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Are the soil properties and organic carbon stocks influenced by different land use systems in tropical semi-arid region, India?

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ABSTRACT

Different land uses significantly affect soil properties due to variations in organic matter addition, decomposition, and stabilization. A study assessed organic carbon stock in soils from various landforms and its use in granite-gneiss and schist geological settings in the semi-arid Chitradurga district, Karnataka. Nine soil profiles (pedons) from upland areas and four from lowland areas were analyzed. Soil characteristics such as pH, electrical conductivity (EC), organic carbon (OC), clay content, bulk density (BD), cation exchange capacity (CEC), base saturation, and calcium carbonate equivalent (CCE) were measured. The results showed a pH range from 6.09 (slightly acidic) to 9.74 (very alkaline) with non-saline soils (EC < 2 dS m^{-1}). Organic carbon levels varied from 1.40 to 7.30 g kg^{-1} in the surface layer and 1.10 to 8.50 g kg^{-1} in the subsurface layer. Clay content ranged from 6.92% to 53.52% (surface) and from 9.83% to 64.81% (subsurface). Bulk density ranged from 1.31 to 1.98 Mg m^{-3} (surface) and 0.78 to 1.89 Mg m^{-3} (subsurface). Cation exchange capacity spanned from 3.44 to 53.14 cmol (p+) kg^{-1} (surface) and from 4.92 to 57.93 cmol (p+) kg^{-1} (subsurface). Base saturation was between 37% and over 100%. Organic carbon stock ranged from 0.33 to 1.95 kg m^{-2} (surface) and from 0.23 to 5.46 kg m^{-2} (subsurface). Fallow land and sapota plantations had higher organic carbon stocks than agricultural lands, with coconut and banana plantations following. Most pedons had low organic carbon content, were alkaline, calcareous, and experienced moderate to severe erosion. To address these issues, implementing management practices like reclamation, irrigation, organic manure application, and soil conservation measures is critical for improving crop yield, controlling erosion, and maintaining soil health and sustainability.

HIGHLIGHTS

- Soil organic carbon stocks (SOCS) influenced by soils of different land use systems.
- Bulk density of soils ranged from 1.31-1.98 on the surface to 0.78-1.89 Mg m^{-3} in subsurface.
- SOCS ranged from 0.33-1.95 on surface to 0.23 to 5.46 kg m^{-2} in subsurface soils.
- Fallow land and plantations recorded higher SOCS compared to agricultural lands.

1 | INTRODUCTION

The stock and stability of soil organic carbon (SOC) are critical to soil functions and the global carbon cycle. However, little quantitative information is available on the precise location across various climatic gradients. SOC storage is regulated by climatic conditions at the regional scale. The soils semi-arid climate regions in Chitradurga district, Karnataka, are prone to erosion, and high temperature influences higher oxidation of organic matter, making the soil maintain soil organic carbon levels, resulting in land / soil degradation due to its changes in climate from humid to semiarid and arid which dominantly influences soil organic carbon stocks and fluxes. Different land use has more significant implications on soil properties due to its differential organic matter addition, decomposition and stabilization rate. Soil fertility is one of the critical factors controlling crop yields in hot, moist, semi-arid eco sub-regions like Chitradurga district; it receives low to moderate rainfall and is one of the drought-prone districts in the state. Intensive agriculture without adequate and balanced use of chemical fertilizers and with little or no use of organic manure caused low C inputs, thereby causing severe fertility deterioration of agricultural soils, resulting in stagnating or even declining crop productivity and soil health and resulting in barren and unproductive lands over long-term cultivation in drought-prone coupled with erosion prone areas like Chitradurga district. Chemical land degradation due to low C levels and nutrient status in soil highly affects rural livelihoods, land productivity, and sustainability, and it then reduces the soil's productive capacity, exacerbating poverty and food and nutritional insecurity. In the context of global warming, understanding the SOC stabilization mechanisms across different climatic and edaphic conditions is of prime importance to improve the prediction of SOC dynamic and global C cycle (Lal, 2004). Soil is the largest carbon sink, leading to atmospheric CO_2 concentrations. Hence, Soil Organic Carbon Stock (SOCS) significantly influences the global carbon cycle. The geology, landform, and land use have impacted soil fertility, agricultural productivity, food security, terrestrial and global carbon cycle and climate change. Climatic conditions such as temperature and precipitation influenced the association of SOC with minerals by governing soil chemical weathering. The slope gradient, topography, biomass production / vegetation, land use, land cover change, erosion-induced topsoil loss, altitude and climate, and fire affect SOCS. Different type of land use influences the quantity of carbon stock due to its differential rate of production, addition and accumulation of biomass and vegetation; various researchers reported significant variation in SOCS due to changes in land use land cover. Long-term cultivation and monoculture without proper nutrients and manure input reduces SOCS and carbon content in soil due to nutrient imbalance. Reducing SOCS and carbon content reduces soil and land productivity and fertility by influencing soil nutrient retention, physical structure, and water-holding capacity. Thus, changes in land use type support soil property and maintain soil health and sustainability by controlling land degradation / deterioration and soil erosion. Similarly to land use, landform positively or negatively influences soil properties by varying vegetation cover and availability of soil moisture content for biomass production. Generally, lowlands will have better AWC than uplands, which influences biomass production and distribution, thereby SOCS. Also, climatic conditions such as rainfall and temperature influence land use cover and SOCS; when precipitation rises, and temperature becomes colder, it changes vegetation distribution, and a rise in temperature leads to oxidation of organic matter and stabilization, thus affecting SOC stock. However, geology such as granite-gneiss and schist are developed under different rates of metamorphism under different heat and pressures, resulted different mineral compositions (gneiss developed under high heat and temperature under high-grade metamorphism resulted in mineral composition of quarts and sodium and potassium feldspar whereas schist developed under medium grade heat and pressure and medium metamorphism resulted in mineral composition of mica, chlorite and talc) which influences differential rate of mineral weathering degree thus influences nutrient composition in soil particularly organic carbon thereby SOCS. With these above views, the present investigation has been undertaken in the semiarid region of Chitradurga district, Karnataka, with the objectives i) to know the soil physicochemical properties in soils of different landforms and land use systems, ii) to determine the bulk density in soils, of different landform and land use systems and iii) to estimate organic carbon stock in soils of different landform and land use systems.

