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Article in *Journal of Arid Environments* · February 2007

DOI: 10.1016/j.jaridenv.2006.06.005

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Carbon stock and organic carbon dynamics in soils of Rajasthan, India

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Received 23 March 2005; received in revised form 8 May 2006; accepted 28 June 2006

Available online 15 August 2006

Abstract

Soil carbon stock (CS), was estimated in the 0–25 and 0–100 cm soil depths of arid and semi-arid regions of Rajasthan. Carbon stock was 2.13 Pg in the 0–100 cm soil depth, of which 1.23 Pg was soil organic carbon and 0.90 Pg was soil inorganic carbon. The surface horizon (0–25 cm) stored 31% of the soil carbon stock. Soil carbon stocks were higher in Entisols (0.72 Pg or 33.6% of CS on 43.6% of the land area) and Aridisols (0.70 Pg or 32.7% of CS on 28.9% of the land area) than in Inceptisols (0.61 Pg or 28.6% of CS on 24.01% of the land area), Alfisols (0.015 Pg or 0.007% of CS on 0.76% of the land area) and Verisols (0.105 Pg or 0.005% of the CS on the 3.2% of the land area). Torripsamments, Haplocambids and Haplustepts together held 80% of CS and 86.9% of soil organic carbon stock, whereas Haplocambids, Petrocalcids and Haplustepts comprised 72% inorganic carbon stock. Soil organic carbon density (SOC) ranged from 4000 to 7000 kg/km² in Haplustalfs, Haplusterts, Haplustepts and Torripsamments, while its inorganic counterpart (SIC) was of higher range (10,000–19,000 kg/km²) in Petrocalcids, Haplocalcids, Halpogypsid and Torrifluents. Under scrub vegetation of semi-arid Rajasthan the mean SOC in the 0–25 cm and 0–100 cm depths were 170 and 203.9 kg/km², respectively. In the arid region with similar situation the mean SOC was 5.5 and 14.0 kg/km², respectively. Excessive tillage and intensive cultivation in semi-arid region reduced soil organic carbon density from 60 kg/km² under single cropping to 10.5 kg/km² under double cropping. Subsistence farming in the arid region maintained 47 kg/km² SOC under croplands. SOC declined regularly from 1975 to 2002 in the arid region. A multiple linear regression model that includes rainfall together with tillage, silt, clay, available water capacity (AWC) and period of canopy cover accounted for 97% of the variation in soil organic carbon density for arid regions. The regression model further pointed out that a

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4200–4600 kg/km²/year SOC could be sequestered in untilled soils of the arid region, which have year-round canopy cover.

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Keywords: Multiple linear regression model; Soil organic and inorganic carbon density; Soil organic carbon dynamics

1. Introduction

Soil organic carbon is essential for enhancing soil quality, sustaining and improving food production, maintaining clean water, and reducing increased CO₂ in the atmosphere, whereas its inorganic counterpart is the cause of organic carbon decomposition, developing salinity, restricting root proliferation (Eswaran and van den Berge, 1992; Pal et al., 1999) and immobilizing soil plasma (Buol et al., 1980). The world mineral soils are a large reservoir of carbon with estimate ranging from 1115 to 2200 Pg in a metre soil profile (Post et al., 1982; Eswaran et al., 1993 and Batjes, 1996). More precisely the IPCC estimates 1750 ± 250 Pg, of which 835 Pg is inorganic carbon (IPCC, 2001). Organic carbon stock is estimated 24.3 Pg (Gupta and Rao, 1994) and 63 Pg (Bhattacharya et al., 2000) in Indian soils. However, no valid information on inorganic carbon stock has been documented. There is little published information in India on organic and inorganic carbon densities for different taxonomic units, needed for extrapolating the results at regional, continental and global scale (Kern, 1994). Moreover, mean annual rainfall, tillage, period of canopy cover, AWC, silt and clays have pronounced effects on carbon dynamics (Bruke et al., 1989). Hence a periodical assessment of carbon stock is required. These kind of data help in refining national and global carbon stocks under the influence of changing land use and management scenario (Turner et al., 1993). Periodical assessment of organic carbon is very important in arid and semi-arid regions of Rajasthan, where shrinking water resources, severe erosion, periodic drought, low biological productivity, summer fallowing have detrimental effect on SOC-level. The objectives of this paper are to estimate organic and inorganic carbon density and stocks in arid and semi-arid regions of Rajasthan and to study organic carbon dynamics from 1975 to 2002, with 1975 as the base year.

