Soil carbon footprints and climate-smart soils

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Carbon is sequestered in the soil in organic (SCSo) and inorganic (SCSi) forms. This sequestration is controlled by different soil properties. SCSo, a boon, enhances the physical and chemical conditions of the soil to improve soil drainage and provide adequate nutrition to the plants. SCSi, contributed mainly by pedogenic calcium carbonates (PCs), is a bane and degrades the soil chemically. Soil acts both as a source and sink of carbon. With the global warming threat looming, conservation of the soil for sustenance has gained more importance in view of its role in providing various ecosystem services, including food production. Therefore, identifying climate-smart soils that can withstand climate change and warming is important. These climate-smart soils will help identify global hotspots for soil conservation. The present study provides a method to measure soil carbon footprints (CFs) to identify climate-smart soils, citing a few examples from tropical India. This effort will help move forward the subject of soil carbon research and its importance for preserving this limited natural resource for humankind. Increased atmospheric carbon footprints (CF) are harmful, while those in the subsurface (soil) are good and will continue to save humanity from the vagaries of climate. It requires global awareness and proper utilization of the soils.

Keywords: Carbon footprints, climate change, climate-smart soils, global warming, sequestration.

SOILS play an important role by removing atmospheric carbon dioxide (CO_2) and storing it. Thus, they act as a source and sink of carbon (C) by carbon capture and storing (CCS)[1]. Nearly 3.67 tonnes of CO_2 (1 tonne C) is sequestered in soils in various pools, primarily by clay colloids. Amorphous materials and free organic matter also contribute to the storage of C in soil pools. Soil C has a role in mitigating greenhouse gases (GHGs) to reduce carbon footprint (CF); hence, it demands attention from planners to save the soil for the sustenance of humankind.

India contributes nearly 5.7% of the total global emissions (50 billion tonnes (Bt) CO_2 (eq.)) of GHGs[2–4]. Agriculture contributes globally 18.4% of the total GHG emissions[4]; India's share is 4.4% of the global agricultural GHG emissions[2–4] (Figure 1 *a*). In the overall contribution of agriculture towards GHGs, agricultural soil contributes 4.1% of the global (50 Bt CO_2 eq.) CF (Figure 1 *b*)[4]. Corresponding figures for the Indian agricultural soils are 0.16% and 19.4% of the global (50 Bt CO_2 eq.) and total Indian carbon footprints (408 million tonnes (Mt) CO_2 eq.) respectively[2,3].

Soil health is fundamental to the survival of humankind. Yet soils are under pressure due to the increasing demand of a growing population for food and shelter. By 2050, soils will be required to provide ~9.6 billion people with supporting, regulating, provisioning and cultural services[5–8]. Soil organic carbon (SOC) is critical for most ecosystem services. Many areas have suffered degradation due to SOC loss globally. Priority should, therefore, be given to save the soils and SOC to protect this natural resource at the global level[9–12]. This necessitates identifying climate-smart soils (CSS) and their preservation using the appropriate methods using soil carbon footprint (CFs). The present study provides tropical examples to develop a model understanding to find similar CSS in India, which may be helpful for others.

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Soil carbon footprints

Soil, as a biological system, acts as a sink of CO_2. Therefore, it indirectly helps negate atmospheric emissions by capturing and storing both organic and inorganic forms of carbon[11]. Soils are essential for enhancing CCS[1] and leaving CF in the pedo-environments. Soil preserves its carbon footprints in two different ways: (i) sequestering organic C (SCSo) and (ii) sequestering inorganic C (SCSi), which may be considered as a negative carbon footprints (CFs).