2 | MATERIALS AND METHODS

2.1 | Study Area

Chitradurga owes its name to “Chitrakaladurga,” or “Picturesque castle”. This massive fortress on top of granite hills rises dramatically from the ground. The present study has taken up in the southern part of the Chitradurga district i.e., Hiriyur and Hosadurga taluks with a total geographical area (TGA) of 1.72 lakh ha and 1.45 lakh ha, respectively lying between the north latitude of 13º 32' 20.721" to 15º 3' 27.178" N latitude to east longitude of 75º 58' 55.046" to 77º 55' 57" E with an elevation ranging from 569 m (main valley) to 760 m (Pediment) above mean sea level (amsl) (Fig.1). These taluks fall under Agroclimatic Region (Planning Commission) Southern Plateau and Hills Region-10 and Agroclimatic Zone-4 i.e. Central Dry Zone and Agroecological sub-region: 8.2. i.e. Central Karnataka Plateau, hot moist semi-arid eco sub-region. Hiriyuru taluk has 32 gram panchayats covering 159 villages in 4 hoblies and Hosadurga taluk has 33 gram panchayats covering 225 villages in 4 hoblies. The soil temperature regime is isohyperthermic. These taluks receive scanty and unevenly distributed rainfall from the southwestern monsoon (June-September) and NE Monsoon (October-December). The average rainfall of the district is 592.5 mm, with 32 rainy days. However, Hiriyuru taluk receives 549.9 mm on 29 rainy days, and Hosadurga taluk receives 626.4 mm on 32.1 rainy days. The district's average minimum temperature is 21.0 °C, and the maximum is 31.8 °C. The minimum and maximum temperatures of Hiriyur are 21.0 °C and 32.0 °C, respectively, whereas that of Hosadurga is 22 °C and 32.0 °C. In Hiriyur and Hosadurga taluks, granitic-gneisses and schists are the main ground water bearing formations. The highest cropping intensity is in Hiriyuru taluk (122%),

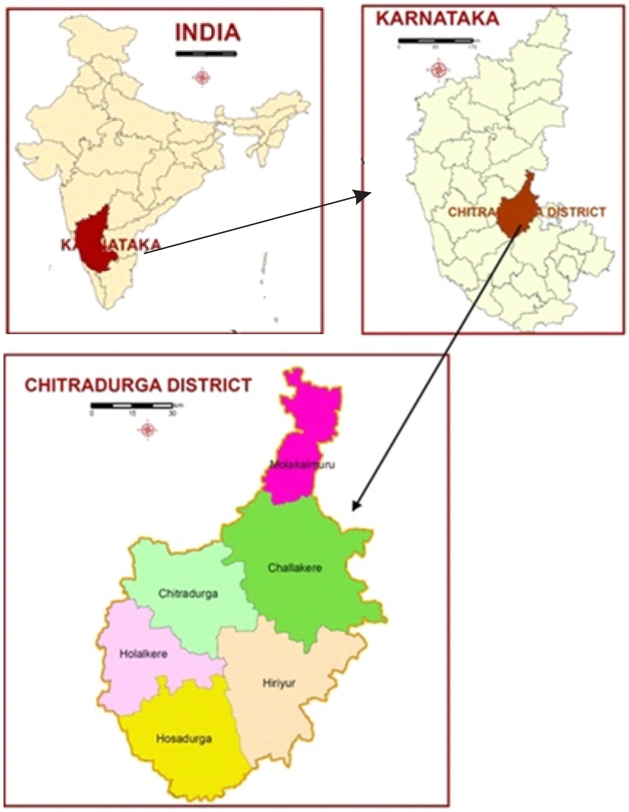

FIGURE 1 Location map of Chitradurga district, Karnataka

mainly because of the area under irrigation. The Chitradurga district has minimal irrigation resources, and the agriculture of the district is mainly rainfed. These taluks have granite-gneiss and schist geology (Fig. 2). Slope of the area is nearly level to (0-1%) and very gently sloping (1-3%), and little area is gently sloping (3-5%) uplands. Agriculture is the major economic activity. Major land use is maize, finger millet, jowar, paddy, red gram, ground nut, sunflower, banana, mango, pomegranate, sapota, onion, chilly, tomato, brinjal, coconut, areca nut, beetle vine, crosandra, jasmine, and chrysanthemum are being cultivated (Fig. 3). Natural vegetation is Prosopis sp., Lantana, Tamarind, Acacia sp., Neem, Cactus etc. (Fig. 4).