2. Materials and methods

2.1. Study area

Rajasthan, the largest state in India, extends between 23°30'–30°12' N latitude and 69°30' to 78°17' E longitude and comprises of 324,765 km², or 11% of the total area of India. The arid western part, constituting nearly 60% of the area of Rajasthan, experiences <100–450 mm annual rainfall, and has drifting sand, high wind velocity, severe wind erosion, low biomass and extremes of diurnal and annual temperature changes. The major land use is arable rainfed cropping with pearl millet as the main cereal crop and *kharif* legumes (clusterbean, moth bean, mung bean). Semi-arid eastern Rajasthan falls in the 500–1000 mm annual rainfall zone and is intensively cultivated for pearl-millet/sorghum/*kharif* pulses/maize–wheat/barley/mustard/*rabi* pulses. Soils were mapped into 375 soil

family association units (Shyampura and Sehgal, 1995) during the late 1980s but the soil classification was modified according to the international system of soil taxonomy with 15 great groups, nine suborders and five orders (Soil Survey Staff, 1998). Torripsamments of Entisols, Haplocambids, Haplocalcids and Petrocalcids of Aridisols, dominantly occur in arid Rajasthan. Haplustepts, Haplusterts and Haplustalfs of Inceptisols, Vertisols and Alfisols, respectively, predominantly constitute semi-arid Rajasthan. Torripsamments, Haplocambids and Haplustepts together accounted for nearly 80% of the area of Rajasthan (Table 1).

2.2. Soil sampling and data computation

Ten pedons from each great group were examined in 1992. Samples were collected from each horizon and analysed for organic carbon (Walkely and Black, 1934), CaCO_3 , bulk density and clay content. Soil inorganic carbon, present as CaCO_3 , was measured by manometer after collection of CO_2 evolved during HCl treatment. CaCO_3 equivalent was converted to soil inorganic carbon by multiplying by 0.12 (the mole fraction of carbon in the substrate). The carbonate impregnated in the Ck horizon was not considered in the estimation of inorganic carbon stock unless it was the part of taxonomic classification. Mean organic and inorganic carbon content (g/g) for 0–25 and 0–100 cm soil depths were calculated for 15 great groups. These were multiplied by horizon thickness

Table 1
Carbon stock (Tg) in soils of Rajasthan during 1992 (1000 Tg = 1 Pg)

Soil orders/great groups	Rainfall (mm)	Area (km ²)	SOC		SIC		CS	
			0–25	0–100	0–25	0–100	0–25	0–100
			cm					
Entisols		138278.4	205.7	578.4	56.2	137.7	261.9	716.1
Torripsamments	247.2	102584.4	159.0	511.9	39.7	88.4	198.7	600.3
Ustipsamments	491.4	8571.2	3.3	12.1	0.5	6.0	3.8	18.1
Ustifluvents	550.0	88.4	0.04	0.2	0.1	0.4	0.14	0.6
Torifluvents	260.4	2733.4	1.0	4.9	4.1	31.0	5.1	35.9
Ustorthents	742.5	17805.0	38.5	44.4	8.2	8.9	46.7	53.3
Torriorthents	261.6	6496.0	3.8	4.8	3.5	3.5	7.3	8.3
Aridisols		93082.6	42.3	225.2	43.9	472.1	86.2	697.3
Haplocambids	255.0	74582.6	35.8	190.1	34.9	210.9	70.7	401.0
Haplocalcids	256.3	4032.2	0.9	3.8	4.3	40.9	5.2	44.7
Petrocalcids	241.9	10399.4	4.2	22.3	2.1	190.4	6.3	212.7
Haplogypsid	292.8	1117.2	0.2	0.7	2.2	17.4	2.4	18.2
Haplargids	200.0	2347.8	0.6	4.9	0.2	10.4	0.8	15.3
Haplosalids	350.0	603.4	0.6	3.4	0	2.0	0.6	5.4
Inceptisols		77141.8	81.6	368.2	22.4	250.6	104.0	610.8
Haplustepts	670.1	77141.8	81.6	368.2	22.4	250.6	104.0	610.8
Vertisols		10212.2	17.3	56.7	9.9	49.2	27.2	105.9
Haplusterts	938.0	10212.2	17.3	56.7	9.8	49.2	27.2	105.9
Alfisols		2460.4	4.1	15.7	0	0	4.1	15.7
Haplustalfs	750.0	2460.0	4.1	15.7	0	0	4.1	15.7
Total		321175.0	337.7	1230.7	302.6	899.2	640.3	2129.9

and bulk density (Burnoux et al., 2002) for soil organic (SOC) and SIC. Thirty percent of gravels were subtracted from the values of organic and inorganic carbon density for loamy-skeletal soils. Burnoux et al. (2002) also used a similar procedure for calculating carbon density in soils of Brazil. In the second step of calculation, organic and inorganic carbon densities of each great group were multiplied with their respective area (Batjes, 1996) for quantification of soil organic and inorganic carbon stock. Summation of both forms of carbon of the 15 great soil groups gave total carbon stock in Rajasthan in 1992.

