black Soils : In the sub-humid (moist) bioclimate zone the soils are in general very dark grayish brown to dark grayish brown. The Nabibagh soils are darker (10YR 3/2) under high management (HM) than the soils under farmers' management (FM) (10YR 3.5/2 to 10YR 4/2). This is also reflected by higher SOC content in HM than FM (Table 7). Darker colour (10YR 3/2) in Boripani surface soils also matches with relatively higher soil organic matter (9-10 g/kg). Although such observations indicate a strong degree of correlation between soil colour and SOC, such interpretation may be accepted based on large number of observations (Bhattacharjee 1997). Interestingly, similar dark colour in Kheri soils in both HM and Low Management (LM) does not, however, indicate a direct relation with colour and organic carbon (Table 7).

In the sub-humid (dry) ecosystem, the soil colour ranges from very dark grayish brown (10YR 3/2) to dark grayish brown (10YR 4/2). The soil with darker chroma (10YR 3/2) in Linga soils contain relatively high SOC than soils in sub-humid (moist) bioclimatic system (Table 7).

In the semi-arid (dry) bioclimate the range of colour is dominantly very dark grayish brown to dark grayish brown with Paral and Teligi soils being exceptions. Lower chroma values in Teligi soils indicate presence of redoximorphic features such as iron and manganese mottles as characteristics of gleyed horizon. Incidentally mottles were not identified during profile examination in the field, although these soils are being continuously cultivated for paddy under bunded condition for more than a decade. Presence of redoximorphic features as mottles or gleyed horizons or if redoximorphic features are not present but 50% or more of the soil matrix have chroma of 1 or less of the profile, then the soil qualifies for aquic moisture regime (Soil Survey Staff, 1999). Identification of aquic moisture regime might justify grouping these soils under great group level as *Aquerts*. However, lack of data on redoximorphic features led to actually classifying these soils as *Usterts*. It has been reported that the waterlogged soils contain higher SOC as compared to other upland soils (Narteh and Sahrawat, 1999; Sahrawat et al. 2005). High organic carbon content in surface soils (1.5%) in particular and relatively high SOC content throughout the soil profile (0.5 to 0.8%) in these Vertisols (Teligi series) perhaps support the earlier observation of Sahrawat *et al.* (2005). This observation, however, does not support a direct relation with SOC and soil colour. For example, Asra soils with almost similar colour register different SOC content. In the arid ecosystem, the soil colour ranges from very dark grayish brown to dark grayish brown.

Table 4. Benchmark spots and their site characteristics in semi-arid (dry) bioclimatic system

Serial No.	District/State	Series	System	MAR (mm)
BLACK SOILS				
1.	Kota/Rajasthan	Jhalipura	Agriculture(FM1)/*Sopybean-Wheat*	842
2.	Kota/Rajasthan	Jhalipura	Agriculture(FM2)/*Paddy-Wheat*	842
3.	Akola/Maharashtra	Paral	Agriculture(LM)/*Cotton+Pigeonpea//Sorghum*	794
4.	Akola/Maharashtra	Paral	Agriculture(HM)/*Cotton+Pigeonpea/Sorghum*	794
5.	Mehboobnagar/ Andhra Pradesh	Jajapur	Agriculture(FM1)/*Sorghum/Pigeonpea+Green- gram*	792
6.	Mehboobnagar/ Andhra Pradesh	Jajapur 1	Agriculture(FM2)/*Paddy-paddy*	792
7.	Medak/ Andhra Pradesh	Kasireddipalli	Agriculture(HM)/*Soybean+Pigeonpea*	764
8.	Medak/ Andhra Pradesh	Kasireddipalli	Agriculture(TM)/*Fallow-Chickpea*	764
9.	Solapur/Maharashtra	Konheri	Agriculture(FM)/*Pigeonpea/Sunflower-Sorghum*	742
10.	Solapur/Maharashtra	Konheri 1	Agriculture(LM)/*Fallow-Sorghum+Safflower*	742
11.	Nashik/Maharashtra	Kalwan	Agriculture(FM)/*Sugarcane/Sorghum-Wheat/Gram*	692
12.	Tuticorin/ Tamil Nadu	Kovilpatti	Agriculture/*Sorghum/Sunflower/cotton*	660
13.	Tuticorin/ Tamil Nadu	Kovilpatti 1	Waste land	660
14.	Tuticorin/ Tamil Nadu	Kovilpatti	Agriculture(HM)/*Cotton + Black Gram*	660
15.	Rajkot/Gujarat	Semla	Agriculture/*Cotton/Groundnut-Wheat*	635
16.	Bellary/Karnataka	Teligi	Agriculture(LM)/*Paddy-paddy*	632
17.	Bellary/Karnataka	Teligi 1	Agriculture(HM)/*Paddy-paddy*	632
RED SOILS				
1.	Rangareddy/ Andhra Pradesh	Hayatnagar	Agriculture(HM)/*Sorghum-Castor*	764
2.	Rangareddy/ Andhra Pradesh	Hayatnagar	Agriculture(LM)/*Sorghum-Castor*	764
3.	Medak/Andhra Pradesh	Patancheru	Permanent Fallow	764
4.	Mehboobnagar/ Andhra Pradesh	Kaukuntla	Agriculture(FM)/*Castor+Pigeonpea*	674
5.	Coimbatore/Tamil Nadu	Palathurai	Agriculture(LM)/*Horsegram/Vegetables*	612

The Nimone soils become very dark brown in colour under HM when compared with FM (Table 7).