2.2 | Detailed soil characterisation and laboratory soil analysis

Detailed soil survey carried out on 1:10000 scale using landform map; land uses land cover map prepared by sentinel-2 satellite imagery and survey of India toposheets (1:50,000 scale) in Hiriyur and Hosadurga taluks during February to March 2023 followed by depth-wise soil samples collected from nine pedons from uplands from different land uses viz., ground nut, sorghum, maize, bengal gram, sunflower, coconut plantation, sapota plantation and fallow land and also four pedons from lowlands of different land uses viz., ground nut, bengal gram, banana plantation

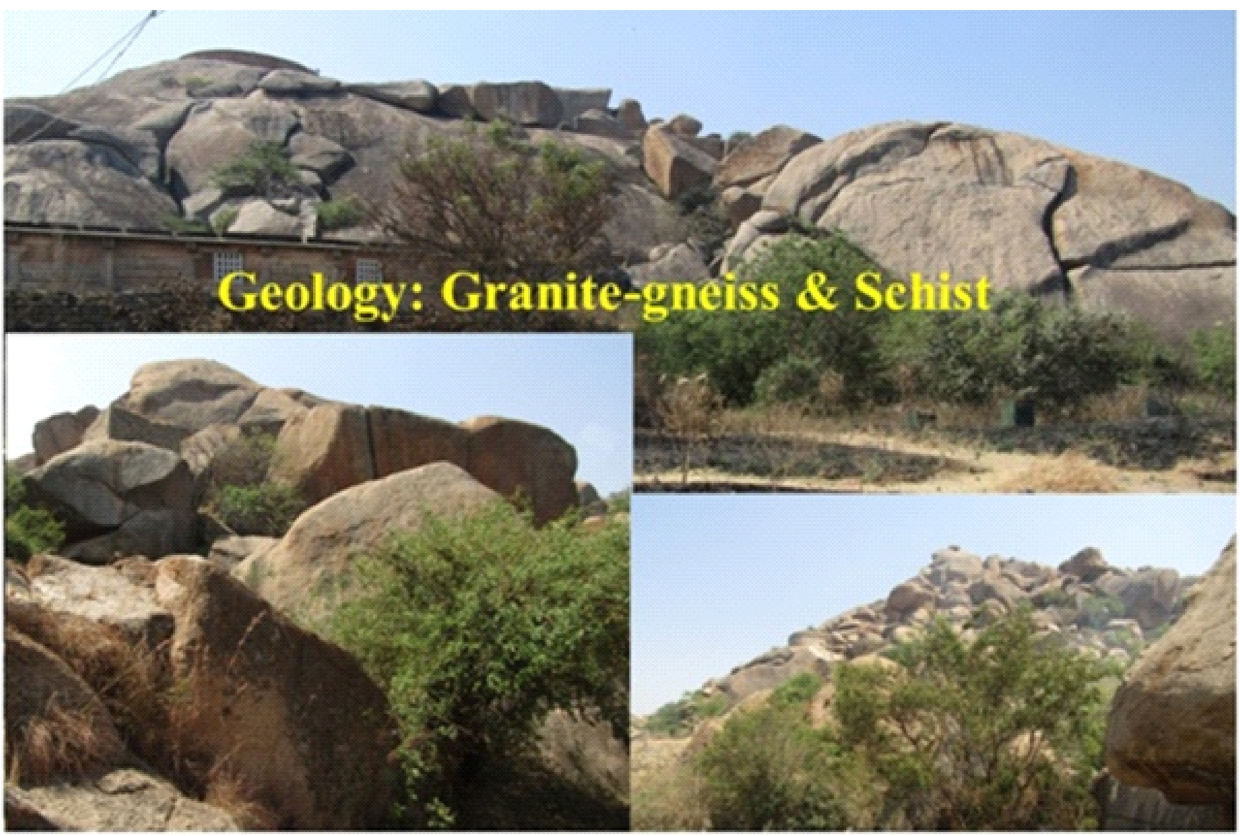

FIGURE 2 Geology of the tropical semi-arid region, Chitradurga district, Karnataka

FIGURE 3 Land use pattern of the tropical semi-arid region, Chitradurga district, Karnataka

FIGURE 4 Natural vegetation in the tropical semi-arid region, Chitradurga district, Karnataka

and coconut plantation of from both the two geology (Granite-gneiss and Schist). Bulk density samples were collected using a standard core from all 13 pedons from all the depths. Horizon-wise soil profile samples were brought to the laboratory, air-dried, ground and sieved through a 2-mm sieve. The samples were analysed for their particle size class, soil reaction, electrical conductivity, organic carbon, cation exchange capacity, exchangeable bases, and calcium carbonate equivalent following standard procedures as outlined in Table 1. Bulk density was estimated using the oven-dry weight of core soil samples divided by core volume, and base saturations were estimated by taking the summation of all the bases divided by CEC for all the pedons. Soil organic carbon stocks were estimated using the equation below.

$$\text{SOCS}\ (\text{kg m}^{-2}) = \text{OC}\ (\text{g kg}^{-1}) \times \text{BD}\ (\text{Mg m}^{-3}) \times \text{Depth (m)}$$

Where, SOCS - representative C stock for the soil of interest in kg m^{-2}. OC - concentration of soil organic carbon in a given soil mass in g C kg^{-1}. BD - Bulk Density - soil mass per sample volume in Mg m^{-3}. Depth - horizon depth or thickness of soil layer in m.