2.3. Database for soil organic carbon dynamics

Soil organic carbon density of Jodhpur soils for 1975 was used as the baseline against which those for subsequent database of 1992 and 1997 (Shyampura et al., 2002) were compared. SOC was also estimated in 2002 during the present investigation. Profiles were dug at the representative locations of each soil series, as established in 1975. Ten additional profiles were sampled from each soil series at an interval of half kilometre or less, depending upon the variability. SOC was calculated for a metre soil profile with respect to each soil series and results were presented in terms of great groups for better interpretations. A metre depth was the lower limit of biological activity in arid and semi-arid regions (Tarafdar et al., 1989). Samples from representative profile in 2002 were also analysed for sand, silt and clay with and without H₂O₂ treatment. The difference of the two estimates gave the amount of soil organic carbon associated with each primary fraction of soils (Tiessen and Stewart, 1983). Core samples were used for bulk density determination (Black, 1965).

2.4. Other database influencing organic carbon dynamics

Spatial variability in rainfall, affecting overall biomass production and annual turnover of organic residue in soils, was determined by superimposing mean annual rainfall on the soil map of Jodhpur in a GIS (Table 2). Tillage opens up the soils for erosion and organic carbon decomposition, while higher AWC promotes build up of soil organic carbon. Although the influences of these factors are pronounced on organic carbon dynamics, valid data for both of them are not available. Consequently, a numerical weighing between 0.1 and 1.0 was given for both of these attributes to generate the correlation matrix. Highest numerical weighing was given to severely eroded sandy and loamy-skeletal soils in the tillage column and the lowest was allocated to slightly eroded fine loamy soils. Weighing was the reverse for AWC. The average period of canopy cover was another factor to be considered because it not only protects organic carbon from erosion but also contributes organic residue in to the soils. A numerical value was generated for the period of canopy cover for each of the soil series, assuming 4 and 8 months duration for single and double crop, respectively. The formula used for calculating the average period of canopy cover was as below:

$$\text{Average period of canopy cover} = (A_m P_m + A_{dc} P_{dc}) / (A_m + A_{dc}),$$

where, A_m is the area under mono crop; A_{dc} the area in double crops; P_m = four months and P_{dc} = eight months.

Table 2
Factors affecting soil organic carbon density in arid Rajasthan

Soil Series	Rainfall (mm)	+C. C period	Clay	Silt	AWC	Tillage
Scores		(%)		Scores		
<i>Coarse loamy, Typic Haplocambids</i>						
Malkosani	361.0	0.4	16.3	26.3	0.5	0.40
Bhagasani	424.0	0.7	9.2	6.5	0.5	0.35
Pal (1)	424.0	0.3	10.5	8.2	0.4	0.65
Pal (2)	361.0	0.3	11.5	18.6	0.5	0.55
Pipar	424.0	0.6	18.5	15.5	0.5	0.50
Kolu	243.7	0.4	8.5	16.5	0.4	0.78
Bap	243.7	0.3	13.2	18.5	0.4	0.80
<i>Loamy-skeletal, Typic Torriorthents</i>						
Soila	251.8	0.6	13.5	6.5	0.3	0.95
Misc. soils	243.7	0.1	4.6	5.2	0.2	0.75
<i>Loamy, Lithic Haplocambids</i>						
Bhopalgarh (1)	424.0	0.7	22.0	8.5	0.4	0.30
<i>Fine loamy, Typic Haplocambids</i>						
Gajsinghpura	424.0	0.8	25.5	17.5	0.7	0.50
Bap variant	243.7	0.4	35.5	20.4	0.75	0.50
Bhopalgarh (2)	424.0	0.6	24.5	10.2	0.5	0.55
Asop	424.0	0.7	36.6	19.6	0.8	0.20
<i>Typic Torripsamments</i>						
Chirai (n)	251.0	0.4	7.2	5.6	0.4	0.80
Chirai (sh)	243.7	0.4	10.6	11.5	0.3	0.80
Chirai (h)	251.7	0.3	5.9	5.7	0.3	0.90
Shergarh	253.8	0.3	5.8	7.3	0.3	0.80
Dune	243.7	0.2	2.2	1.2	0.3	0.90

+C.C- canopy cover, Scores- 0.1–1.0, n- normal, sh- slightly hummocky- h-hummocky.

2.5. Data analysis

Pearson's correlation coefficient (r) was determined for the correlation matrix of all the variables (period of canopy cover, tillage, silt, clay, AWC and rainfall). A multiple linear regression model (MLR) was developed to relate the organic carbon density to a set of outlined independent variables, which is a direct extension of a polynomial regression equation with one independent variable:

$$\text{SOC} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 - \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 - \beta_6 X_6, \quad (1)$$

where β_0 is the intercept, β_1 – β_6 the slopes of the regression line for each independent variable and X_1 – X_6 the independent variables.

