



## Carbon Sequestration Potential of Semi-arid Soils Under Different Land Use Systems

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**DOI:** 10.31080/ASAG.2026.10.1545

**Received:** February 12, 2026

**Published:** February 28, 2026

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### Abstract

Information on the geographical distribution of carbon (C) sequestration potential of soils across geographical and management units can help in understanding the agronomic, climatic, topographic and pedological factors controlling the potential for C sequestration and guide prioritized targeting of strategies to promote C sequestration. A study was conducted at ICAR-Central Research Institute for Dryland Agriculture, Hyderabad during 2018-20 to estimate the C sequestration potential of soils under different land use systems using the C saturation concept. Soil samples were collected from two depths, 0-20 cm and 20-40 cm from seven land use systems (Native forest, Planted forest, Rainfed fodder grass, Irrigated fodder grass, Cropping with large C input, Cropping with no external C input and Cultivated fallow). Bulk density, soil organic carbon (SOC) and soil fraction <20  $\mu\text{m}$  were determined and C sequestration potential was estimated assuming that 85% of SOC is associated with the fine soil fraction (<20  $\mu\text{m}$ ). The carbon saturation deficit, or potential for further C sequestration in the soils, up to a depth of 40 cm ranged from 4.92 kg  $\text{m}^{-2}$  (native forest land use system) to 7.57 kg  $\text{m}^{-2}$  (cropping with large C input land use system). Soils under cultivation had greater potential for C sequestration than soils under undisturbed systems, and C sequestration potential was higher in the soil from 20-40 cm depth. The organic carbon actually associated with the soil fraction <20  $\mu\text{m}$  (SSOC) was determined to verify the validity of the 85% assumption for soils under different land use systems. SSOC as % of SOC ranged from 52.45% to 87.37% and was lower in undisturbed systems compared to cultivated systems, and in the 0-20 cm depth compared to 20-40 cm. Assuming SSOC as 85% of SOC led to underestimation of C sequestration potential up to 40 cm soil depth ranging from 0.02 kg  $\text{m}^{-2}$  (cultivated fallow) to 1.00 kg  $\text{m}^{-2}$  (planted forest). The results of this study provide a basis for targeting C sequestration in soils.

**Keywords:** Soil; Carbon; Saturation; Sequestration; Land Use; Depth

### Introduction

The global soil organic carbon (SOC) pool of 1550 Gt is the largest terrestrial C pool and is about twice the size of the atmospheric pool (760 Gt) and three times the size of the biotic pool (560 Gt) [1]. Since the soil organic carbon pool is so large, even small increases in soil organic carbon can contribute significantly to compensating

anthropogenic greenhouse gas (GHG) emissions [1,2]. The process of transfer and secure storage of atmospheric  $\text{CO}_2$  into other long-lived C pools that would otherwise be emitted or remain in the atmosphere is called carbon sequestration [1]. Of the many options for terrestrial C sequestration, sequestering C in soil organic matter is among the most preferred, as it offers a win-win solution to the

problem of climate change. Transferring atmospheric C to relatively long-lived soil organic matter pools not only reduces atmospheric CO<sub>2</sub> levels, but also enhances the productive capacity of the soil, which in turn enables greater C fixation and transfer, resulting in an atmospheric C negative (desirable) feedback loop.

The capacity of soils to sequester carbon is not infinite. The ability to sequester carbon on a long-term basis is governed by the organic carbon protective capacity of the soil, which in turn is linked primarily to the proportion of fine soil particles (<20 µm) and mineralogy of the soil [3,4]. Since the protective capacity of fine soil particles is limited, it is possible to calculate the C saturation deficit of the fine soil particles, which represents the potential of the soil to sequester carbon or carbon sequestration potential. This approach is widely employed in preparing regional and national estimates of carbon sequestration potential [5-7]. Hassink's equation [8] has been widely used for the estimation of C sequestration potential of soils. Knowledge of the geographical distribution of C saturation at the regional/national level can help in understanding the agronomic, climatic, topographic and pedological factors controlling the potential for C sequestration in soils and thus guide the development and targeting of strategies and policies to promote C sequestration.

