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Characteristics of coffee-growing soils and their organic carbon stocks in Karnataka state

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Abstract : Nine typical pedons supporting *Robusta* and *Arabica* plantations, four each from Chickmagalur and Kodagu districts and one from Hassan district representing per-humid, humid, moist sub-humid and dry sub-humid climate were studied for assessing the land quality particularly related to soil organic carbon stocks. The soils were classified into Ultisol, Inceptisol and Alfisol orders. The highest SOC stocks (17.3 kgm^{-2}) were reported in Pedon-4 (Kelagur), followed by Pedon-6 (Siddapur) and Pedon-1 (Shuntikoppa). Pedon-8 (Belur) and Pedon-9 (Chikmagalur) had low soil organic stocks (5.3 and 3.7 kgm^{-2}).

Additional key words: *Soil characterisation, SOC stocks, land quality, coffee-growing soils*

Introduction

Soil organic carbon influences a wide range of physical, chemical and biological properties and is considered as the most important indicator of soil quality (Larson and Pierce 1994). Soil is the largest pool of organic carbon with global estimates of 1115 to 2200 Pg and top 30 cm of soil surface holds 1500 Pg C in the world (Batjes 1996) and 9 Pg in India (Bhattacharrya *et al.* 2000).

Coffee is the second most traded commodity in the world and, in India, it is cultivated in 3.8 lakh ha area with an annual production of 2.7 lakh tons. In Karnataka, coffee is commercially grown in the districts of Chikmagalur, Kodagu and Hassan. Coffee productivity in a given situation is dependent on agro-climatic factors and production technologies. There is a notion that conversion of forests into farming systems will lead to land degradation and is detrimental to sustainability of the system. Simulations by Kamoni *et al.* (2007) suggest that conversion of natural vegetation to annual crops leads to the greatest soil C losses. However, there are reports that coffee plantations enrich the soil organic carbon (Anil Kumar 2002). Organic carbon status will give an indirect indication of the sustainability of the land use. The present study was undertaken to characterize the soils of coffee plantations under different agro-climatic situations and species and estimate the organic carbon stocks in the soils at different depths, (0-30 cm, 30-100 cm and 0-100 cm) and confirm the above observations.

Material and Methods

In Karnataka state, Chikmagalur, Kodagu and Hassan districts have largest area under coffee. Extensive field traversing of the area was done. On the basis of variability in site characteristics and productivity of coffee, nine pedons were studied to assess the land quality at different locations. Horizon-wise soil samples were collected from all the pedons for the analysis of physical and chemical properties. Morphological properties of the soils were studied as per the procedure outlined in Soil Survey Manual (Soil Survey Staff 1951). Particle-size analyses were done by International Pipette method (Sarma *et al.* 1987) and bulk density was determined by core method. pH was determined in 1:2.5 soil-water suspension and electrical conductivity in its supernatant portion (Jackson 1973). Cation exchange capacity of the soils was determined by the ammonium acetate leaching method (Sarma *et al.* 1987). Soil organic carbon was determined by Walkley and Black's wet oxidation method (Jackson 1973). The soils were classified as per Soil Taxonomy (Soil Survey Staff 1998).

For the estimation of SOC stocks in the soils, the bulk density and organic carbon data pertaining to the typifying pedons were used. In all the profiles, the SOC stocks were estimated to a depth of 100 cm and the recovery assumed was 77 per cent. The total soil organic carbon stock in kg m^{-2} soil for each pedon was estimated using the general equation (Grossman *et al.* 2001) presented below.

$$SOC = \frac{\frac{L_1 \times SOC\,P_1 \times \rho 33_1\,(1 - V{>}2_1)}{100} + \frac{L_2 \times SOC\,P_2 \times \rho 33_2\,(1 - V{>}2_2)}{100} + \ldots}{10}$$

Where, SOC = Soil organic carbon in kg m^{-2} soil

$SOC\,P_1, SOC\,P_2$ = Soil organic carbon per cent of different horizons 1, 2,... in order from surface to bottom

$L_1, L_2, \ldots$ = Thickness of different horizons 1, 2,... in order from surface to bottom.