In general, the black soils under study do not show variation in colour with different bioclimatic systems.

However, there are examples where darker colour indicates a direct relation with SOC content (Table 6). It is expected to have black soils with darker colour in relatively moist soil environment in bioclimatic systems experiencing higher

Table 5. Benchmark spots and their site characteristics in arid bioclimatic system

Serial. No.	District/State	Series	System	MAR (mm)
BLACK SOILS				
1.	Rajkot/Gujarat	Sokhda	Agriculture(FM1)/*Cotton- Bajra*	533
2.	Rajkot/Gujarat	Sokhda 1	Agriculture(FM2)/*Cotton- Bajra/Linseed*	533
3.	Ahmednagar/Maharashtra	Nimone	Agriculture (HM)/ *Cotton-Wheat/Chick pea*	520
4.	Ahmednagar/Maharashtra	Nimone	Agriculture (FM)/*Sugarcane –Soybean/Wheat/Chick pea*	520

rainfall than those with lower rainfall. Incidentally introduction of irrigation in drier part of SAT (Semi-Arid (dry) and Arid eco-systems) might have influenced the soil to have darker colour (Teligi soils, Table 7).

Red Soils : The red soils in sub-humid moist bioclimate have dark brown colour in the surface (Dadarghugri and Karkeli) that has also high SOC (Table 6). The direct relation between higher SOC and darker soil colour is observed in these forest soils. Such relation was not observed for other red soils.

It is known that presence of $CaCO_3$ (SIC) particularly powdery lime in high amounts might influence soil colour. However no such relation was found with soil colour and SIC content (Table 7).

Roots vis-à-vis SOC and SIC

Quantity of roots in a soil profile is described in terms of number of roots of different sizes per unit area.

Black Soils : In the Nabibagh soils under farmers' management very fine and fine roots are common. Boripani soils, under forests, show many fine, medium and coarse roots. In the Kheri soils under high management fine roots are limited to surface horizon only. This could be due to the continuous cultivation of paddy-wheat for a considerable period of time.

Fresh and decayed roots of crops and trees identified in a soil profile do not contribute for SOC determined by Walkley and Black method (Walkley and Black 1934; Jackson 1973) until and unless they are humified. Higher root concentration leads to release of greater amount of root exudates. These exudates in turn dissolve $CaCO_3$ present in soil, which help in better Ca nutrition in plants as well ; developing a better soil structure, enhancing aeration ar hydraulic conductivity (Bhattacharyya et al., 2004). Th process again brings better soil environment for crop grow and biological activities. It, therefore, appears th concentration of roots either in surface or throughout tl depth of the pedon has a role in modifying soil structure ar other physical properties to enhance organic carbc sequestration and retard the sequestration of inorgan carbon. A closer look at the root distribution indicate relatively low $CaCO_3$ (0.4 - 2.6 g/kg of SIC) content in the surfa soil, where most of the roots are concentrated (Table 8).

Coarse Fragments, Nodules and Effervescence vis-à-v SOC and SIC

The quality and quantity of coarse fragments (> and <2.5 cm in diameter) are studied in the field itself sin they largely influence soil moisture storage, infiltration ar runoff and particle-size fraction, soil structure ar consistence. They also have an influence on plant growth terms of shoot emergence, root proliferation and penetratic especially in high clay soils such as Vertisols. It is al reported that they protect the fine particles from wash ar blowing. Nodules, also known as concretions, are harden materials which form indurated structure of various size shapes and colours. They could be formed by induratic from materials like $CaCO_3$, $MgCO_3$, Fe/Mn oxides present the soil particles. In Vertisols, a major fraction of the coar fragments are the calcareous nodules. In the red and bla soils of arid bioclimatic systems, coarse fragments identifi in the field are generally observed as lime concretions nodules (*conca*). For other red soils, iron and mangane

Table 6. Level of management in different BM sites

Serial. No.	High Management	Low Management
1.	Higher NPK	Low NPK
2.	Regular application of manures	Manures rarely applied
3.	Intercropping with legumes	Sole crop
4.	Incorporation of residues	Removal of residues & biomass
5.	Soil moisture conservation (Ridge furrows, Bunding, BBF*)	–

* BBF: Broad base furrow

concretions have also been identified, which are basically coarser fragments in these soils.