Total CF for Indian agriculture is measured as 1.72% of total CO_2 (eq.) stored in the soil[2,3]. A total of 15,029 and 12,078 Mt CO_2 (eq.) is held as SCSo and SCSi up to a depth of 150 cm, as seen in five major Indian soils (Figure 1 *c*). Desert soils contribute low organic C and very high inorganic C, mainly due to low rainfall and increased atmospheric temperature. In India, organic C sequestration in the soils constitutes 2% and 6% of the world and tropical regions respectively; the corresponding SCSi values are 3% and 11% respectively (Figure 1 *d*). Carbon footprints

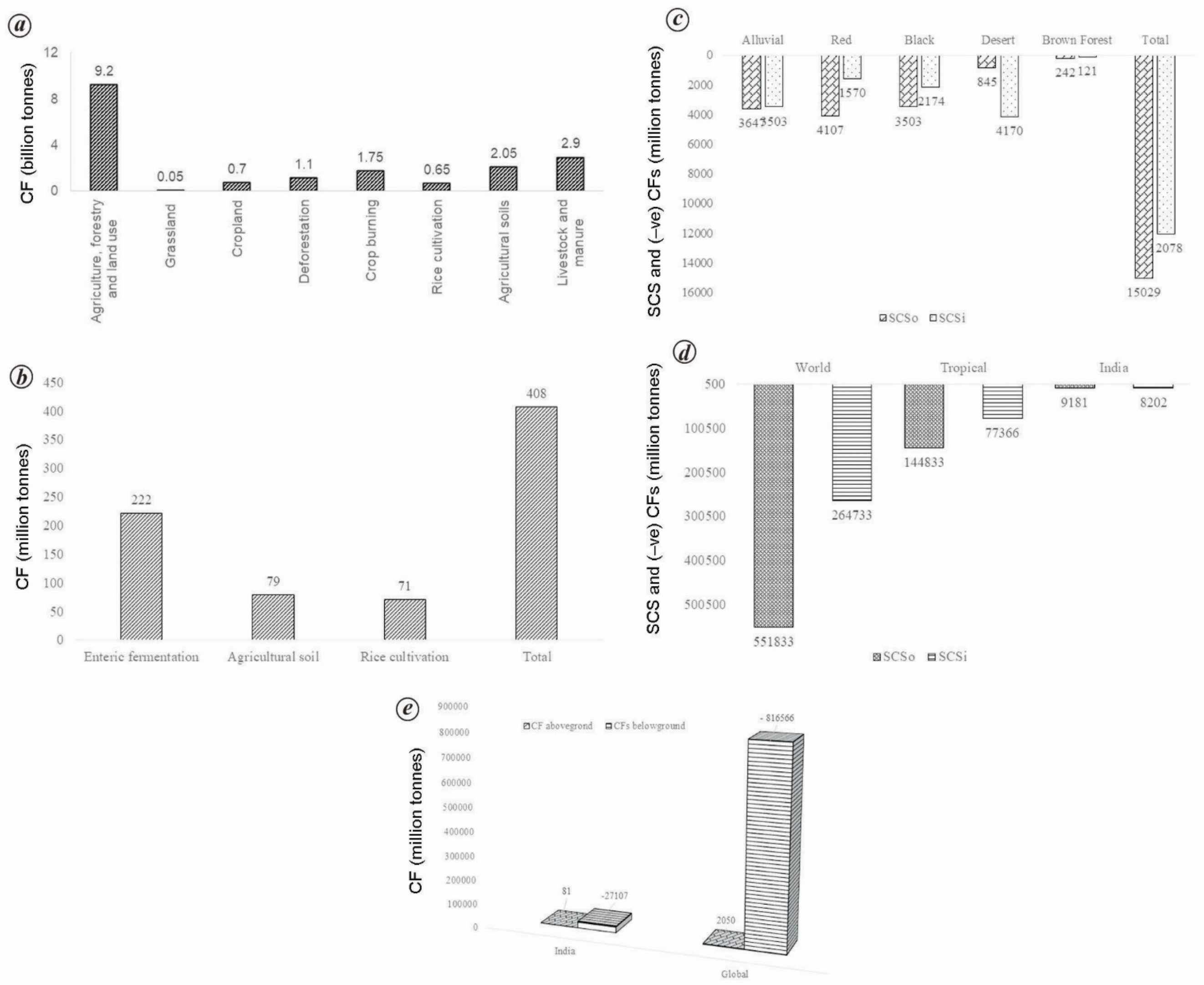

Figure 1. Soil carbon sequestration (SCS) and carbon footprints (CFs). ***a***, ***b***, Carbon Footprints: (***a***) World scenario of agricultural soil contribution as 2.05 billion tonnes (ref. 4) and (***b***) Indian scenario in agriculture showing the contribution of agricultural soils as 79 million tonnes (refs 2, 3). ***c***, SCS, soil organic and inorganic carbon sequestration (SCSo and