$\rho 33_1, \rho 33_2, \ldots$ = Moist bulk density of < 2 mm fraction of the core samples of horizons 1, 2,..

$V{>}2_1, V{>}2_2, \ldots$ = Volume per cent of > 2 mm fraction of core samples of horizons 1, 2,..

Results and Discussion

Ideal climatic, site and soil requirements for coffee are given in table 1. The requirement of dry spell to cater to the dormancy of flower buds is 1.5 to 3 months for coffee. Rainfall during February-July is crucial for both species of coffee for breaking dormancy and blossoming, to assist fruit set and for fruit swelling. *Robusta* coffee can withstand higher temperature and require relatively

Table 1. Ideal climatic, site and soil characteristics for *Arabica* and *Robusta* coffee

Sl. No.	Characteristic	*Arabica* coffee	*Robusta* coffee
Climatic			
	Total rainfall (mm)	>1400[1], 1600-1800[5,12], 1400- 1600[2], 1600-2500[7,10,11]	1550-2000[1], 1800-2000[7,12], 1000-2000[2]
	Blossom period rainfall (mm)	(March-April) 10-40[1,4,5]	(Feb- March) 10-40[1,2]
	Fruit set period rainfall (mm)	(April-May) >50[1],	(March-April) 50-75[1,2]
	Fruit swell period rainfall (mm)	(June-July) >300[1]	(June-July) >300[1]
	Dry period (Months)	2-3[1,4,5]	1.5-2.5[1], <1[9]
	Mean Annual Temperature (°C)	15-24[1,4,5,6,8,10]	15-30[1,2,6,7,10,11]
	Mean annual maximum Temp. (°C)	24-28[1,4,5]	29-32[1,10,11]
	Average daily min. of coldest month (°C)	10- >15[1,6,7]	13- >20[1,10,11]
	Relative Humidity (%)	70-95[1,4,5,8]	80-95[6,8]
Site			
	Elevation (m above MSL)	1000-1650[1,3,6]	500-1000[1,2]
	Slope (%)	0-40[1,5,11,12]	0-8[1,9,10,11]
Soil physical			
	Drainage	Well[1]	Well[1]
	Texture	L-Cl-C[1,4]	l-Cl[1]
	Depth (cm)	>150[1,5]	>150[1]
	Available Water Capacity (mm m^{-1})	>100[1]	>100[1]
	Coarse fragments (Vol. %)	0-15[1,4]	0-15[1,10,11]
Soil chemical			
	pH	5.0-6.5[6,8,11]	5.0-6.5[1,7,10,11]
	CEC per kg clay (cmol (p+) kg^{-1})	>24[5,11]	16->24[1,11]
	Base Saturation (%)	65-80[1,11]	35-65[1,11]
	Organic Carbon (%)	1.5->2.5[1,4,11] (Top 25 cm)	1.5->1.5[1,11] (Top 25 cm)

References: 1. Anil Kumar (2002), 2. Anonymous (1997), 3. Harrer (1962), 4. Kharche (1996), 5. Kharche *et al.* (1999), 6. Krishnamurthy Rao (1993), 7. Landon (1984), 8. Muller (1966), 9. Sys (1985), 10. Sys *et al.* (1991), 11. Sys *et al.* (1993), 12. Wellman (1961).

high relative humidity than *Arabica*. Compared to *Robusta*, *Arabica* coffee can grow well even at higher elevations and steeper slopes. Both species prefer very deep, well drained, non-gravelly, fine-loamy to clayey soils having slightly to moderately acid reaction, high organic carbon contents, high base saturation and good water and nutrient retention capacities.