Quantification of carbon sequestration potential using carbon saturation concept has not been attempted for Indian soils. The assumptions underlying the calculation of C sequestration potential need to be tested for soils under different land uses under Indian conditions. The present study aimed to estimate the C sequestration potential of soils under different land uses in semi-arid India using assumptions from reported literature, and to test the validity of the assumptions.

## Materials and Methods

The study was conducted at ICAR-Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad during 2018-20. Soil samples were collected from two depths, 0-20 cm and 20-40 cm from 7 different land use systems, Native forest (mixed tree, shrub and herb vegetation), Planted forest (plantation of *Leucaena leucocephala*), Rainfed fodder grass (Congo grass, *Brachiaria ruziziensis*), Irrigated fodder grass (Hybrid Napier grass), Cropping with large C input (Maize with crop residue recycling), Cropping with no external C input (Horsegram with no organic materials applied), and Cultivated fallow (Cultivated but no crop grown) at Hayathnagar research farm of ICAR-CRIDA, Hyderabad. All the 7 land use systems were under the specified land use for a minimum period of 10 years and situated at different locations in the 280

ha research farm. The soils are Alfisols, characterized by low base saturation and illuvial accumulation of clay in the argillic horizon in the subsoil [9]. The land use systems were chosen to represent soils of varying soil organic carbon content and soil texture. Soil samples were collected using 20 cm tall metal cores. For the 0-20 cm sample, surface soil was cleared of litter and the 20 cm metal core was driven into the soil until the top of the core was flush with the soil surface. The soil around the core was removed by excavating the soil to a depth of 20 cm, and the core was removed and soil was transferred to a polyethylene bag. For the 20-40 cm sample, the core was placed in the pit excavated up to 20 cm and driven into the soil. The core was removed by excavating the soil around it to a depth of 40 cm from the surface. For determination of bulk density, a second core was collected from each sampling point, just beside the pit excavated for the main soil sample. Separate soil cores were drawn for samples meant for analysis and for determination of bulk density as the former are to be dried at 65°C, and the later, at 105°C. Samples were collected from two different locations only (1 sample for analysis and 1 sample for bulk density at each of the two locations) in each land use system for just 2 depths up to 40 cm due to the difficulty of sampling in the stony soils of the study area.

The bulk density core soil samples, including coarse fragments, were dried at 105°C and weighed. Bulk density was determined as weight of soil divided by the volume of the core [10]. The other set of soil samples were air dried, sieved through 2 mm sieve and dried at 65°C. Coarse fragments retained on the 2 mm sieve were quantified, and measured soil properties were adjusted for coarse fragment fraction as described by Srinivas., *et al.* (2023) [11]. The fraction of soil particles <20 µm was determined following the procedure described by Hassink (1997) [8]. Dry 2 mm sieved soil (50 g) was suspended in 250 mL water for 24 hours. The samples were dispersed by ultrasonication for 15 minutes with a probe-type ultrasonicator. The dispersed soil suspension was transferred to a 1 L glass cylinder. The cylinder was shaken end over end until the soil was completely suspended and placed on a level surface for settling of the soil particles. Particles <20 µm were isolated by siphoning the suspension at 10 cm depth after the appropriate settling time as indicated by Gee and Bauder (1986) [12] according to particle size, temperature of the soil suspension and a particle density of 2.65 Mg m<sup>-3</sup>. The temperature of the soil suspension was measured just before siphoning, using a laboratory thermometer. The siphoned suspension was dried for 4 days at 65°C and weighed to determine the soil fraction <20 µm and corrected for coarse fragment fraction. Organic carbon in the 2 mm sieved soil was determined by Walkley and Black wet oxidation [13] and corrected

for coarse fragment fraction [11] to obtain soil organic carbon of the bulk or whole soil (SOC).