SCSi) by five major Indian soils stored below the surface effecting negative emission (negative carbon footprints of soils, {(–ve) CFs}). ***d***, Comparison of SCS in the world, tropical and Indian soils. Tropical SCSo and SCSi are 26% and 29% of the world respectively; Indian SCSo and SCSi are 2% and 3% of the world respectively; India contributes SCSo and SCSi of 6% and 11% of the tropical world[9,13]. ***e***, Carbon footprints both aboveground[2,3,10] and belowground (soil: negative CFs). Total CFs are 335 times that of CF (aboveground) in India and 398 times globally.

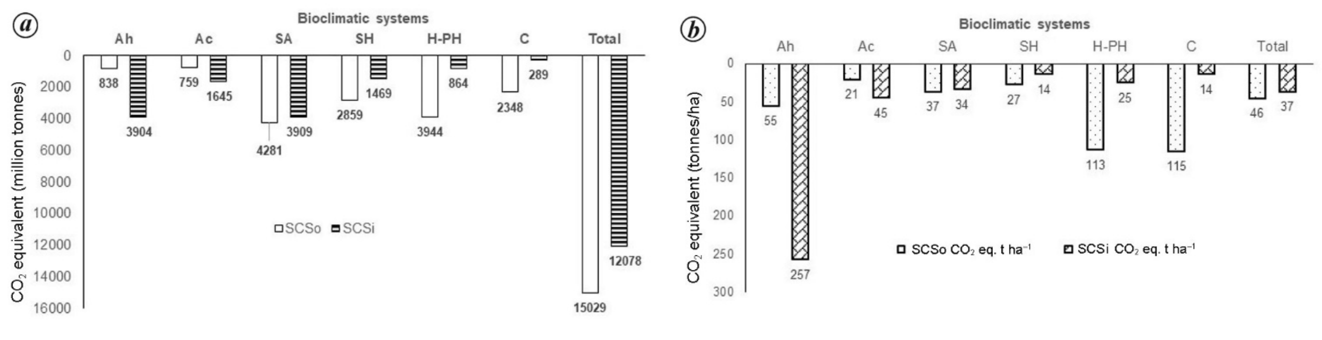

Figure 2. Distribution of soil carbon in different bioclimatic systems (BCS). ***a***, SCS in different BCS. ***b***, Rate of SCS (organic (SCSo) and inorganic (SCSi)) (Ah, Arid hot (mean annual rainfall, MAR <550 mm); Ac, Arid cold; SA, Semiarid (MAR 850–550 mm); SH, Sub-humid (MAR 850–1200 mm); H–PH, Humid (MAR 1600–2200 mm)–per-humid (MAR >2200 mm); C, Coastal (MAR, 900–3000 mm) (Revised[13]).