3 | RESULT AND DISCUSSION

3.1 | Morphological properties of soils under different landforms and land use

Morphological properties of soils of different landforms and land use are presented in Table 2, which shows that soils are shallow (25-50 cm) to deep (100-150 cm). Different soil depths are due to differences in landform, physiography and slope gradient of the land; however, this indicates that soils are under development and climatic conditions are not congenial for weathering; hence, very deep soils have not been identified. Soil colour varied from dark red (2.5YR 3/6), dark reddish brown (5 YR 3/3), dark brown & brown (7.5YR 3/4; 4/3; 4/4), very dark grey, very dark greyish brown, dark yellowish brown (10YR 3/1, 10YR 3/2, 10YR 4/3) in surface to dark reddish brown, red (2.5YR3/4; 4/6), dark reddish brown, reddish brown, (5YR 3/3, 4/3), dark brown, (7.5YR3/4, 3/3), very dark grey, very dark greyish brown, dark brown, dark yellowish brown (10YR 3/1; 3/2; 3/3, 3/4) in subsurface. Different colour due to different parent materials and mineral composition (quartz, potassium and sodium feldspar, mica, talc, chlorite) and iron is oxidised more readily due to the higher oxygen content as the semi-arid climatic conditions with low rainfall imparted red and red associated colour and coatings of organic compounds on soils by organic matter addition, accumulation and decomposition with the parent materials during weathering process imparted brown and grey associated colour (Chandrakala *et al*., 2023) Texture of the soil varied from loamy sand, sandy loam, sandy clay loam, clay loam and clay in surface to loamy sand, sandy loam, sandy clay loam, silty loam, silty clay loam, clay loam and clay in subsurface. Different textures are due to differential rates of weathering degree of minerals and soils. Generally, the texture will not change in a short-term period; changes occur over a very long period under intense weathering and soil-forming processes. The soil structure varied from weak to moderate, with medium sub-angular blocky. Consistency varied from friable to firm and very firm, non-sticky to moderately sticky, slightly sticky, sticky and very sticky and non-plastic to moderately plastic, plastic and very plastic. The rate of organic matter addition and soil aggregate formation influenced soil structure and consistency. Coarse fragments/ gravels varied from 0 to 60 %. Erosion was slight to moderate in the lowlands to moderate to severe in the uplands. In the drought prone areas of the Karnataka state, moisture stress during crop growth period is a major challenge to crop production, emphasizing needs of conserving soil moisture. For conserving soil moisture, adoption of soil and water conservation (SWC) technologies is critical because of their various synergetic and positive impact on sustaining natural resources and rendering resilience to crop production in drought prone areas like Chitradurga district (Kumar *et al.,* 2021). Erosion was slight under soil / land covered with soil conservation measures like graded bunding and contour bunding with lower slope (0-1%) areas. Severe erosion was noticed in uplands with higher slopes (2-5%) without proper soil conservation measures. Hence, suitable soil conservation measures like residue recycling, mulching, cover cropping in conjunction with contour farming, terracing and simple engineering structures and also reliable and proven soil conservation technologies include ridge-planting, no-till cultivation, crop rotation, strip cropping and contour planting, and cover crops can be adopted to control soil erosion in uplands (Sharda *et al.,* 2019).

TABLE 1 Methods employed for soil analysis in the present study

S.No.	Analytical Parameter	Method	Reference (s)
1.	Particle size analysis	International pipette method	Piper (1966)
2.	Bulk density	Core sampler method	Blake and Hartge (1986)
3.	Soil reaction (pH)	pH meter with a glass electrode (soil water ratio 1:2.5)	Jackson (1973)
4.	Electrical Conductivity (EC)	Conductometry (soil water ratio 1:2.5)	Jackson (1973)
5.	Organic carbon	Chromic acid wet digestion	Walkley and Black (1934)
6.	Free calcium carbonate	Rapid titration method	Piper (1966)
7.	Cation Exchange Capacity (CEC)	Neutral Normal Ammonium acetate method	Schollenberger and Dreibelbis (1930)

TABLE 2 Morphological properties, bulk density and soil organic carbon stock (SOCS) in soils of different landforms and land use, tropical semi-arid region, Karnataka