The value of C saturation (C<sub>sat</sub>), the maximum amount of carbon that can be associated with soil particles smaller than 20 µm, was calculated according to Hassink's equation [8].

$$C_{sat} = 4.09 + 0.37 (\text{Clay} + f\text{Silt})$$

Where C<sub>sat</sub> is the C saturation (g C kg<sup>-1</sup>) and Clay + fSilt is the percentage (%) of particles <20 µm (clay + fine silt) in whole soil.

The C saturation deficit (C sequestration potential) of soil was calculated as

$$\text{C saturation deficit (g kg}^{-1}\text{)} = C_{sat} (\text{g kg}^{-1}) - \text{SSOC (g kg}^{-1}\text{)}$$

where SSOC (stable soil organic carbon) is the carbon currently associated with soil particles smaller than 20 µm, calculated as 85% of organic carbon content of whole soil (SOC), assuming that 85% of the total organic carbon in the soil is associated with the fine fraction of soil [5]. Thus, SSOC was calculated as SOC (g kg<sup>-1</sup>) X 0.85. The C saturation deficit represents the soil's potential for carbon sequestration. As soils approach C saturation, the potential for sequestering C further, decreases [14].

To test whether the assumption of SSOC being 85% of SOC is valid for the soils in this study and can be used as a generalization, the organic carbon content of the <20 µm soil fraction was determined by Walkley and Black wet oxidation [13] and the actual SSOC (SOC in the <20 µm soil fraction) as percent of SOC in the bulk soil was calculated.

Since this was technically a characterization study and not a comparison study, no statistical analysis of data was performed.

However, some broad and generalized comparisons across depths and land use systems without statistical analysis are mentioned in results and discussion.

## Results and Discussion

Bulk density (BD) of the study soils across depths and land use systems (Table 1) ranged from 1.538 (0-20 cm, cultivated fallow) to 1.746 Mg m<sup>-3</sup> (20-40 cm, cropping with no external input). There was no discernible pattern with respect to land use system or soil depth. Soil organic carbon (SOC) across the land use systems and depths ranged from 2.14 (20-40 cm, cultivated fallow) to 7.78 g kg<sup>-1</sup> (0-20 cm, irrigated fodder grass). As a generalization, SOC was higher in undisturbed land use systems (native forest, planted forest, rainfed fodder grass and irrigated fodder grass) compared to cultivated systems (cropping with large C input, cropping with no external C input, cultivated fallow). In a study involving both top soil and subsoil of 4 uncultivated and 7 cultivated (15 years of cultivation) calcareous soils of the island of Malta, soil organic matter was reported to be significantly higher in uncultivated soils [15]. One of the major reasons for lower organic carbon in soils under cultivated land use systems compared to undisturbed land use systems is tillage, which breaks down soil aggregates and leads to loss of organic matter by decomposition and erosion [16]. Soil organic carbon was lower in the lower depth (20-40 cm) in all the land use systems. Sacco, *et al.* (2024) [15] also observed that soil organic matter was higher in top soils compared to subsoils in the uncultivated soils in their study. However, they found that in cultivated soils, differences in soil organic matter between topsoil and subsoil were not significant. The stock of SOC up to 40 cm depth ranged from 1.603 (cultivated fallow) to 4.414 kg m<sup>-2</sup> (irrigated fodder grass) and followed a similar pattern as SOC across land use systems.