The effervescence identified in these soils with the help of cold 2.87 *N* HCl (which corresponds to 1:10 :: HCl : water) is due to the reaction of carbonate present in the soil with the acid. Depending on the quantity of coarse fragments, the degree of effervescence is noted as *very slight* to *slight* (e), *strong* (es), and *violent* (ev). It was also noted in the field whether the effervescence observed was due to carbonate present in the matrix of the soil (pedogenic carbonates) or due to the calcareous nodules (non-pedogenic carbonates) (Pal *et al.* 2000). In relatively high rainfall zone (sub-humid, moist) amount of coarse fragments (i.e. $CaCO_3$) content and the degree of effervescence are compatible. In sub-humid (dry) and semi-arid (dry) climate both the coarse fragments and $CaCO_3$ content increase. The degree of effervescence also increases from wet to dry climate. In terms of SOC content, the general trend is that more coarse fragments show less SOC content (Table 9). Earlier such inverse relation of SOC and SIC ($CaCO_3$) has been reported in Indian soils (Bhattacharyya *et al.* 2000). For the red soils the coarse fragments consist of gravels of parent rock and they do not contain $CaCO_3$ (Table 9).

Other Morphological Features of the soils vis-à-vis SOC and SIC

Other features include slickensides, cracks, gilgai microrelief in the black soils which appear to be related indirectly with SOC and SIC.

It has earlier been reported that depth of occurrence of slickenside is related to soil moisture regime viz. udic and ustic (Vadivelu and Challa 1985). These authors reported that depth of initiation of slickensided zone increases in areas where the rainfall is high. These observations allowed developing a mathematical equation to calculate linear distance of cyclic horizon in Vertisols (Bhattacharyya *et al.* 1999). Our study from sub-humid moist to arid bioclimatic system generally agrees with the above observations (Fig. 2). It is interesting to find that slickensides appear in relatively deep layers in Nimone soils under arid ecosystem. The Nimone soils are under irrigation both in farmers' and high management. This may be the reason for the appearance of slickensides at lower depth. The influence of irrigation is thus similar to that of humid climate experiencing rainfall more than that of drier climate. This demonstrates how management interventions can influence morphological properties of Vertisols. Table 10 gives an overall view of depth of occurrence of slickensides in Vertisols of semi-arid area. It has been reported earlier that soils in the central India generally contain low SOC (<0.5% in the surface). It is known that SOC content decreases with depth, whereas SIC and SOC have an inverse relation in terms of their occurrence in soil profile. Interestingly, SOC content in most of the soils range between 0.3-0.8% cutting across the bioclimatic system.

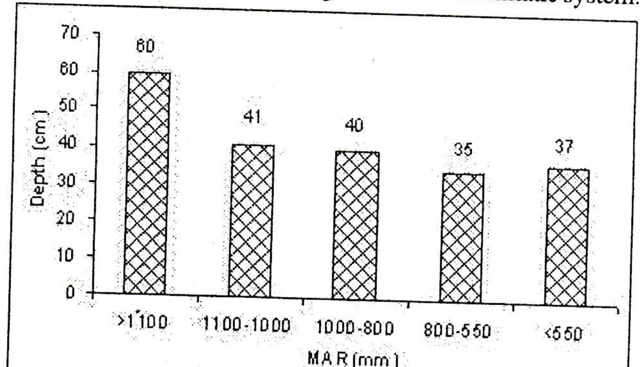

Fig. 2. Relation between rainfall and depth of occurrence

Table 7. Colour of soils and their carbon content (0-20 cm)

Soil Series	Management	Matrix Colour (moist) Notation	Colour	SOC (g/kg)	SIC (g/kg)
BLACK SOILS					
			Sub-humid (moist)		
NABIBAGH	HM	10YR 3/2	Very dark grayish brown	8.0	6.1
	FM	10YR 4/2	Dark grayish brown	7.0	4.6
BORIPANI	Forest	10YR 3/2	Very dark grayish brown	9.0	4.8
KHERI	HM	2.5Y 5/2	Greyish brown	6.0	4.2
	LM	2.5Y 4.5/3	Olive brown	7.0	4.3
			Sub-humid (dry)		
LINGA	HM	10YR 3/2	Very dark grayish brown	9.0	7.8
	FM	10YR 3/2	Very dark grayish brown	10.0	7.2
	LM	10YR 3/2	Very dark grayish brown	10.0	8.3
			Semi-arid (moist)		
ASRA	FM	10YR 2.5/2	Very dark grayish brown	8.0	11.2
	FM	10YR 2/2	Very dark brown	8.0	9.7
	HM	10YR 2.5/2	Very dark grayish brown	11.0	6.2
			Semi-arid (dry)		
TELIGI	LM	10YR 3/1	Very dark gray	15.0	12.6
	HM	10YR 3/1	Black	10.0	6.5
PARAL	LM	7.5YR 3/2	Dark brown	7.0	11.6
	HM	7.5YR 3/1	Very dark grey	6.0	11.4
			Arid		
NIMONE	HM	7.5YR 2.5/2	Very dark brown	9.0	16.9
	FM	10YR 4/1.5	Dark grayish brown	26.5	7.0
RED SOILS					
			Semi-arid (dry)		
DADARGHUGRI	Forest (Teak)	7.5YR 3/2	Dark brown	33.0	–
	R. Forest (Sal)	7.5YR 3.5/3	Brown	24.0	–
KARKELI	LM	7.5YR 4.5/6	Strong brown	19.0	–