The site characteristics of soils and their land use are given in table 2. Elevation in the location ranged from 840 to 1100 m above MSL and the study area falls in two classes *i.e.* 840 to 980 m (P1, P3, P5, P6 & P7) and 1040 to 1100 m (P2, P4, P8 & P9). The first group elevation is ideal for *Robusta* coffee (Anonymous 1997) whereas that of second group is ideal for *Arabica* (Kharche *et al.* 1999; Krishnamurthy Rao 1993). Six sites fall under gentle slopes (1-3 %) and one under moderate slope. Except P2 and P4, the slope attribute requirement was met for *Arabica* (Kharche 1996) and *Robusta* (Sys *et al.* 1993). The drainage in most of the pedons is optimum (Anil Kumar 2002) and found to be well-drained, except in P5 and P6, where it was moderately well drained. The colour of the surface layer varied from reddish brown to very dark grayish brown and the structures of all the soils were subangular blocky, barring that of P2 (granular). This could be attributed to the high amount of organic matter in these soils. Amongst the soil characteristics, thin patchy clay cutans were observed in all the pedons except in P2 and P4 indicating the formation of argillic sub-surface horizons.

In all the pedons barring P9, the soil depth, drainage and texture were found to be ideal for growing coffee (Kharche 1996; Kharche *et al.* 1999; Sys *et al.* 1991) (Table 3). In the surface horizons of all the pedons (except P9), coarse fragments were absent. The sub-surface horizons upto 40 cm of all the pedons (except those of P2 and P9) were devoid of coarse fragments. For successful coffee-growing, 0-5 per cent coarse fragments is recommended as ideal (Kharche 1996). In the sub-soils of pedons, 25 to 50 per cent coarse fragments were observed that even exceeded 50 per cent in P3, P7, P8 and P9 (in some of the horizons).

The chemical characteristics of the soils including the SOC stocks are presented in table 4. The pH of the coffee-growing soils was slightly acidic to moderately acidic and considered as optimum with the exception of P8 (extremely acidic). The CEC of the surface soils ranged from 16.6 to 38.1 cmol (p+) kg^{-1} and decreased with depth. The higher CEC at surface may be due to high organic matter contents. At Shuntikoppa site, where both *Arabica* and *Robusta* are cultivated, the CEC was found to be optimum for *Robusta* cultivation, but not for *Arabica*. At different locations, CEC was optimum for *Robusta* but it was suitable only in P4 and P9 for *Arabica*. The base saturation was found to be ideal for *Robusta* coffee-growing in all the locations except in P7. However, for *Arabica*, it did not meet the optimum value in P1, P4 and P9. The relatively high base saturation at surface layer could be attributed to the recycling of basic cations through vegetation. The organic carbon content in the surface layers of the profiles ranged from 1.5 to 5.3 per cent. The high soil organic carbon content may be due to the slow organic matter decomposition at higher altitudes, where temperature is low and rainfall is high (Muller 1966; Sys *et al.* 1993; Kharche *et al.* 1999).

The highest SOC stock of 17.3 kg m^{-2} was reported in P4, followed by that in P6 and P1. In P8 and P9, the SOC stocks were very low owing to moist to dry subhumid climate. The surface horizons of all the pedons had high carbon stocks except in that of pedon 4, where the sub-soil organic carbon stock was higher. This can be attributed to the amount of coarse fragments and thin surface horizon. The amount and distribution of SOC stocks is affected by plant production (Jobbagy and Jackson 2000). Carbon storage in soils indicates a dynamic balance between detrital inputs (primarily by litter, pruned twigs with leaves and dead roots) and organic matter outputs in the form of carbon dioxide efflux from soils. Temperature and moisture are the two vertical environmental factors influencing soil respiration and soil carbon storage. Typically, SOC is a function of climate and land use. The SOC stock values are mainly interpreted based on the climate prevailing in the area. In general, soil organic carbon increases with increase in precipitation, decrease in temperature and evaporation-precipitation ratio (Post *et al.* 1982; Amundsen *et al.* 1989; Jobbagy and Jackson 2000; Bhattacharrya *et al.* 2007a).