Land use system	BD (Mg m <sup>-3</sup> )		SOC (g kg <sup>-1</sup> )		SOC Stock (kg m <sup>-2</sup> )*		
	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-40 cm
Native forest	1.687	1.634	6.93	4.40	2.337	1.436	3.773
Planted forest	1.654	1.678	7.36	4.71	2.432	1.585	4.017
Rainfed fodder grass	1.687	1.660	6.32	4.33	2.134	1.435	3.569
Irrigated fodder grass	1.729	1.653	7.78	5.21	2.694	1.720	4.414
Cropping with large C input	1.679	1.592	6.03	3.45	2.021	1.100	3.121
Cropping with no external C input	1.634	1.746	3.25	2.23	1.064	0.783	1.847
Cultivated fallow	1.538	1.647	2.93	2.14	0.900	0.703	1.603

$$\text{*SOC stock (kg m}^{-2}\text{)} = \text{SOC (g kg}^{-1}\text{)} \times \text{Bulk density (Mg m}^{-3}\text{)} \times \text{Depth (cm)} / 100.$$

**Table 1:** Organic carbon, bulk density and carbon stock in 0-20 cm and 20-40 cm soil depths under different land use systems.

The percentage of fine particles <20 µm (clay + fine silt) ranged from 16.37 to 35.41% across land use systems and depths (Table 2). Soil from lower depth (20-40 cm) had distinctly higher content of fine soil. Alfisols generally have higher content of clay in the subsoil [17] due to illuvial accumulation in the argillic horizon. The saturation level of organic C in fine soil (C sat) ranged from 10.15 to 17.19 g kg<sup>-1</sup> and was higher for 20-40 cm depth. The C saturation deficit (potential for further C sequestration by fine soil) was estimated assuming the proportion of carbon currently associated with soil particles smaller than 20 µm (SSOC) as 85% of organic carbon content of whole soil (SOC). The carbon saturation

deficit, or potential for further C sequestration in the soils, up to a depth of 40 cm ranged from 4.92 kg m<sup>-2</sup> (native forest) to 7.57 kg m<sup>-2</sup> (cropping with large C input). Soils under cultivation had greater potential for C sequestration than soils under undisturbed systems, and C sequestration potential was higher in 20-40 cm soil than 0-20 cm soil. Harikiran., *et al.* (2023) [18] reported mean C sequestration potential values of 5.52 kg m<sup>-2</sup> and 6.51 kg m<sup>-2</sup> for 0-25 cm and 25-50 cm soil respectively in Alfisols and Inceptisols of Vemagal Hobli block of Kolar district, Karnataka, India.

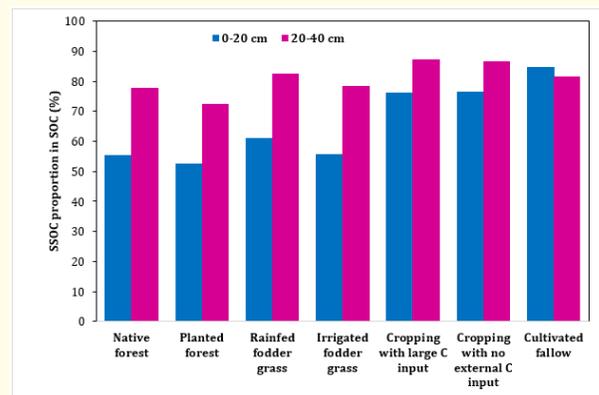
Land use system	<20 µM fraction (%)		C <sub>sat</sub> (g kg <sup>-1</sup> )		SSOC (g kg <sup>-1</sup> )		C saturation deficit (g kg <sup>-1</sup> )		C saturation deficit (kg m <sup>-2</sup> )		
	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-40 cm
Native forest	19.87	24.27	11.44	13.07	5.89	3.74	5.55	9.33	1.87	3.05	4.92
Planted forest	16.37	30.37	10.15	15.33	6.26	4.01	3.89	11.32	1.29	3.79	5.08
Rainfed fodder grass	22.69	27.99	12.48	14.45	5.38	3.68	7.11	10.77	2.40	3.57	5.96
Irrigated fodder grass	17.79	32.53	10.67	16.13	6.61	4.43	4.07	11.70	1.40	3.87	5.26
Cropping with large C input	27.29	35.41	14.19	17.19	5.12	2.94	9.07	14.26	3.04	4.53	7.57
Cropping with no external C input	21.06	28.86	11.88	14.77	2.77	1.90	9.12	12.87	2.98	4.48	7.46
Cultivated fallow	24.04	23.64	12.98	12.84	2.49	1.82	10.49	11.02	3.23	3.63	6.86