3. Results

3.1. Carbon stock in 1992 for a metre soil profile

Total CS was estimated as 2129.9 Tg (1 Tg = 10^{12} g) or 2.13 Pg (1 Pg = 10^{15} g). The surface layer (0–25 cm) had 0.64 Pg, which was about 31% of total carbon (Table 1). Torriorthents and Ustorthents, mainly present on the hills, which comprised about 7.6%

of total area of Rajasthan, together contained 61.6 Tg carbons. Ustifluents, Ustipsamments and Torrifluents (3.5% area) were located along the riverbanks, having 54.6 Tg carbon. Torripsamments and Haplustepts, occupying 31% and 24% of the area respectively, contained the highest carbon stocks—600.3 and 610.8 Tg carbons. Haplocambids, which occupy the second largest area (23.2% area), contained 401.0 Tg carbons. Petrocalcids, Haplocalcids, Haplogypsid and Haplosalids (5.0% area), mapped as subdominant counterparts of Torripsamments in the arid region, together were responsible for 296.3 Tg of carbon in the state. Haplargids (0.73% area) and Haplustalf (0.76% area), contained 15.3 and 15.7 Tg carbon, respectively. Haplusterts (3.1% area) associated with basalt and basaltic alluvia, held only 105.9 Tg carbons.

Soil organic carbon stock was 1230.7 Tg, comprising 58.9% of the carbon stock in the state. Torripsamments, Haplustepts and Haplocambids (79.2% area) together accounted for 86.9% of this form of carbon. The great soil groups Alfisols and Entisols held most of their carbon in the organic form, while Inceptisols, Vertisols and Aridisols contained 60%, 53% and 42% of total carbon stock, respectively, in the organic form. The first 25 cm of soils accounted for 82% of organic carbon in Ustorthents and Torriorthents, whereas for other great groups of Entisols, Inceptisols, Alfisols and Vertisols only 22–32%. The share of organic carbon stock was the lowest (18–23%) in Aridisols.

The soil inorganic carbon stock was 899.2 Tg, constituting 41.1% of carbon stock in Rajasthan. Haplocambids, Petrocalcids and Haplustepts (28.5% area) together comprised 72% of the soil inorganic carbon stock (Table 1). Haplocalcids and Petrocalcids contained around 90% of their carbon in the inorganic form. Surface horizons (0–25 cm) in Torripsamments, Ustorthents and Torriorthents had more inorganic carbon density, whereas in other great groups subsurface horizons contained more inorganic carbon density.

3.2. Carbon density in 1992 for a metre soil profile

Mean carbon density under Aridisols was highest (20,450 kg/km²) in Petrocalcids, followed by Haplogypsid (16,250 kg/km²) and Haplocalcids (11,080 kg/km²), while Haplargids and Haplosalids had carbon densities of 6520 and 9030 kg/km² (Table 3). A higher mean carbon density (13,170 kg/km²) was noticed in Torrifluents among the great groups of Entisols. Mean carbon density in Haplusterts (10,370 kg/km²) was higher than Haplustepts, Haplargids and Haplosalids, however, it was lower than Petrocalcids, Haplogypsid and Haplocalcids. The top 25 cm of Haplusterts, Ustorthents and Haplogypsid had carbon densities above 2150 kg/km² (Table 3), while it was lower in other great groups.

The maximum organic carbon density (SOC) was observed (6360 kg/km²) in Haplustalfs followed by Haplosalids (5670 kg/km²) and Haplusterts (5560 kg/km²), whereas lower SOC was noted in Haplogypsid (650 kg/km²), Torriorthents (740 kg/km²) and Haplocalcids (940 kg/km²). Surface horizons in Ustorthents contained higher (2160 kg/km²) mean SOC than corresponding horizons of other great groups (Table 3). Haplustalfs (6200 kg/km²) and soils of desert ecosystems (5000–6000 kg/km²) in the US (Schlesinger, 1977) showed a resemblance to Haplustalfs (6340 kg/km²) and Torripsamments (4990 kg/km²) of Rajasthan for mean SOC.

SIC was higher in Petrocalcids (18,310 kg/km²) followed by Haplogypsid (15,600 kg/km²) and Torrifluents (11,350 kg/km²). Haplustepts and Haplusterts showed only 3000–5000 kg/km²

Table 3
Mean soil carbon density (kg/km²), Rajasthan 1992

Great groups	Organic		Inorganic		Total	
	0–25 cm	0–100 cm	0–25 cm	0–100 cm	0–25 cm	0–100 cm
<i>Entisols, with Psammments, Fluvents and Orthents sub orders</i>						
Torripsammments	1550	4990	390	860	1940	5850
Ustipsammments	380	1420	60	700	440	2110
Ustifluvents	450	1920	1470	4980	1920	6900
Torifluvents	380	1820	1510	11350	1880	13170
Ustorthents	2160	2490	460	470	2620	2960
Torriorthents	580	740	540	540	1120	1280
<i>Aridisols, with Cambids, Calcids, Gypsid and Salids sub orders</i>						
Haplocambids	480	2550	470	2830	950	5380
Haplocalcids	220	940	1070	10150	1290	11080
Petrocalcids	410	2140	210	18310	610	20450
Haplogypsid	130	650	2010	15600	2150	16250
Haplargids	240	2080	90	4440	340	6520
Haplosalids	1080	5670	0	3360	1080	9030
<i>Inceptisols, with Ustepts sub order</i>						
Haplustepts	1060	4770	290	3250	1350	7920
<i>Vertisols, with Usterts sub order</i>						
Haplusterts	1690	5560	970	4810	2660	10370
<i>Alfisols, with Ustalfs sub order</i>						
Haplustalfs	1680	6360	0	0	1680	6360