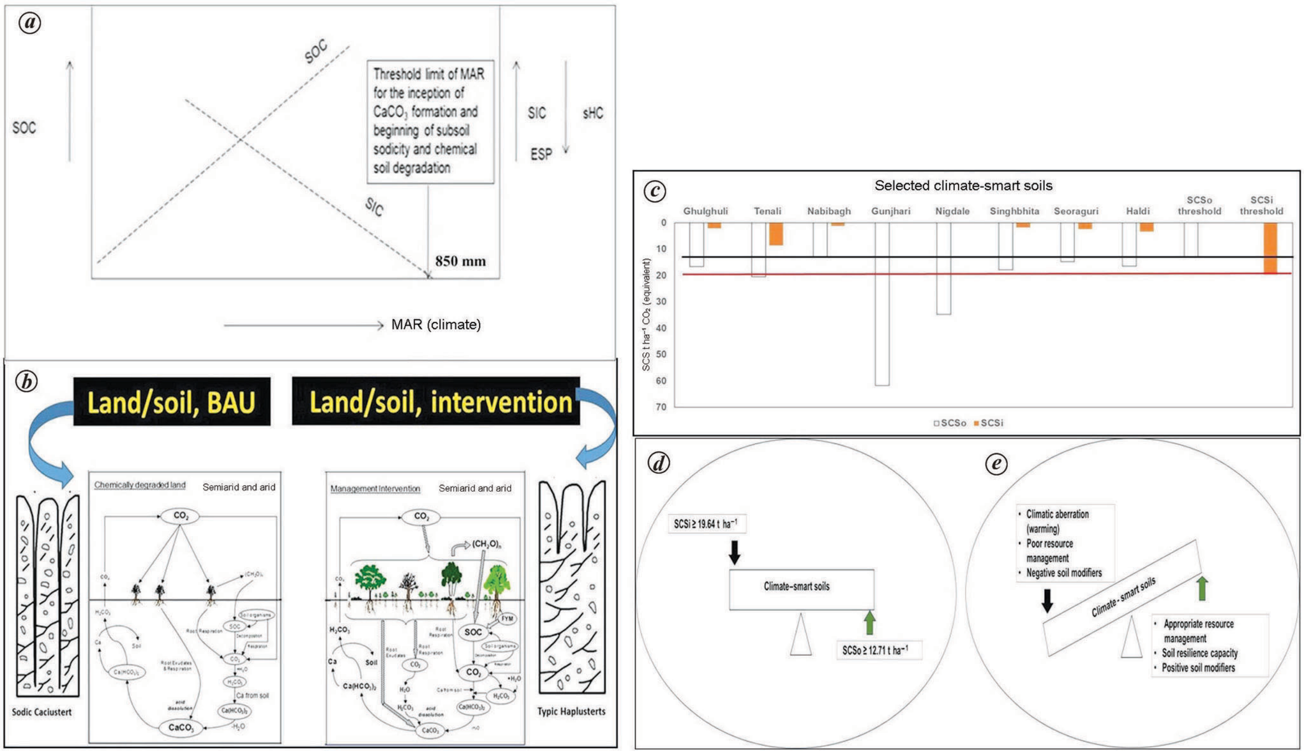

Figure 3. Climate-smart soils (CSS) and their relation with different soil parameters. ***a***, Soil organic and inorganic carbon, and their relation with climate and soil properties. (SOC, Soil organic carbon; SIC, Soil inorganic carbon; ESP, Exchangeable sodium per cent (controls soil pH and other soil properties); sHC, Saturated hydraulic conductivity (controls soil drainage); MAR, Mean annual rainfall (mm)[1]). ***b***, Chemically degraded sodium-dominated black soils (Sodic Calciusterts[32]) with low SCSo and high SCSi (left of the Figure) following business as usual (BAU). Under better management intervention these black soils are reclaimed (Typic Haplusterts[32]) (right side of the Figure) suggesting that no parcel of land should be kept fallow in the dry land tracts. ***c***, Examples of a few Indian climate-smart soils. ***d***, ***e***, Climate-smart soils need an exact balance of organic and inorganic carbon sequestration.

both aboveground and belowground (soil: negative CFs) suggest that large amounts of CO_2 eq. are stored regionally (India) and globally (Figure 1 *e*).