**Table 2:** Carbon saturation deficit (sequestration potential) of soils under different land use systems estimated using SSOC as 85% of SOC.

$$C \text{ saturation deficit (kg m}^{-2}\text{)} = C \text{ saturation deficit (g kg}^{-1}\text{)} \times \text{Bulk density (Mg m}^{-3}\text{)} \times \text{Depth (cm)}/100.$$

The actual SSOC, measured by determining the organic carbon associated with the <20 µm soil fraction as % of SOC (Figure 1) ranged from 52.45% (0-20 cm, planted forest) to 87.37% (20-40 cm, cropping with large C input) with mean values of 65.99% for 0-20 cm and 80.93% for 20-40 cm, as against the assumed value of 85%. Higher proportions of SSOC in SOC in subsoils compared to topsoils have been reported [14,19].

The percentage of SSOC in SOC was generally lower in undisturbed systems compared to cultivated systems, especially in the 0-20 cm layer. This could be due to the higher SOC content of undisturbed soils (Table 1) and also due to higher fresh carbon inputs to the soil in these systems, from roots, residues and

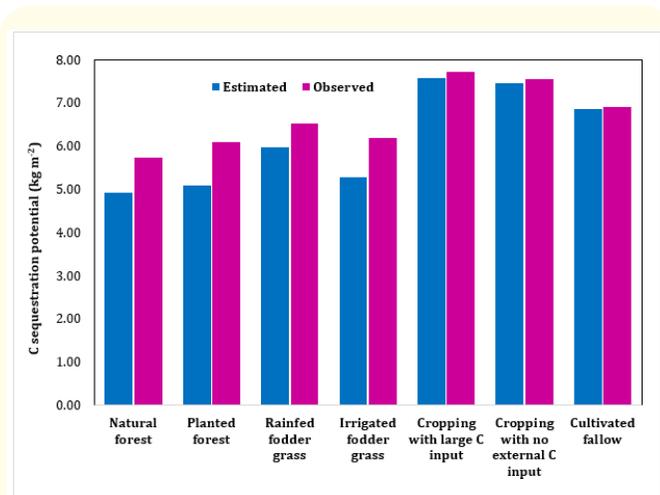


**Figure 1:** SSOC, the organic carbon associated with the <20 µm soil fraction as a percentage of SOC, bulk soil organic carbon, for soils from two depths under different land use systems

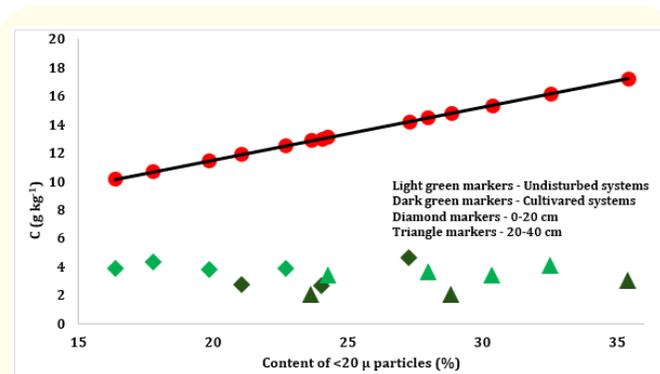
litterfall which accumulate primarily as POC, particulate organic carbon (organic carbon not associated with <20 μm soil mineral fraction). The proportion of mineral associated organic carbon in bulk soil organic carbon generally decreases with increase in bulk soil organic carbon [20]. Wiesmeier, *et al.* (2014) [6] found that for cropland soils, the proportion of OC in the soil fraction <20 μm in the total OC content of the bulk soil had a median value of 77% for cropland soils, 60% for grassland soils and 38% for forest soils in southeast Germany. A global study that synthesized 11,495 globally distributed observations of the proportion of mineral-associated organic carbon in SOC revealed higher values for cropland over grassland and forest land cover [19].