SIC. Mean SOC in Aridisols of Rajasthan was found lower than the similar soils (Arid Ecosystem of Arizona) in the US (Schlesinger, 1982).

3.3. Soil organic and inorganic carbon density in 1992 for a metre soil profile by land use

Mean SOC (0–25, 0–100 cm) for soils of the arid region under scrub vegetation was lower (5.5, 14.0 kg/km²) than corresponding soils of the semi-arid region (170.0, 203.9 kg/km²). Soils under single and double cropping systems in the arid region contained a higher mean SOC (Table 4) than their counterparts under scrub vegetation, while the reverse was the case for soils of the semi-arid region. In general soil inorganic carbon density was higher in soils used for single cropping.

3.4. Soil organic carbon dynamics from 1975 to 2002 in the arid region

Mean SOC varied with soil texture and depth (Fig. 1). It was the highest in fine loamy soils (3600 kg/km²) and lowest in loamy-skeletal soils (800 kg/km²). Mean SOC in deep coarse loamy soils (3000 kg/km²) was higher than their moderately deep counterparts (2250 kg/km²). SOC depletion varied from 1.6% to 8.3% from 1975 to 1992. Subsequent depletion was 6–7% and 4.0–4.1% in loamy-skeletal and sandy soils from 1992 to 1997 and 1997 to 2002, respectively. SOC depletion from 1975 to 2002 was around 3% in coarse loamy soils. Loamy and fine loamy soils witnessed SOC depletion of only 0.6% in each of the 5 years from 1992 to 1997 and 1997 to 2002, after a 4.5% initial depletion during

Table 4

Mean organic and inorganic carbon density (kg/km^2) by land use for the 0–25 cm soil horizon/layer in 1992

Cropping Pattern	Arid region		Semi arid region	
	Organic	Inorganic	Organic	Inorganic
Scrub	5.5 (14.0)	3.0 (7.9)	170.0 (203.9)	59.0 (120.6)
Single	47.2 (195.9)	1.0 (596.5)	64.1 (88.9)	88.0 (283.1)
Double	44.1 (258.6)	54.0 (146.0)	10.5 (42.8)	11.0 (30.4)

Figure in parenthesis, soil organic carbon density in 0–100 cm soil layer.

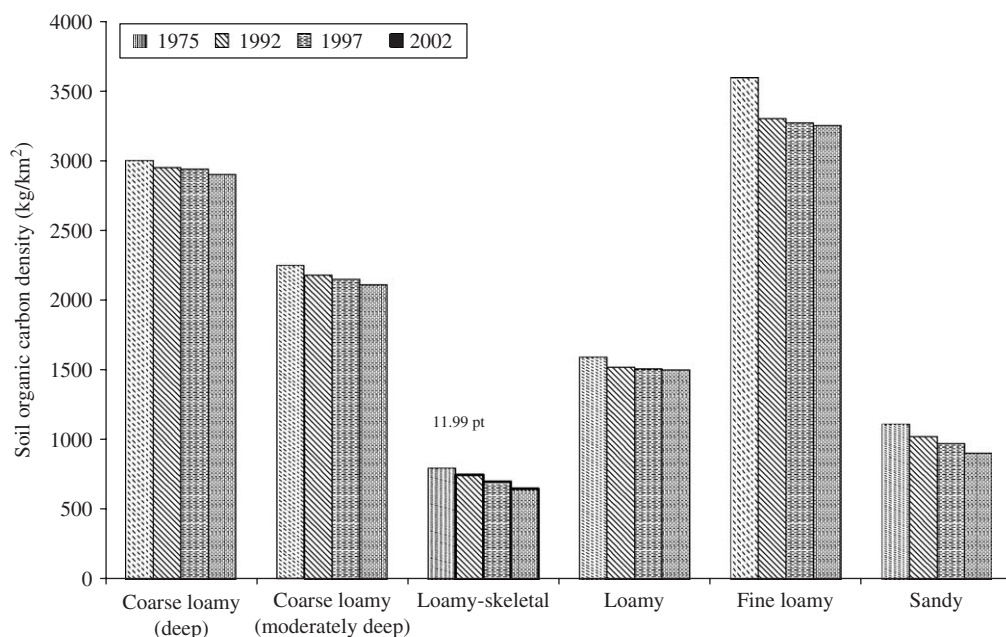


Fig. 1. SOC in chronosequence for arid Rajasthan.