Depth (cm)	Horizon	Colour	Texture	Structure	Consistence	Coarse fragments	Erosion	BD ($mg\ m^{-3}$)	SOCS ($kg\ m^{-2}$)
Granite -gneiss : Uplands									
Pedon 1: P71: Ground nut									
0-14	Ap	2.5YR3/6	scl	2msbk	fr, ms, mp	-	severe	1.68	0.33
14-35	Bt	2.5YR3/4	sc	1msbk	fr, s, p	40-50		1.48	1.80
Pedon 2: P46: Sorghum									
0-12	Ap	7.5YR3/4	scl	2msbk	fr, ss, sp	25-30	severe	1.31	0.80
12-38	Bw1k	10YR3/4	scl	2msbk	fi, s, p	-		1.45	0.68
38-57	Bw2k	2.5Y5/4	cl	2msbk	fi, s, p	-		1.70	0.45
57-85	Bw3k	2.5Y5/4	scl	2msbk	fi, s, p	-		1.17	0.46
Pedon 3: P63: Maize intercrop with sunflower									
0-16	Ap	10YR3/1	c	3msbk	fi, vs, vp	-	moderate	1.35	0.87
16-38	Bw1k	10YR3/1	c	3msbk	fi, vs, vp	-		1.54	1.36
38-57	Bw2k	10YR3/1	c	3msbk	fi, vs, vp	-		1.54	1.17
57-82	Bw3k	10YR3/1	c	3msbk	fi, vs, vp	-		1.23	1.02
82-100	Bw4k	10YR3/1	c	3msbk	fi, vs, vp	-		1.16	0.23
Pedon 4: P37: Fallow land									
0-13	Ap	5YR3/3	sl	2msbk	fr, ms, mp	-	moderate	1.54	1.93
13-32	Bt	5YR3/3	scl	2msbk	fr, ms, mp	35-50		1.48	0.31
32-70	BC	5YR4/3	sl	1msbk	fr, ss, sp	>50		1.61	5.46
Pedon 5: P119: Fallow land									
0-13	Ap	2.5YR3/4	sl	1msbk	fr, ss, sp	20-30	severe	1.57	1.12
13-32	Bt	2.5YR4/6	sl	1msbk	fr, ss, sp	20-25		1.26	0.79
32-50	BC	2.5YR4/6	sl	1msbk	fr, ns, np	5-10		1.41	0.56
Pedon 6: P22: Coconut plantation									
0-17	Ap	7.5YR4/3	ls	1msbk	fr, ns, np	-	moderate	1.98	1.11
17-33	AB	5YR4/3	ls	1msbk	fr, ns, np	-		1.89	1.00
33-60	Bt1	2.5YR3/4	c	1msbk	fr, s, p	>60		1.34	1.59
Lowlands									
Pedon 7: P21: Ground nut									
0-13	Ap	2.5YR3/4	scl	1msbk	fr, ss, sp	10-15	moderate	1.50	0.51
13-28	Bt	2.5YR3/4	sl	2msbk	fr, ss, sp	10-15		1.48	0.58
28-55	BC	7.5YR3/4	scl	2msbk	fr, ms, mp	-		1.23	0.96
Pedon 8: P72: Bengal gram									
0-15	Ap	10YR3/2	scl	3msbk	fi, s, p	-	slight	1.65	0.54
15-35	Bw1k	10YR3/3	scl	2msbk	fi, s, p	-		1.50	0.42
35-64	Bw2k	10YR3/2	sl	2msbk	fi, s, p	-		1.53	0.98
64-95	Bw3k	10YR3/2	scl	2msbk	fi, s, p	-		1.44	1.16
95-120	Bw4k	10YR3/2	cl	2msbk	fi, s, p	-		1.55	2.44
Pedon 9: P4: Banana plantation									
0-20	Ap	5YR4/3	scl	1msbk	fr, s, p	35-60	moderate	1.92	1.69
20-30	Bt	2.5YR3/4	cl	1msbk	fr, vs, vp	35-60		1.30	0.89
Schist : Uplands									
Pedon 10: P20: Sunflower									
0-15	Ap	10YR3/2	c	2msbk	fi, s, p	-	severe	1.33	0.80
15-40	Bwk	10YR3/2	c	3msbk	fi, vs, vp	-		1.54	2.00
Pedon 11: P11: Bengal gram									
0-12	Ap	10YR3/2	c	2msbk	fr, vs, vp	-	moderate	1.04	0.50
12-22	Bw1k	10YR3/2	c	2msbk	fi, vs, vp	-		0.94	0.41
22-33	Bw2k	10YR3/2	c	2msbk	fi, vs, vp	-		0.78	0.38
33-50	Bck	2.5Y3/2	sl	1msbk	fr, ms, mp	-		1.53	0.68
Pedon 12: P52: Sapota plantation									
0-17	Ap	10YR4/3	scl	1msbk	fr, ss, sp	15-35	slight	1.57	1.95
17-38	Bw1	10YR3/2	c	2msbk	fr, s, p	-		1.49	2.65
38-58	Bw2	10YR3/2	c	2msbk	fr, s, p	-		1.28	1.97
58-84	CB1k	2.5Y6/3	sil	1msbk	vfr, ms, mp	5-10		1.26	1.25
84-100	CB2k	2.5Y6/3	sil	1msbk	vfr, ms, mp	5-10		1.33	0.32
100-130	CB3k	2.5Y6/3	sl	1msbk	vfr, ms, mp	5-10		1.21	0.40
Schist: Lowlands									
Pedon 13: P2: Coconut plantation									
0-13	Ap	7.5YR4/4	cl	3msbk	fi, s, p	-	moderate	1.46	0.64
13-41	Bt1	7.5YR3/4	sicl	2msbk	fi, s, p	-		1.47	1.24
41-73	Bt2	7.5YR3/3	cl	2msbk	fi, s, p	-		1.63	1.77
73-110	Bt3	7.5YR3/3	cl	2msbk	fi, s, p	-		1.69	1.69

TABLE 3 Physico-chemical properties in soils of different landforms and land use in a tropical semi-arid region, Karnataka