Soil carbon footprints in different bio-climatic systems

Climate is one of the important factors controlling soil carbon sequestration. SCSo follows the trend of arid cold < arid hot < coastal < subhumid< humid–per humid < semiarid. The scenario for SCSi is slightly different; it follows the trend coastal = humid–per humid < arid cold < subhumid < semiarid = arid hot (Figure 2 *a*). Absolute estimates of soil carbon sequestration are area-dependent, making semiarid black cotton soils a higher contributor to SOC sequestration. This is in spite of the fact that most soils in semiarid areas contain low organic carbon (Figure 1 *c*)[13]. This is true for the entire black cotton soil area as well as for an individual soil site. This anomaly was removed by making the estimates per unit area (Figure 2 *b*), which shows that humid–per-humid and coastal black soils store five times more soil C than the total of all the Indian soils together (46 t ha^{-1}) (Figure 2 *b*). This aligns with the general understanding and observation of more carbon sequestration in soils in higher rainfall areas (H–PH) (Figure 2 *b*). The arid and hot bio-climate showed more SCSi per unit area and contributed seven times more than the total of all the Indian soils together (37 t ha^{-1}) (Figure 2 *b*). Inorganic C footprints in these dryland soils are thus larger than those of organic C.

Climate-smart soils

Soils are climate-smart, provided they are used appropriately. Climate is the most important factor affecting soil formation, and soils preserve different climatic episodes over time[1]. The formation of inorganic carbon in the soil in India becomes more prominent if the mean annual rainfall is less than 850 mm[1] (Figure 3 *a*). Enhanced SCSo helps the soil maintain its quality and health. At the same time, SCSi impairs soil's physical, chemical and microbiological activities. SCSo is considered a boon, and SCSi (with reference to pedogenic carbonates (PCs) as the source of inorganic carbon) is a bane[8]. PCs in the soil are formed in the subsurface and gradually engulf the entire soil. With high bulk density (BD) and poor drainage (low saturated hydraulic conductivity, sHC), these soils become as hard as rock in the arid and semiarid bio-climatic zones. Such soils make the land barren under business-as-usual (BAU) management practices (left, Figure 3 *b*). However, the soils show resilience under improved management intervention, enriching more SCSo and reducing SCSi. Such interventions make the land green to restore the soil ecosystem (right, Figure 3 *b*). These resilient soils can withstand climatic vagaries with their inherent qualities aided by management practices and are CSS. These soils may be identified using the following steps with the available datasets[14,15].

Estimating SCS (t ha^{-1} CO_2 eq.)[1,9]:

$$\text{SCS (t/ha } CO_2 \text{ eq.)} = \{[\text{SOC (\%)} * \text{BD (Mg/m}^3) * \text{soil depth (m)}] * (44/12) * 100\}. \quad (1)$$

Identifying soils which maintain the total SCSo as 12.71 t ha^{-1} (CO_2 eq.) (eq. (2)) in such a way that the total SOC stock (eq. (3))[9] remains unchanged at 11.97 Pg (1 peta gram (Pg) = 10^{15} gram) in India[13]. Since SOC and soil inorganic carbon (SIC) have an inverse relationship[1], these soils bind the maximum content of SIC (1.19%) and SCSi as 19.64 t ha^{-1} (CO_2 eq.) (eq. (4)).

$$\text{SCSo}\left(\frac{\text{t}}{\text{ha}} CO_2 \text{ eq.}\right) = \left[\left\{\frac{0.77 * 1.5 * 0.3}{10}\right\} * \frac{44}{12} * 100\right] = 12.71. \quad (2)$$

$$\text{Soil C stock (Pg)} = \text{Soil C (\%)} * \text{BD (Mg/m}^3) * \text{soil depth (m)} * \text{area (m ha)}\}/10. \quad (3)$$

$$\text{SCSi}\left(\frac{\text{t}}{\text{ha}} CO_2 \text{ eq.}\right) = \left[\left\{\frac{1.19 * 1.5 * 0.3}{10}\right\} * \frac{44}{12} * 100\right] = 19.64. \quad (4)$$

These CSS should have a minimum threshold of SOC, SIC and BD to effect 12.71 t ha^{-1} of SCSo CO_2 (eq.) along with characteristic features and the threshold values for identifying CSS as shown in Boxes 1 and 2.