1975–1992 (Fig. 1). Sand size organic carbon depletion was 360, 270 and 11 kg/km^2 in fine loamy, coarse loamy and sandy soils, respectively from 1975 to 2002, while corresponding silt size loss was of 80, 30 and 0 kg/km^2 during the estimated period. Clay size SOC depletion was 50 and 7 kg/km^2 in coarse loamy and sandy soils, while fine loamy soils attained a gain of 30 kg/km^2 organic carbons from 1975 to 2002. Over all SOC loss was higher in fine loamy than coarse loamy and sandy soils.

3.5. Multi-linear regression model

A multi-linear regression model has been developed for predicting SOC in the arid region using the database of Jodhpur district where data was collected from maps at

1:50,000 scales (Table 2). This scale of database eliminates the impact of major variations in land use, mineralogical makeup and mode of weathering. Factors which have a significant correlation ($n = 21$, $P < 0.01$) with SOC, such as mean annual rainfall ($r = 0.72$), silt ($r = 0.64$), clay ($r = 0.73$), AWC ($r = 0.89$), period of canopy cover ($r = 0.70$) and tillage ($r = -0.89$), were chosen for the regression model. Bruke et al. (1989) used these factors, with the addition of temperature, to develop a regression equation in grassland soils of US. However, mean annual temperature was not included in this study because there is no temperature gradient across the arid region. A first-order multi-linear regression equation to predict SOC on a yearly basis was found in Eq. (2). These factors account for 97% of variations in SOC:

$$\begin{aligned} \text{Organic carbon density (kg/km}^2\text{)} &= 4.4 + 0.0001052 \\ &(\text{rainfall, mm}) + 0.43914 (\text{canopy cover}) \\ &- 0.00505 (\text{clay}) + 0.008722 (\text{Silt}) \\ &+ 0.955712 (\text{AWC}) - 4.53 (\text{Tillage}), r^2 = 0.97. \end{aligned} \quad (2)$$

Performance of the model was tested with SOC data of 1992 and 1997 for different soil series of Jodhpur district (Fig. 2). The regression analysis showed good agreement for the estimated and predicted SOC with slope very close to 1 (Fig. 3). However, a scattering of observed values from the regression line at higher SOC values (Fig. 3) signified limited applicability of model, perhaps restricted to arid regions where SOC ranges from less than 1000 to 3600 kg/km² and rainfall varies from 200 to 500 mm.

3.6. Soil organic carbon potentials in arid Rajasthan

The regression model predicts that in a normal rainfall year, a maximum of 4200–4600 kg/km²/yr SOC could be sequestered in untilled soils that have a year-round canopy cover. Of the sequestered carbon, 500–3200 kg/km² could be held by the clay and silt fractions of soils, while 900–4400 kg/km² by the sand fraction. The calculations from our model indicated that 2800–3500, 700–2900, 200–1400 and 2600–4000 kg/km² SOC could be sequestered in sandy, coarse loamy, fine loamy and loamy-skeletal soils, respectively.

4. Discussion

4.1. Reasons for variation in organic carbon density and stock

A higher SOC in Alfisols, Vertisols and Inceptisols as compared to Aridisols could be explained by higher rainfall, larger vegetative input and higher clay content. Organic carbon associated with sand particles was readily decomposable as compared to that in silt and clay. Clay with high surface area protects organic carbon from decomposition on developing stable clay- organic complexes (Bruke et al., 1989). However, this relationship between clays and organic carbon does not always occur. Theoretically Haplusterts of Vertisols in the semi-arid region should have higher SOC than Haplustalfs of Alfisols on account of higher rainfall, higher AWC and larger quantity of 2:1 type of clay minerals (Singh et al., 2003a,b). However, the reverse has emerged in the present investigation because of stable ferro-organo complexes in Alfisols (Shyampura et al., 1994).