Depth (cm)	Particle size distribution (% of <2 mm)			pH	EC ($dS\ m^{-1}$)	OC ($g\ kg^{-1}$)	Exchangeable bases ($cmol\ (p+)\ kg^{-1}$)				CEC ($cmol\ (p+)\ kg^{-1}$)	B.S (%)	CCE (%)
	Sand	Silt	Clay				Ca	Mg	K	Na			
Granite-gneiss: Uplands													
Pedon 1: P71: Ground nut													
0-14	56.71	22.84	20.45	7.58	0.052	1.4	5.01	2.24	0.16	0.02	10.33	72	0.00
14-35	46.27	7.18	46.56	7.07	0.048	5.8	11.33	3.82	0.10	0.06	18.70	82	0.00
Pedon 2: P46: Sorghum													
0-12	62.14	10.65	27.21	7.28	0.066	5.1	32.53	5.04	0.13	0.03	29.89	126	2.62
12-38	56.49	16.45	27.07	7.89	0.157	1.8	54.95	6.52	0.06	0.19	41.33	149	4.88
38-57	43.98	28.11	27.91	8.69	0.135	1.4	80.78	8.21	0.03	0.08	36.04	247	21.84
57-85	56.46	22.05	21.49	8.89	0.166	1.4	82.20	7.43	0.02	0.11	29.64	303	23.07
Pedon 3: P63: Maize intercrop with sunflower													
0-16	32.14	14.34	53.52	9.05	0.144	4.0	64.50	8.46	0.29	0.70	52.15	142	12.27
16-38	27.94	14.80	57.25	9.13	0.170	4.0	75.80	7.51	0.17	1.12	54.74	155	11.99
38-57	24.42	10.77	64.81	9.14	0.193	4.0	75.08	9.20	0.13	1.71	57.20	151	11.52
57-82	25.52	12.85	61.63	9.25	0.233	3.3	81.68	9.44	0.18	2.19	57.93	161	13.84
82-100	25.63	12.65	61.72	9.12	0.251	1.1	76.23	9.65	0.14	2.70	57.07	155	16.26
Pedon 4: P37: Fallow land													
0-13	65.43	20.92	13.65	7.78	0.062	9.6	13.37	3.84	0.10	0.48	18.08	98	8.97
13-32	62.10	8.05	29.85	8.41	0.092	1.1	15.76	3.88	0.05	0.07	21.53	92	3.02
32-70	79.21	1.55	19.24	8.51	0.071	8.9	7.20	1.93	0.03	0.10	9.47	98	2.78
Pedon 5: P119: Fallow land													
0-13	73.79	9.92	16.30	6.09	0.038	5.5	2.99	1.74	0.16	0.03	7.38	66	0.00
13-32	80.06	6.62	13.32	6.25	0.041	3.3	2.69	1.49	0.05	0.19	6.40	69	0.00
32-50	77.82	9.43	12.75	6.54	0.041	2.2	2.85	1.73	0.03	0.07	4.92	95	0.00
Pedon 6: P22: Coconut plantation													
0-17	84.95	8.12	6.92	7.34	0.126	3.3	2.33	0.98	0.07	0.14	3.44	102	0.00
17-33	82.90	7.27	9.83	7.88	0.078	3.3	1.49	0.92	0.06	0.10	4.92	52	0.00
33-60	42.98	4.75	52.27	7.56	0.093	4.4	10.74	6.52	0.37	0.34	21.03	85	0.00
Granite-gneiss: Lowlands													
Pedon 7: P21: Ground nut													
0-13	54.79	18.56	26.65	8.71	0.131	2.6	64.55	8.09	0.06	0.07	25.46	286	14.79
13-28	68.64	13.80	17.57	8.74	0.181	2.6	36.33	4.26	0.05	0.12	19.56	208	3.64
28-55	64.94	14.08	20.97	8.35	0.123	2.9	14.98	4.03	0.13	0.02	21.40	89	3.10
Pedon 8: P72: Bengal gram													
0-15	52.41	22.82	24.77	9.21	0.413	2.2	26.30	4.22	0.18	1.38	26.32	122	9.78
15-35	51.86	21.41	26.73	9.73	0.398	1.4	55.35	5.45	0.14	2.74	26.69	239	8.80
35-64	72.44	9.89	17.67	9.64	0.411	2.2	54.88	4.55	0.06	3.60	16.48	383	9.59
64-95	48.39	16.98	34.63	9.74	0.620	2.6	40.45	4.79	0.12	4.34	32.96	151	10.36
95-120	44.75	18.76	36.50	8.28	0.462	6.3	34.08	4.71	0.14	4.99	34.69	127	8.33
Pedon 9: P4: Banana plantation													
0-20	64.92	12.60	22.48	7.51	0.137	4.4	6.87	2.87	0.14	0.85	12.67	85	1.03
20-30	43.51	18.87	37.62	7.03	0.244	6.9	9.94	3.35	0.39	0.34	17.96	78	0.00
Schist: Uplands													
Pedon 10: P20: Sunflower													
0-15	26.09	24.90	49.01	8.19	0.159	4.0	75.03	7.06	0.21	0.05	45.88	179	14.52
15-40	18.60	27.32	54.08	8.69	0.182	5.2	96.13	8.37	0.09	0.07	47.60	220	21.78
Pedon 11: P11: Bengal gram													
0-12	23.46	26.77	49.77	6.09	0.038	5.5	52.10	4.92	0.20	0.06	53.14	108	0.00
12-22	22.20	27.23	50.58	6.25	0.041	3.3	57.18	6.23	0.13	0.11	52.64	121	0.00
22-33	27.27	24.66	48.07	6.54	0.041	2.2	65.05	5.53	0.10	0.28	45.88	155	0.00
33-50	62.95	24.35	12.70	6.09	0.038	5.5	44.45	3.07	0.03	0.18	11.19	426	0.00
Pedon 12: P52: Sapota plantation													
0-17	51.60	18.80	29.61	7.90	0.082	7.3	13.20	7.55	0.29	0.06	26.20	81	0.52
17-38	34.03	24.09	41.88	8.71	0.221	8.5	26.70	4.96	0.12	0.86	35.67	92	3.01
38-58	30.71	22.27	47.01	8.97	0.172	7.7	54.13	5.95	0.15	1.47	36.41	169	4.37
58-84	41.52	42.13	16.35	9.42	0.153	3.8	56.80	5.99	0.06	1.25	21.65	296	3.37
84-100	51.70	31.76	16.55	9.29	0.163	1.5	37.90	4.75	0.04	1.44	25.46	173	5.00
100-130	64.35	28.60	7.05	9.49	0.130	1.1	40.88	5.08	0.03	1.37	23.00	206	0.77
Schist: Lowlands													
Pedon 13: P2: Coconut plantation													
0-13	22.67	32.44	44.90	8.98	0.249	3.4	2.51	3.85	0.19	1.23	21.03	37	1.44
13-41	14.94	34.60	50.47	9.49	0.331	3.0	2.32	4.18	0.24	5.68	25.58	49	1.29
41-73	26.03	38.45	35.52	9.42	0.491	3.4	10.12	4.92	0.28	10.25	24.48	104	1.44
73-110	31.98	35.23	32.79	9.51	0.680	2.7	8.38	8.74	0.29	10.55	22.63	124	2.06