The C sequestration potentials of 0-40 cm soil calculated based on actual measurements of SSOC in the <20 μm soil fraction were higher than those calculated for soils under all land use systems (Figure 2). The extent of underestimation by assuming SSOC as 85% of SOC ranged from 0.02 kg m<sup>-2</sup> (cultivated fallow) to 1.00 kg m<sup>-2</sup> (planted forest). This underestimation is due to the fact that the SSOC made up less than 85% of SOC in the soils (Figure 1). While the value of 85% may be close to realistic for cultivated soils, the findings of this study as well as results reported by Wiesmeier, *et al.* (2014) [6] suggest that it is better to measure and use the actual SOC content of <20 μm soil fraction for accurate estimation of C sequestration potential than using any value reported in literature, especially when diverse soils are involved. Di., *et al.* (2017) [7] used a value of 77% as the proportion of SSOC in bulk SOC in the estimation of C saturation deficit of Chinese soils under different managements. While measuring the SOC content of <20 μm soil fraction for all soil samples may be difficult, it can be done for a few representative soil samples from each group, as done by Wiesmeier, *et al.* (2014) [6].

A plot of C saturation against percentage fine fraction (Figure 3) showed that the all the soils in the present study were considerably unsaturated and therefore have considerable potential for C sequestration. In general, cultivated soils showed greater C sequestration potential compared to undisturbed soils, and soils of 20-40 cm depth showed greater C sequestration potential than soils of 0-20 cm depth. Similar results were reported by Wiesmeier, *et al.* (2014) [6] who found that grassland and forest soils had lower C sequestration potentials compared to cropland soils.



**Figure 2:** C sequestration potential (C saturation deficit) of 0-40 cm soils under different land use systems estimated assuming OC in <20 μm soil as 85% of OC in 2 mm soil (estimated), and from actual measurement of OC in <20 μm soil (observed).



**Figure 3:** C associated with <20 μm soil particles vis-à-vis C saturation level of soils from two depths under seven different land uses.

Green markers represent the C associated with the <20 μm soil fraction (measured), the red marker above each green marker is the maximum amount of C that can potentially be associated with the <20 μm soil fraction (C<sub>sat</sub>). The vertical distance between them represents the C saturation deficit or C sequestration potential.

## Conclusion

The assessment of carbon sequestration potential of soils from two depths under seven different land use systems showed that soil organic carbon and organic carbon stock were higher in undisturbed land use systems compared to cultivated systems, and 0-20 cm depth compared to 20-40 cm depth. Carbon sequestration potentials (C saturation deficit) of 0-40 cm soil under different land use systems, determined using actual measurement of organic carbon in the soil fraction <20  $\mu\text{m}$ , ranged between 5.73 to 7.72 kg m<sup>-2</sup> and were higher for cultivated systems compared to undisturbed systems. Among soil depths, C sequestration potentials were higher for 20-40 cm soil than 0-20 cm soil suggesting that inputs or management practices targeted for sequestering carbon should be directed towards the subsoil in addition to topsoil. Carbon sequestration potentials estimated assuming SSOC as 85% of SOC were lower than those determined through actual measurement of OC in the soil fraction <20  $\mu\text{m}$ . It is suggested to measure and use the actual SOC content of <20  $\mu\text{m}$  soil fraction, at least for representative soils, for more accurate estimation of C sequestration potential.

## Acknowledgements

The research was supported by the Indian Council of Agricultural Research, Department of Agricultural Research and Education, Government of India.

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