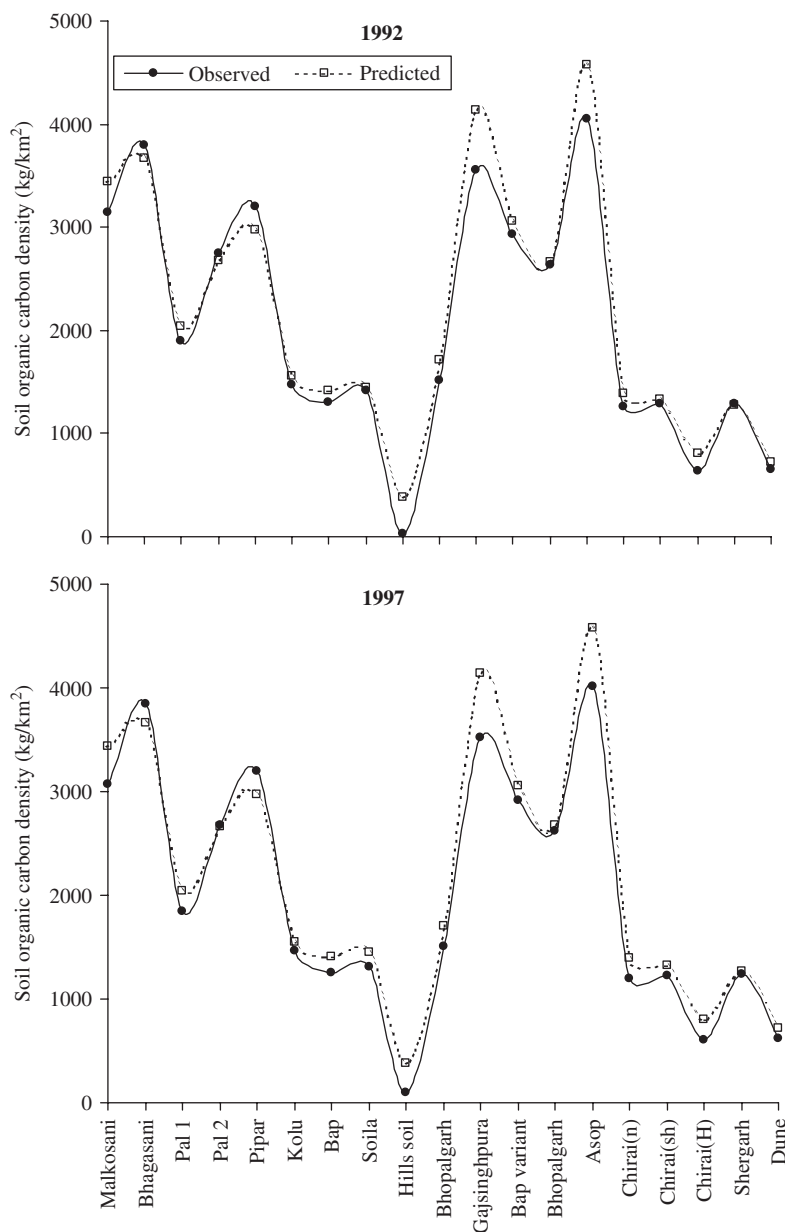


Fig. 2. Observed and predicted SOC for a meter soil profile in soil series of Jodhpur for the years 1992 and 1997.

and year-round canopy cover in the traditional agroforestry system that prevails in the area. In contrast, intensive agriculture with commercial annual crops that demands extensive tillage reduced the positive implication of 2:1 type of clays in Vertisols. Velayutham et al. (2002) gave a similar interpretation for lower SOC in Vertisols than Alfisols of Maharashtra, India. Decrease of SOC on account of intensive cropping was also