This shows that in both LM and HM the SOC content (in the first 30 cm of dry bioclimate to 70 cm of wet bioclimate depth of soil) ranges between 0.3 - 0.8%. The $CaCO_3$ content in the slickensided horizons also shows an increasing trend from sub-humid moist to arid climate (Table 10).

It is observed that the depth of initiation of slickensides in soils varies according to the bioclimatic system (Fig. 3). Relative proportion of SOC is more in the soil depth occurring above the slickensides. The SOC content is 26%, 60%, 28%, 57% and 27% more in the soil depth above slickensides (than that below the depth of slickensides) in subhumid (moist), subhumid (dry), semi-arid (moist), semi-arid (dry) and arid bioclimate, respectively. The SIC content at this soil depth (above slickensides) is less than the lower depth (below slickensides) by 8%, 8%, 16%, 25% and 5% in subhumid (moist), subhumid (dry), semi-arid (moist), semi-arid (dry) and arid bioclimate respectively. Figure 3 shows the distribution of SOC and SIC content above and below

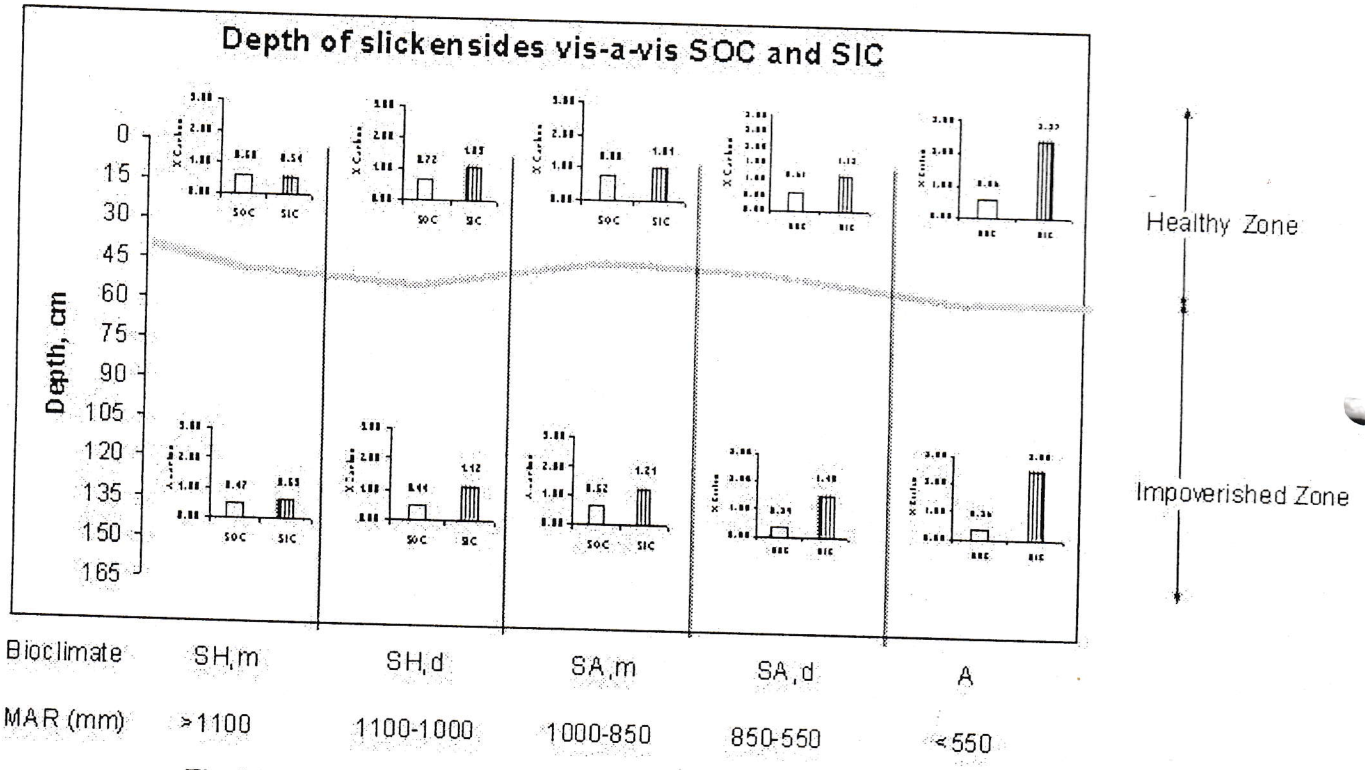

Fig. 3. Depth of occurrence of slickensides (shown by darker line) vis-a-vis SOC and SIC.