3.2 | Physico-chemical properties in soils of different landform and land use

Physico-chemical properties of soils of different landforms and land use in Table 3 show that soil properties did not differ among landforms and land use except for organic carbon content. The sand was the dominant size fraction identified in the semi-arid region (22.67-84.95% in the surface to 14.94-82.90 % in subsurface), followed by clay (6.92-53.52% on the surface to 9.83-64.81% in sub-surface) and silt content (8.12-32.44% in surface to 1.55-42.13% in subsurface). Differential soil textural classes / size fractions are expected due to the differential rate of weathering of parent materials by different soil-forming processes. Due to moderate to severe erosion in the study area (Table 1), upward movement of coarser particles occurred due to selective surface erosion of clay and biological activity and swelling and shrinking, and a combination of two or more soil-forming processes resulted in sand as a dominant size fraction (Chandrakala *et al.,* 2021). Generally, the subsurface recorded higher clay content than the surface due to clay illuviation, and the vertical distribution of clay in the subsurface resulted in the formation of Bt and Bw sub-surface horizons (Table 1). The sand content was recorded lower in subsurface because more silt and clay percentage shows sufficient vertical migration of clay and silt. Soils are slightly acidic (pH: 6.09) to very strongly alkaline (pH: 9.21) on the surface and slightly acidic (pH: 6.09) to very strongly alkaline (pH: 9.74) in the subsurface. Higher soil reaction was recorded due to the presence of higher content of base saturation and also calcium carbonate both in the surface and subsurface (CCE ranged from 0-14.79 % in the surface to 0-23.07 % in the subsurface) resulting in formation of calcic horizon (Bwk) in subsurface (CCE > 5%) however, there was a positive correlation existed between pH and calcium carbonate equivalent (r = 0.436). Since the optimum pH for crop production is up to neutral soil reaction (pH: 6.50-7.30) the study area is not suitable for most of the crops due to alkalinity; thus, it needs suitable management practices like soil reclamation by application of organic manures and amendments (application of gypsum) along with irrigation with good quality water is necessary and also in the case of calcareous soil flooding and draining out calcium salts is recommended (Chandrakala *et al*., 2021). Soils are non-saline (EC was <2.0 dS m^{-1}). Organic carbon content was low to high, ranging from 1.4-9.6 on the surface to 1.1-8.9 g kg^{-1} in the subsurface. Fallow land and plantations recorded higher organic carbon content than agricultural lands. Lower organic carbon content recorded in agricultural land was due to intensive cultivation, lower biomass production, and the addition and application of lower external organic inputs to soils during crop production. Among bases, exchangeable calcium content was highest (2.33-75.03 cmol (p+) kg^{-1} in surface to 1.49- 96.13 cmol (p+) kg^{-1} in subsurface) followed by exch. magnesium and exch. sodium. Exch. potassium was recorded lowest among all the bases (0.03-1.38 cmol (p+) kg^{-1} in surface to 0.02-10.55 cmol (p+) kg^{-1} in subsurface). Exchangeable bases are recorded in the order of Exch.Ca > Exch.Mg > Exch. Na > Exch. K. Cation exchange capacity was generally good and it ranged from 3.44-52.15 cmol (p+) kg^{-1} in surface to 4.92-57.93 cmol (p+) kg^{-1} in subsurface.

Clay content and CEC are directly related, and lower CEC was recorded wherever lower clay content was recorded, as the correlation between CEC and clay was highly positive (R = 0.840) (Table 4). Base saturation was high in all the soils, and it recorded 37 to >100 % on the surface and 49 to >100 % in the subsurface, irrespective of geology, landform and land use, which was highly and positively correlated with calcium carbonate equivalent (r= 0.674). All the soils have Iso-hyperthermic temperature and Ustic soil moisture regime. Based on morphological and physicochemical properties, soils are classified as alfisols, inceptisols, and vertisols.

3.3 | Soil organic carbon stock (SOCS) in soils of different landform and land use

The bulk density in Table 2 ranges from 1.33-1.92 Mg m^{-3} on the surface to 0.78-1.89 Mg m-3 on the subsurface. It was reported that bulk density higher than 1.6 Mg m^{-3} is unfavourable for plant growth as it can restrict the penetration of plant roots in clay loam soil. The soil bulk density in most of the areas was found to be below the critical value, denoting that there was no extreme soil compaction.

TABLE 4 Correlation coefficient (r) among soil properties of different landforms and land use, tropical semi-arid region, Karnataka

	SOCS	pH	Clay	CEC	BS	CCE	BD	OC
SOCS	1							
pH	-0.058	1.00						
Clay	0.054	0.272	1.00					
CEC	-0.142	0.476	0.840	1.00				
BS	-0.222	0.478	-0.122	0.129	1.00			
CCE	-0.188	0.436	0.320	0.542	0.674	1.00		
BD	0.313	-0.163	-0.372	-0.497	-0.126	-0.180	1.00	
OC	0.739	-0.298	0.174	-0.009	-0.332	-0.213	0.033	1