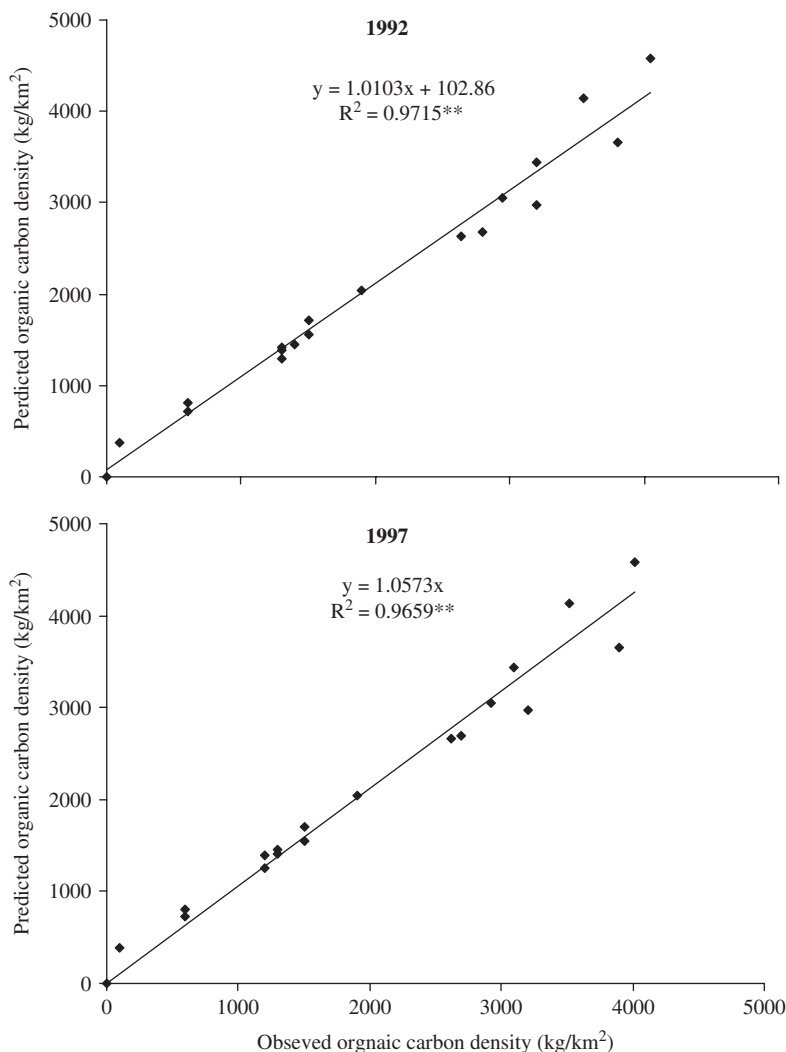


Fig. 3. Relationship between observed and predicted SOC for the year 1992 and 1997 in arid Rajasthan (** $P < 0.01$).

reported by Jolivet et al. (1997), Walker et al. (2000), Shepherd et al. (2001), Murty et al. (2002) and Keeny et al. (2002). In the arid region, croplands have higher SOC than their uncultivated counterparts. This result corroborates with the findings of Kumar et al. (1997) who reported an increased SOC in the pearl-millet legume sequence over an untilled control. This could be explained by the prevailing agroforestry system in the region, where cropping was practiced only in good rainfall years. Existing trees and lands were left untilled with native vegetation during drought years. Animals were allowed to graze so that deposition of excreta and decay of natural grasses might have enriched the soils. Occasional tillage only on these lands further restricted the loss of organic carbon because decomposition and erosion have lessened. Thus the agroforestry system of cultivation has

a profound impact on SOC that not only regulates the impacts of rainfall, clay and type of clay in semi-arid region but also corrects the negative influence of high temperature and poor physical condition of soils in the arid region. Improper selection of crops, even within the agroforestry system, adversely affected the organic carbon dynamics as evident from declining SOC from 1975 to 2002 in the arid region. Observations indicated that imbalance of any of the factors including rainfall; tillage, AWC, clay and silt content with canopy cover resulted in SOC loss. Thus a multi-linear regression model, depicting the combined influence of these factors explains 97% variation in SOC of arid Rajasthan.

Besides the above-mentioned factors, bulk density and area of the individual soils have conspicuous influence on organic carbon density and stocks, respectively. A close resemblance of SOC in Torripsamments to that of Haplustepts, in spite of lower organic carbon content, demonstrated the influence of bulk density, i.e. %C was lower, but the bulk density was higher, giving high C density. Similarly inclusion of area in organic carbon stock calculations overshadowed the influence of organic carbon density (Burnoux et al., 2002), i.e. %C was higher, but the area was lower, giving lower carbon stock. A higher soil organic carbon stock in Torripsamments than the great groups of Alfisols, Inceptisols and Vertisols confirmed the observation.

4.2. Reasons for variation in inorganic carbon density and stock

Aridisols had more inorganic carbon density than any other soil orders tested because of CaCO_3 weathering and its subsequent precipitation in the soil solum (Singh et al., 2003a, b). Recurring drought and lower organic ion activity (Schlesinger and Pitmanis, 1998) in the arid region further increased the process of calcium precipitation. A negative significant interrelationship ($r = -0.50$, $P < 0.05$) between organic and inorganic forms of carbon further support the present contentions as well (Eswaran et al., 1993). However, impact of irrigation with high RSC water could not be discounted on the increased soil inorganic carbon density in Aridisols (Suarez, 2000). The fact is evident from higher SIC in the 0–25 cm than 0–100 cm soils of Torripsamments, Ustorthents and Torriorthents cultivated for cereals with support of life saving irrigation (Table 3). Comparatively good quality of ground water and presence of carbonate rich substratum below a metre of soil profile explained the lower inorganic carbon density in Alfisols, Vertisols and Inceptisols. Excessive leaching and occasional cultivation might have precluded inorganic carbon accumulations in Entisols. Therefore, combined influence of carbonates as parent materials and irrigation with carbonate and bicarbonate rich water explained high inorganic carbon density in Aridisols, which are generally used for single cropping.

5. Conclusions

The present data showed that parent material, frequency and quality of irrigation water govern SIC, while rainfall, clay content and land use pattern influenced organic carbon density. Intensive agriculture without proper management in the semi-arid region was the cause of rapid SOC depletion in cropland as compared to untilled soils under scrub vegetation. Subsistence farming under agroforestry systems in the arid region during good rainfall years not only protected SOC from degradation but also improved soil organic carbon density in croplands. However, improper selection of crops and management, even in an agroforestry system, leads to the depletion of SOC in the arid region. Respective

areas of the soils in Rajasthan have profound impact on soils organic carbon stock, while inorganic carbon density was the dominant factor governing inorganic carbon stock in the state.

Acknowledgements

We thank Prof. Damián Andres Ravetta and anonymous reviewers for their constructive suggestions and ICAR for financial support.

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