slickensided zone on the basis of 307 samples studied. It has earlier been pointed out that higher SIC content indirectly shows development of subsoil sodicity which is a sign of natural chemical degradation of soils (Pal *et al.* 2000; Srivastava et al. 2002; Bhattacharyya *et al.* 2000). The soil depth above the slickensides, with 26-60% more SOC and 5-25% less SIC (43-56 cm) may be considered relatively safe zone as compared to the soil depth below the slickensides.

Taxonomic group and C content of soils

On the basis of the dominant properties the black soils in the arid bioclimatic system are found to be dominantly Sodic Haplusterts. The pedon P30 is an exception (Table 5). When the soil classification at subgroup level was compared with the bioclimatic system vis-à-vis mean annual rainfall pattern, it was found that upto about 800 mm annual rainfall, covering sub-humid (moist), sub-humid (dry) and semi-arid (moist) bioclimatic systems, the majority of the soils are classed as Typic Haplusterts. The Gypsic and Calcic Haplusterts are found only in semi-arid (dry) bioclimatic system experiencing a mean annual rainfall between

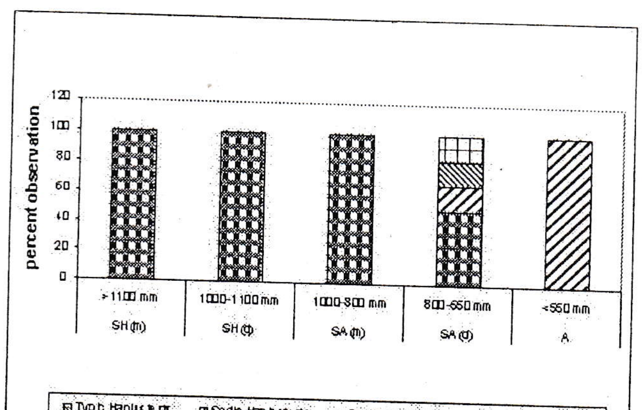

Fig. 4. Soil Taxonomy as influenced by rainfall in different bioclimatic system

800-550 mm. The Sodic Haplusterts occurs in semi-arid (dry) bioclimatic system and gradually these soils dominate the entire arid bioclimatic system showing decrease in SOC and increase in SIC (Fig. 4).

As indicated earlier the 52 pedons are broadly identified as Inceptisols, Vertisols and Alfisols (Tables 1-5) orders. These soils can again be broadly grouped into two temperature classes such as hyperthermic and

Table 8. Distribution of roots in soils and their carbon content (0-20 cm)

Soil Series	Management	Roots*		Depth (cm)	SOC	SIC
		Size	Quantity		(g/kg)	(g/kg)
BLACK SOILS						
		Sub-humid (moist)				
Nabibagh	HM	Very fine, fine	Common	0-13	8.0	0.61
	FM	Very fine	Common	0-23	7.0	0.46
Boripani	Forest	Fine, medium	Many	0-16	9.0	0.48
Kheri	HM	Fine	Common	0-20	--	0.42
	LM	Fine	Many	0-14	--	0.43
		Sub-humid (dry)				
Linga	HM	Fine, medium	Few	0-15	9.0	0.78
	FM	Very fine	Common	0-13	10.0	0.72
	LM	Very fine	Many	0-16	10.0	0.83
		Semi-arid (moist)				
Asra	FM	Very fine	Many	0-14	8.0	1.12
	FM	Very fine	Common	0-14	8.0	0.97
	HM	Very fine	Many	0-12	11.0	0.62
		Semi-arid (dry)				
Teligi	LM	Very fine	Many	0-9	15.0	1.26
	HM	Very fine	Many	0-8	10.0	0.65
Paral	LM	Very fine	Common	0-10	7.0	1.16
	HM	Very fine	Common	0-10	6.0	1.14
		Arid				
Nimone	HM	Very fine	Common	0-13	9.0	1.69
	FM	Very fine	Common	0-12	7.0	2.65
RED SOILS						
		Semi-arid (dry)				
Dadarghugri	Forest (Teak)	Very fine, medium	Many	0-10	24.0	0
	R. Forest (Sal)	Very fine, medium	Many	0-10	33.0	0
Karkeli	LM	Very fine, fine medium	Many	0-15	19.0	0