Table 2. Site characteristics and land use of the study area

Pedons	Village / Taluk	Location	Elevation (m)	Slope (%)	Drainage	Structure	Topography	Erosion	Parent material	Land use
P1	Suntikoppa Somvarpet	12° 25' 30"N 75° 49' 50"E	980	3-5	Well	Sub-angular blocky	Gently sloping upland	Slight	Granitic	*Arabica* and *Robusta*
P2	Balur, Mudigere	13°08'30"N 75° 30' 30"E	1040	25-33	Well	Granular	Steep sloping hills	Severe	Granitic ferruginous quartzite schist	*Arabica*
P3	Gabbugal, N. R. Pura	13° 13' 45"N 75° 29' 10"E	840	3-5	Well	Sub-angular blocky	Gently sloping hills	Slight	Granitic	*Robusta*
P4	Kelagur, Mudigere	13° 09' 50"N 75° 27' 15"E	1040	10-15	Well	Sub-angular blocky	Medium steep sloping hills	Slight	Granitic	*Arabica* and tea
P5	Nellikkad, Virajpet	12°14' 00" N 75° 57' 20"E	920	1-3	Moderately Well	Sub-angular blocky	Gently sloping upland	Slight	Granitic	*Robusta*
P6	Mekuri, Polibetta, Virajpet	12° 15' 40"N 75° 54' 50"E	920	1-3	Moderately Well	Sub-angular blocky	Gently sloping upland	Slight	Granitic	*Robusta*
P7	Arekkad, Madikeri	12° 19' 45"N 75° 50' 00"E	980	3-5	Well	Sub-angular blocky	Steep sloping hills	Slight	Granitic	*Robusta*
P8	Gandhehalli, Belur	13° 10' 45"N 75° 44' 15"E	1060	1-3	Well	Sub-angular blocky	Very gently sloping upland	Slight	Granitic	*Arabica*
P9	Sathihalli, Chickmagalur	13°12' 00"N 75° 39' 00"E	1100	5-10	Well	Sub-angular blocky	Moderately sloping upland	Slight	Granitic	*Arabica* and *Robusta*

The SOC in 0-30 cm decreased from 8.8 kgm^{-2} in P7 to 2.4 kg m^{-2} in P9. In P1 and P6, the SOC stocks ranged from 8 to 10 kgm^{-2}. These two areas are under moist sub-humid to humid region where the biomass production is high. Age of the plantation as well as the numbers of replanting after conversion from forestland also decide the organic carbon stock in the surface soils. In P3, P4, P5 and P7, the SOC ranged from 5 to 6 kg m^{-2}. These areas are under humid to per-humid area where rainfall is very high. Though the biomass production is higher here due to high rainfall and steepness of slope, leaching of organic matter occurs to lower layers. This could be attributed to the low level of SOC in the upper layers. P8 and P9 (sub-humid climate) had very low SOC (2 to 4 kg m^{-2}) in 0 to 30 cm depth. The total biomass production was lower than other regions, which could be attributed to the low rainfall and lighter texture of the soil (Table 3). Soil organic carbon decomposition is lower in the surface horizons of fine textured soils (sand to clay ratio less than one) than those of the coarse textured soils (sand to clay ratio ranging from 2 to 8). P3, P8 and P9 had sand to clay ratio of more than 2 (Table 3) and that seems to be responsible for too low SOC stocks (Tables 5 and 6) in P8 and P9. The relatively high SOC stocks (12.1 kg m^{-2}) in P3 could be attributed to the good management practices, which is evident from the organic carbon content and nutrient status of soil.

The highest SOC stock (17.3 kg m^{-2}) at 0 to 100 cm was reported in P4, where high rainfall resulted in high biomass production. In P1, P3, P5 and P6, the SOC stocks ranged from 10 to 15 kg m^{-2}. In P2 and P7, SOC stocks were in the range 9 to 11 kg m^{-2}. In the 30 to 100 cm depths, the same trend is seen. The higher rainfall subsequently causes translocation of organic matter in suspension (Simonson 1959) to lower layers. The lowest SOC stock at 0 to 100 cm was reported in P8 and P9, which could be attributed to the low rainfall and relatively high temperature in the area and lighter texture of the soil.