Organic carbon stock did not differ much among geology and landforms (Table 2). However, it recorded higher in fallow lands (1.12-1.93 kg m^{-2} in the surface to 0.31-5.46 kg m^{-2} in the subsurface) followed by plantations like sapota plantations, coconut plantations and banana plantations (0.64-1.95 kg m^{-2} in surface to 0.32-2.65 kg m^{-2} in the sub-surface) and agricultural land recorded lower SOCS and it ranged from 0.33-0.80 kg m^{-2} in surface to 0.23-2.44 kg m^{-2} in the subsurface which expresses the lowest SOC, and confirm that the most intensively cultivated plots are the most exhausted and tillage practices, which exposes SOC through layer inversion to microbial attack leading to higher rate of decomposition. Frequent cultivation could have increased soil aggregate disturbance and microbial activities, thus lowering SOCS concentration. Soils with lower SOCS generally have a higher potential to sequester further carbon, and more clay and silt fractions influence higher carbon sequestration potential. Land use systems and cultivation practices such as tillage, manuring, etc., also influence SOCS to a greater extent. The carbon sequestration potential was inversely related to SOCS, i.e., soils with higher SOCS generally have a lower potential to sequester further carbon in them and vice versa. Soil texture is a predictor of SOC storage, and clay content influences SOC stabilization by protecting it against microbial activities. Therefore, different rates of clay and silt fractions play key roles in carbon storage in different land use systems and depths, particularly in sub-surfaces. Root exudates and faunal bioturbation could have significantly increased SOC stock accumulation in plantations. Different vegetation has different quantities of nutrient composition (particularly N levels), which creates different soil microclimates and thus influences SOCS. Land use change causes changes in soil quality and land productivity over time and space by altering the structure and functioning of ecosystems and biogeochemical cycles. It influences soil organic carbon content, stock and C stabilization. The quantity of SOC / SOCS that can be stored in a specific soil / land is estimated by the difference between the rate of carbon input (vegetation and roots biomass) and output (CO_2 emission to the atmosphere). There are many factors*, viz. topography, climate, soil type, soil sampling depth, mineralogical composition, soil biota, land use and management practices and the interaction between them that control* the total amount of SOC / SOCS in the soil profile (Hanamantappa *et al.,* 2024). Generally, in the study area, i.e., the semiarid region of Chitradurga district recorded lower SOCS, which was due to lower precipitation and higher temperature, which are not congenial for biomass (above and below) production, resulting in lower biomass production and addition coupled with higher temperature influenced higher oxidation and decomposition of organic matter makes the soil critical to maintaining higher SOCS. Precipitation and temperature are the two major factors of climatic conditions that act as a key driver of SOCS across scales, influencing organic carbon accumulation and decomposition through altering C input and decomposition and stabilization in any specific region (Zeng *et al.,* 2021). Land use and management influence soil to act as either a source or a sink to atmospheric carbon (Lal, 2004) and land management practices with less soil disturbance due to lesser cultural operations increase soil organic carbon accumulation by reducing soil erosion in the present study fallow land and plantations recorded higher SOCS compared to agricultural land. However, crop rotations, minimum / zero tillage, intercropping, organic farming, and crop residue management contribute to SOC/SOCS build-up in the soil. Correlation studies among soil properties of different landforms and land use (Table 4) show that SOCS highly and positively correlated with organic carbon content (r = 0.739), bulk density (r = 0.313) and clay (r = 0.054), whereas negatively correlated with pH, CEC, base saturation and calcium carbonate equivalent. SOCS are mainly controlled by C inputs, including residues, secretion and exudates of plant, animal and microbial and C outputs, such as mineralization, soil erosion and losses; thus, increasing the above and below-ground biomass helps to sequester more carbon from the atmosphere and further increases the carbon stocks in the study area (Prabakaran *et al*., 2023). Further, the type of vegetation influences the content of organic carbon through the influence of substrate, root exudate, litterfall, microbial activity, soil chemistry, root biomass and root turnover. Thus, to achieve sustainability in the carbon resource in any cultivated lands, suitable management practices such as crop residue incorporation, reduced tillage, cover crops, enrichment with organics, *etc*., have to be manifested (Prabakaran *et al.,* 2023) along with soil conservation measures to control erosion in order to prevent loss of C associated with clay and productive / fertile topsoil. The C stock production rate influences by different tree species present in the specific area depending upon their growth and biomass production capacity (Singh *et al.,* 2020). The SOCS varied significantly in the sub-surface due to several factors, including differential depths, gravel content, bulk density, soil types (mineralogy and texture), clay content, soil pH, soil moisture, temperature, structure, porosity, microbial community composition, topography, land use, nutrient management, and the dynamics of SOC. Notably, the proportion of microaggregate - associated SOC increased significantly in subsoils compared to topsoils, indicating that SOC in subsoils is crucial for long-term carbon stabilization (Zeng *et al.,* 2021).

Soil organic matter (SOM) and SOCS increase with higher clay content because the complexation of organic matter with clay slows down decomposition. Additionally, greater clay content in subsoil enhances the likelihood of aggregate formation, influencing the differential rates of SOCS in these layers. This variation can also be attributed to high root density, which increases micropores and facilitates the percolation of SOC in the form of dissolved organic carbon to deeper soil layers, largely due to elevated faunal activity. Furthermore, land use types and management practices aimed at soil organic carbon sequestration are critical in mitigating global warming by reducing carbon buildup in the atmosphere.

5 | CONCLUSIONS

The soil properties in the semiarid region of Chitradurga district, Karnataka, did not significantly vary across geology, landforms, and land uses. However, SOCS was influenced by climatic conditions and varied by land use, with the highest being fallow land and sapota plantations and the lowest being agricultural land due to intensive cultivation and reduced organic inputs. Overall, SOCS levels were low in this region, primarily due to lower precipitation and higher temperatures, which affected biomass production and increased oxidation of organic matter. The soils were generally low in organic carbon, alkaline, calcareous, and subject to moderate to severe erosion. Management practices are needed to improve soil health and productivity, including soil reclamation for alkaline soils, proper water management to address calcium salts, and adding organic inputs. Implementing soil conservation measures is essential to combat erosion and enhance regional agricultural sustainability.

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DATA AVAILABILITY STATEMENT

Data is available with the corresponding author and will be provided if its required.

CONFLICT OF INTEREST

There are no conflicts of interest

AUTHOR'S CONTRIBUTION

Chandrakala M., the present study's principal investigator, conducted the investigation and wrote the manuscript. Ranabir Chakraborty and the principal investigator contributed to the field soil survey. Parvathy, S., contributed to laboratory soil analysis. Seema, K.V., contributed to GIS work. Sunil P. Maske contributed to the literature search review. Ramamurthy, V., and Ramesh Kumar, S.C., have coordinated the work. Nirmal Kumar prepared the cLHS sampling strategy for the soil survey, and Obi Reddy G.P. contributed to delineating the landform map.

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