* Size of roots : Very fine (<1 mm diameter), fine (1-2 mm), medium (2-5 mm), coarse (5-10 mm), very coarse (>10 mm)
Quantity of roots : Few (<1/sq.cm), common (1-5/sq.cm), many (>5/sq. cm)
(Soil Survey Division Staff, 1995)

isohyperthermic at family level of soil classification. In the study area, the western part of Maharashtra (Nasik, Solapur and Ahmednagar), Andhra Pradesh, Karnataka and Tamil Nadu represent isohyperthermic temperature class and are grouped under arid, semi-arid (moist), semi-arid (dry) and sub-humid (dry) bioclimatic system. On the other hand, the hyperthermic temperature class, in the study area covers the entire sub-humid (moist) bioclimatic system, other than few observations in sub-humid (dry), semi-arid (moist), semi-arid (dry) and arid (Table 11). It has been earlier reported that Vertisols under isohyperthermic temperature regime show better cropping performance than those under hyperthermic temperature regime (NBSS&LUP-ICRISAT 1991). In the sub-humid (dry) bioclimate, the effervescence in soils under

Table 9. Distribution of coarse fragments and its relation with SOC and SIC (0-20 cm)

Soil Series	Management	Coarse fragments (%) (v/v)	SOC (g/kg)	CaCO3 (%)	Effervescence*
BLACK SOILS					
		Sub-humid (moist)			
Nabibagh	HM	4	8.0	4.9	e
	FM	4	7.0	3.8	e
Boripani	Forest	2	9.0	4.0	e
Kheri	HM	0	--	3.5	e
	LM	6	--	3.6	e
		Sub-humid (dry)			
Linga	HM	7	9.0	6.5	es
	FM	4	10.0	6.0	es
	LM	4	10.0	6.9	es
		Semi-arid (moist)			
Asra	FM	4	8.0	9.3	es
	FM	2	8.0	8.1	es
	HM	1	11.0	5.2	es
		Semi-arid (dry)			
Teligi	LM	9	15.0	10.5	es
	HM	9	10.0	5.4	es
Paral	LM	7	7.0	9.7	es
	HM	7	6.0	9.5	es
		Arid			
Nimone	HM	7	9.0	14.1	es
	FM	1	7.0	22.1	es
RED SOILS					
		Semi-arid (dry)			
Dadarghugri	Forest (Teak)	12	24.0	0	--
	R. Forest (Sal)	2	33.0	0	--
Karkeli	LM	1	19.0	0	--

* e = slight effervescence (<5.0%); es = strong effervescence (5.0-13.0%); ev = violent effervescence (>13.0%),Nil= No efferevescence (%) (Bhattacharyya et al., 2003)

isohyperthermic regime is slight (e). In hyperthermic temperature regime almost all the soils show slight effervescence upto a depth of 100-130 cm beyond which the effervescence is strong. In arid bioclimatic system, soils under hyperthermic temperature regime indicate violent effervescence throughout the depth. Influence of temperature regime on effervescence and the formation of $CaCO_3$ (SIC) is given in table 12. In hyperthermic temperature regime strong to violent effervescence was observed throughout the profile depth (Table 12). Recently, the rate of formation of pedogenic carbonate in terms of different degree in various bioclimatic system has been reported from the black soils of India (Pal *et al.* 2006). The relation between the content of $CaCO_3$ (in terms of degree of effervescence) and the soil taxonomic temperature regime may explain the different rate of formation of $CaCO_3$ in soils even under same bioclimatic system.

Table 10. Slickensides* (SS), SOC, and $CaCO_3$ content in the corresponding depths in SAT, India

Bioclimate	Rainfall (MAR, mm)	HM			LM		
		Depth of SS (cm)	SOC (%)	$CaCO_3$ (%)	Depth of SS (cm)	SOC (%)	$CaCO_3$ (%)
Sub-humid moist	>1100 mm	60-69	0.3-0.6	3-7	42	0.5-0.6	4-7
Sub-humid dry	1100-1000	41-57	0.4-0.7	6-7	44-57	0.5-0.6	5-7
Semi-arid moist	1000-800	40	0.7	6	37-59	0.6-0.8	10-11
Semi-arid dry	800-550	31-35	0.4-0.5	6-13	35-58	0.3-0.8	5-23
Arid	<550	55	0.6	14	37-55	0.3-0.6	21-22

* Presence of slickensides or wedge-shaped peds with an upper boundary within 100 cm of the soil surface is mandatory to qualify a soil to be Vertisols. A slickenside is a smooth, striated surface, formed in shrink-swell clays by the sliding of one surface against the other due to differential swelling pressures (Soil Survey Staff, 1999).