Table 3. Physical characteristics of surface soils

Pedons	Soil depth (cm)	Clay (%)	Coarse fragments (Vol. %)	Texture	Sand/ clay ratio
P1	160	50.24	Nil	Clay	0.97
P2	143	44.40	40-60	Clay	0.39
P3	151	22.25	0-60	Sandy clay loam	2.15
P4	151	36.72	Nil	Clay loam	1.19
P5	160	37.30	0-15	Sandy clay	1.61
P6	156	42.31	0-30	Sandy clay	1.1
P7	152	31.50	40-60	Sandy clay loam	1.8
P8	151	26.52	30-60	Sandy clay loam	2.4
P9	107	19.26	05-30	Sandy loam	3.6

Table 4. Chemical characteristics of surface soils and SOC contents (in top 100 cm soil)

Pedons	pH	EC (d Sm^{-1})	Bulk density (Mg m^{-3})	O.C. (%)	CEC [cmol(p+) kg^{-1}]	B.S. (%)	SOC (kg m^{2})
1	6.2	0.08	1.38	2.13	21.21	40	13.33
2	6.1	0.15	0.85	5.29	23.52	95	10.25
3	5.9	0.19	1.22	2.43	33.60	59	12.10
4	6.3	0.11	0.92	2.86	38.05	54	17.32
5	5.3	0.05	1.52	1.47	20.10	98	11.07
6	6.3	0.13	1.42	3.00	21.84	52	14.90
7	4.1	0.06	1.25	1.84	16.59	24	9.44
8	5.5	0.07	1.34	1.61	19.08	60	5.28
9	5.8	0.11	1.38	2.43	28.98	54	3.74

Table 5. Horizon-wise soil organic carbon stocks in different pedons

Depth (cm)	Horizon	OC (%)	BD (Mg m^{-3})	SOC Stock (Kg m^{-2})
Pedon 1: Fine, mixed Ustic Haplohumults				
0-18	Ap	2.13	1.38	5.29
18-31	Bt1	1.54	1.42	2.84
31-47	Bt2	0.66	1.49	1.57
47-87	Bt3	0.48	1.43	2.75
87-125	Bt4	0.47	1.44	2.57
125-160	Bt5C	0.26	1.41	1.28
Pedon 2 : Clayey-skeletal, mixed Dystric Haplustepts				
0-20	Ap	5.29	0.85	4.24
20-41	AB	2.43	0.92	2.04
41-68	Bt1	1.42	0.96	1.89
68-102	Bt2	1.37	0.90	2.21
102-143	BC	0.75	1.15	0.82
Pedon 3: Fine, mixed Ultic Paleustalfs				
0-12	Ap	2.43	1.22	3.56
12-28	AB	1.07	1.28	2.19
28-53	Bt1	0.89	1.37	3.05
53-71	Bt2	0.57	1.34	1.37
71-110	Bt3	0.45	1.43	2.51
110-151	BC	0.33	1.38	1.87
Pedon 4 : Clayey, mixed Ustic Palehumults				
0-16	Ap	2.86	0.92	3.64
16-32	Bt1	1.34	0.96	1.76
32-61	Bt2	1.28	0.98	6.20
61-98	Bt3	0.92	0.99	5.50
98-129	Bt4	0.57	1.10	2.95
129-151	Bt5	0.48	1.20	1.69
Pedon 5 : Clayey, mixed Ustic Palehumult				
0-18	Ap	1.47	1.52	4.02
18-32	Bt1	0.87	1.53	1.86
32-61	Bt2	0.72	1.53	3.19
61-96	Bt3	0.36	1.48	1.86
96-110	Bt4	0.29	1.43	0.52
110-160	Bt5	0.03	1.47	0.15
Pedon 6 : Clayey, mixed Ustic Palehumults				
0-16	Ap	3.01	1.42	6.84
16-38	Bt1	0.98	1.45	3.13
38-71	Bt2	0.75	1.39	3.44
71-107	Bt3	0.39	1.32	1.85
107-135	Bt4	0.24	1.32	0.88
135-156	Bt5	0.24	1.31	0.66
Pedon 7 : Clayey-skeletal Kanhaplic Haplustalfs				
0-21	Ap	1.84	1.25	4.34
21-44	Bt1	1.25	1.41	3.63
44-70	Bt2	0.53	1.67	1.08
70-93	Bt3	0.42	1.88	0.30
93-133	Bt4	0.32	1.60	0.53
133-156	Bt5	0.24	1.71	0.09
Pedon 8 : Loamy-skeletal, mixed Ultic Haplustalfs				
0-14	Ap	1.61	1.34	2.58
14-39	Bt1	0.75	1.57	2.26
39-57	Bt2	0.39	1.67	0.17
57-83	Bt3	0.24	1.63	0.17
83-110	Bt4	0.12	1.67	0.16
110-151	Bt5	0.51	1.60	1.43
Pedon 9 : Fine-loamy, mixed Ultic Haplustalfs				
0-13	Ap	2.43	1.38	1.93
13-39	Bw1	0.86	1.64	0.72
39-60	Bw2	0.78	1.57	0.64
60-88	Bw3	0.42	1.49	0.34
88-107	BC	0.15	1.56	0.12