Table 11. Classification of Black Soils in arid bioclimatic system

Soil Series Name	Textural Class	Mineralogy Class	Temperature Class	Subgroup Classification
Sokhda	Fine	Smectitic	Hyperthermic	Leptic Haplusterts
Sokhda 1	Fine	Smectitic	Hyperthermic	Sodic Haplusterts
Nimone	Very fine	Smectitic	Isohyperthermic	Sodic Haplusterts
Nimone	Fine	Smectitic	Isohyperthermic	Sodic Haplusterts

Table 12. Effervescence as influenced by temperature regime in the study area

Bioclimatic system	Temperature Regime	
	Hyperthermic	Isohyperthermic
Sub-humid (dry)	e (100-130 cm); es (>130 cm)	e
Semi-arid (moist)	e (90 cm); es (>90 cm)	e
Semi-arid (dry)	es-ev	e (35-100 cm)
Arid	ev	es-ev

Parentheses indicate soil depth, if not mentioned shows throughout the depth

Conclusions

- Soils under HM are darker in colour indicating more SOC content. Black soils under waterlogged condition show very dark grey colour which correlates well with higher SOC content.
- Higher concentration of roots in soils corresponds with lower degree of $CaCO_3$ concentration as indicated by slight effervescence with dil. HCl in the field.
- Black soils contained coarse fragments ranging between 3-8%, 1-10%, 1-10% and 5-15% in sub-humid (moist), semi-arid (moist), semi-arid (dry) and arid bioclimatic system. In general, the degree of effervescence is in line with size and quantity of coarse fragment and calcium carbonate concretions observed in the field.
- Sequestration of high inorganic carbon lead to the formation of Sodic Haplusterts which manifest natural chemical degradation in semi-arid tropical part of India.

Acknowledgements

The present work forms a part of the National Agricultural Technology Project (NATP). The financial assistance received from ICAR, Krishi Bhavan, New Delhi to carry out the study is gratefully acknowledged.

References

Bhattacharjee, J.C. (1997). "Introduction to Pedology Vol. 1. Soil Genesis". Oxford and IBH Publishing Co. Pvt. Ltd., New Delhi.

Bhattacharjee, J.C., Roychoudhury, C., Landy, R.J. and Pandey, S. (1982). "Bioclimatic Analysis of India". NBSSLUP Bull. 7, Nagpur, India, 21p + map.

Bhattacharyya, T. and Pal, D.K. (1998). Occurrence of Mollisols-Alfisols-Vertisols associations in central India - their mineralogy and genesis. Paper abstracted in National Seminar on Developments in Soil Science, Hisar, India.

Bhattacharyya, T., Pal, D.K. and Deshpande, S.B. (1993). Genesis and transformation of minerals in the formation of red (Alfisols) and Black (Inceptisols and Vertisols) soils on Deccan basalt in the Western Ghats, India. *Journal of Soil Science* **44,** 159-171.

Bhattacharyya, T., Pal, D.K. and Velayutham, M. (1999). A Mathematical equation to calculate linear distance of cyclic horizons in dark clays. *Soil Survey Horizons* **40,** 127-133.

Bhattacharyya, T., Pal, D.K., Velayutham, M., Chandran, P. And Mandal, C. (2000). Total carbon stock in Indian Soils : Issues, Priorities and management. In 'Spec[illegible] publication of the International Seminar on Land Resource Management for Food, Employment and Environmental Security (ICLRM)' (Eds. S.P. Gawande, J.S. Bali, D.C. Das, T.K. Sarkar, D.K. Das, G. Narayanasamy) pp. 1-46 (New Delhi),.

Bhattacharyya, T., Pal, D.K., Chandran, P., Mrs. Mandal, C., Ray, S.K., Gupta, S.K. and Gajbhiye, K.S. (2004). Managing soil carbon stocks in the Indo-Gangetic Plains, India, Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi - 110 012, India, pp. 44.

Bhattacharyya, T., Pal, D.K., Chandran, P. And Ray, S.K. (2005). Landuse, clay mineral type and organic carbon content in two Mollisols-Alfisols-Vertisols catenary sequences of tropical India. *Clay Researc[illegible]* **24,** 105-122.

Bhattacharyya, T., Pal, D.K., Lal, S., Chandran, P. and Ray, S.K. (2006). Formation and persistence of Mollisols on zeolitic Deccan basalt of humid tropical India. *Geoderma* **136,** 609-620.

Dalal, R.C. and Conter, J.U. (2000). Soil organic matter dynamics and carbon sequestration in Australian Tropical Soils. In 'Global Climate Change and Tropical Ecosystems' (Eds. R. Lal, J.M. Kimble and B.A. Stewart) pp. 283-314 (Boca Raton, Washington).

Jackson, M,L. (1973). "Soil Chemical Analysis", Prentice Hall, India.

Jackson, M.L. (1979). "Soil Chemical Analysis : Advanced Course". Published by the author, University of Wisconsin, Madison, WI, USA.

Jenny, H. 1941. "Factors of Soil Formation", McGraw Hill Book, Co., New York.

Kalbande, A.R., Pal, D.K. and Deshpande. S.B. (1992). b-fabric of some Benchmark Vertisols of India in relation to their mineralogy. *Journal of Soil Science* **43,** 375-385.

Naitam, R. and Bhattacharyya, T. (2004). Quasi-equilibrium of organic carbon in swell-shrink soils of sub-humid tropics in India under forest, horticulture and agricultural system. *Australian Journal of Soil Research* **42,** 181-188.

Narteh, L.T. and Sahrawat, K.L. (1999). Influence of flooding on electrochemical and chemical properties of West African soils. *Geoderma* **87,** 179-207.

NBSS&LUP-ICRISAT (1991). The Suitabilities of Vertisols and Associated Soils for Improved Cropping System in Central India, NBSS&LUP, Nagpur and ICRISAT, Patancheru, India.

Pal, D.K. and Deshpande, S.B. (1987a). Genesis of clay minerals in a red and black complex soils of southern India. *Clay Research* **6:** 6-13.

Pal, D.K. and Deshpande, S.B. (1987b). Characteristics and genesis of minerals in some Benchmark Vertisols of India. *Pedologie* **37:** 259-275.

Pal, D.K., Dasog, D.S., Vadivelu, S., Ahuja, R.L., Bhattacharyya, T. (2000). Secondary calcium carbonate in soils of arid and semi-arid region of India In 'Global Climate Change and Pedogenic Carbonates' (Eds. R. Lal, J.M. Kimble, H. Eswaran and B.A. Stewart) pp. 149-185 (CRC Press, Boca Raton, Washington).

Pal, D.K., Deshpande, S.B., Venugopal, K.R. and Kalbande, A.R. (1989). Formation of di and trioctahedral smectite as evidence for paleoclimatic changes in southern and central Peninsular India, *Geoderma* **45,** 175-184.

Pal, D.K., Bhattacharyya, T., Ray, S.K., Chandran, P., Srivastava, P., Durge, S.L. and Bhuse, S.R. (2006). Significance of soil modifiers (Ca-zeolites and gypsum) in naturally degraded Vertisols of the Peninsular India in redefining the sodic Vertisols. *Geoderma* **136,** 210-228.

Poonia, S.R. and Niedderbudde, E.A. (1990). Exchange equilibria of potassium in soils, V Effect of natural organic matter on K-Ca Exchange. *Geoderma* **47,** 233-242.

Sahrawat, K.L., Bhattacharyya, T., Wani, S.P., Chandran, P., Ray, S.K., Pal, D.K. and Padmaja, K.V. (2005). Long-term lowland rice and arable cropping effects on carbon and nitrogen status of some semi-arid tropical soils. *Current Science* **89,** 2159-2163.

Saikh, H., Varadachari, C. and Ghosh, K. (1998). Changes in carbon, nitrogen and phosphorus levels due to deforestation and cultivation : a case study in Simlipal National Park, India. *Plant and Soil* **198,** 137-145.

Shaw, F.G. (1928). "A definition of term used in soil literature", 1st International Congress of Soil Science Proceedings and Paper, **5:** 38-64, Washington, DC.

Soil Survey Division Staff (1995). "Soil Survey Manual", United States Department of Agriculture, Handbook No. 18. Scientific Publishers; Jodhpur, India.

Soil Survey Staff (1999). "Soil Taxonomy : A Basic System of Soil Classification for Making and Interpretating Soil Surveys", 2nd Edition, Agriculture Handbook No. 436, SCS-USDA, US Govt. Printing Office, Washington, DC.

Soil Survey Staff (2003). "Keys to Soil Taxonomy", 9th edition, United States Department of Agriculture, Natural Resources Conservation Service, Washington, D.C.

AIS&LUS (1970). "Soil Survey Manual", IARI, New Delhi.

Srivastava, P., Pal, D.K., Bhattacharyya, T. (2002). Significance of the formation of calcium carbonate minerals in the pedogenesis and management of cracking clay soils (Vertisols) of India. *Clays and Clay Minerals* **50,** 111-126.

Influ Vadi Vela

Vadivelu, S. and Challa, O. (1985). Depth of slickensides occurrence in Vertisols. *Journal of the Indian Society of Soil Science* **33,** 452-454.

Velayutham, M., Mandal, D.K., Mandal, C. and Sehgal, J.L. (1999). Agro-ecological subregions of India for Development and Planning, National Bureau of Soil Survey and Land Use Planning, No. 35, Nagpur, India.

Velayutham, M., Pal, D.K. and Bhattacharyya, T. (2000). Organic carbon stock in soils of India. In 'Global Climate Change and Tropical Ecosystem' (Eds. R. Lal, J.M. Kimble and B.A. Stewart),. pp. 71-95 (CRC Press, Boca Raton, Washington).

Walkley, A. and Black, I.A. (1934). An examination of the Degtjareff method for determining soil organic matter and proposed modification of the chromic acid titration method. *Soil Science* **37,** 29-38.

Received : June, 2006 ; Accepted : April, 2007