The highest productivity of 1380 kg ha^{-1} of *Robusta* coffee was reported in P5 followed by that in P7 and P6 (Table 6). In case of *Arabica* coffee, P1 and P4 recorded the maximum productivity of 780 kg ha^{-1} followed by P2. Low productivity in P9 (560 kg ha^{-1}), could be due to low rainfall and also other physical and chemical

Table 6. Annual precipitation, SOC status and productivity of *Arabica* and *Robusta* coffee at different pedon sites

Pedons	Location	Annual Precipitation (mm)	SOC status (kg m^{-2}) 0-30 cm	30-100 cm	0-100 cm	Productivity of dry coffee beans (kg ha^{-1}) *Arabica*	*Robusta*
P1	Shuntikoppa (Somvarpet)	2206	7.91	5.42	13.33	780	1150
P2	Balur (Mudigere)	2379	5.21	5.04	10.25	700	820
P3	Gabbugal (N.R. Pura)	2791	5.99	6.11	12.10	650	920
P4	Kelagur (Mudigere)	2338	5.18	12.11	17.32	780	740
P5	Polibetta (Virajpet)	2083	5.60	5.47	11.07	700	1380
P6	Siddapur, (Virajpet)	2061	8.83	6.06	14.90	620	1100
P7	Arekkad (Madikeri)	3311	5.76	3.68	9.44	630	1240
P8	Gandhehalli (Belur)	1045	4.03	1.25	5.28	700	890
P9	Sathihalli (Chikmagalur)	1575	2.40	1.33	3.74	560	710

*Productivity data collected from Pedon sites at farmers' fields and nearby areas

constraints of soils. Since land quality and carbon sequestration depend on many other factors, productivity cannot be considered as a determining factor. Among the nine pedons, severe erosion was reported in P2, where the SOC stock was 10.3 kg m^{-2}. The relatively lowstock in the otherwise favourable climate may be attributed to the topography, which is steeply sloping hill (25 to 33 % slope).

The correlation of SOC stocks with other soil parameters at different depth ranges was also worked out (Table 7). It is evident that per cent of coarse fragments shows a significant negative correlation at all these depths with soil organic carbon stocks. The content of coarse fragments is the main factor controlling SOC stocks in

Table 7. Correlation of SOC with soil parameters at different depth ranges

Depth range cm	Mean SOC stocks (kg m-2)	Correlation coefficients for Coarse fragments	Per cent clay	pH	Bulk density
0-30	5.56	- 0.4315	0.7821*	0.1762	0.1874
30-100	5.50	- 0.6937*	0.5801	- 0.4561	- 0.7219*
0-100	10.83	- 0.9136**	0.6952*	- 0.2029	- 0.7616*

*Significant at 5% level **Significant at 1% level sub-soil. The coarse fragments act as diluents and determine the quantity of fine earth available for sequestering carbon. The increase in per cent coarse fragments is inversely related to the soil organic carbon stocks and hence to land quality. The per cent clay is positively correlated to SOC stocks at all depths. The soil pH is positively correlated with SOC at 0-30 cm depth, as it is near neutral in reaction. But in lower depths, it is negatively correlated with SOC as pH is reduced to highly acidic levels, especially in P7. Bulk density is negatively correlated with SOC at lower depths.

A range of factors determine the stabilization of carbon in soils, but key variables are clay content and type, pH, hydrology, climate and organic matter inputs. For a given climate, three principal mechanisms account for SOC decline, namely, reduced organic matter input, increased erosion and increased oxidation as a result of tillage.

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