Box 1.

Features of climate-smart soils

CSS should store at least SCSo 12.71 t ha^{-1} CO_2 in the first 30 cm depth of soil.
Store maximum SCSi 19.64 t ha^{-1} CO_2 in the first 30 cm depth of soil.
Be relatively deep to preserve SOC to withstand the effect of global warming[15,18].
Have a moderate bulk density (BD) of 1.5 M gm^{-3} in the first 30 cm depth of soil.
Indicate a low level of SIC as calcium carbonate (~1.19%) in the first 30 cm depth of soil to reduce chemical soil degradation[14].

Soils have an inherent capacity to withstand the vagaries of climate. If adequately managed, soils can balance the extent of organic and inorganic carbon sequestration. For the Indian scenario, these soils could be identified using the method described above. SOC stock in the 0–30 cm depth was estimated as 11.97 Pg in India[13]. Assuming soil BD as 1.5 M gm^{-3}, we arrived at a SOC value of 0.8% for 0.3 m (30 cm) soil depth in India with an area of 328.7 million ha. Among many selected benchmark soils studied across the country, these values of minimum SOC and maximum BD of soil are considered the threshold limits to identify CSS without affecting the total organic carbon sequestration of soils for the whole country. Since SOC and SIC have an inverse relation (Figure 3 *a*), the criteria of CSS also bind the maximum content of SIC as 1.19%, as observed from the datasets of selected soils in India[14].

Therefore, each CSS should store at least 12.71 t ha^{-1} CO_2 (eq.) in the first 30 cm depth of the soil. A few selected CSS were identified using these threshold values (Figure 3 *e*). Roth*C* (Rothamsted carbon) model experiments showed that deep to very deep soils (~150 cm) can withstand the effect of warming in an effective manner[15–17]. Low soil carbonates and high organic carbon help control land degradation to sustain ecological balance[18,19]. CSS also need an exact balance of organic and inorganic carbon, which maintains a seesaw relationship with these soils and various other factors. Among other factors, favourable natural endowments like calcium-rich zeolites, non-pedogenic carbonates, and gypsum help the soil remain climate-smart (Figure 3 *f* and *g*)[1].

The arid and semiarid environment prevailing in central and southern peninsular India has been ascribed to the global warming phenomenon[20], which is the primary reason for the low organic C in the soils of these areas. Despite the low organic C, total organic C sequestration in these black cotton soil areas is high due to greater aerial extent.

Box 2.

Threshold values (0–30 cm soil depth) to identify climate-smart soils

Soil parameters
SOC (minimum): 0.77%
BD (maximum): 1.5 M gm^{-3}
SIC (maximum): 1.19%

Soil carbon sequestration values

Total SCSo (CO_2 (eq.)): 4176 Mt
SCSo (CO_2 (eq.)) per unit area: 12.71 t ha^{-1} (4176/328.7) (area of India as 328.7 mha)
Total SCSi (CO_2 (eq.)): 6454 Mt
SCSi (CO_2 (eq.)) per unit area: 19.64 t ha^{-1} (6454/328.7).

Table 1. Management levels for increased soil carbon sequestration

Management	High management	Low management
Business as usual		
Fertilization	Higher doses of N, P and K fertilizer applications	N, P and K fertilizer applications at a relatively low rate
Manure	Regular application of farmyard manure (FYM)	Rarely applied
Legumes as intercrop	Very common with leguminous intercropping, broad-bed furrow[19] and green manuring (*Sesbania* sp., sun hemp)	Almost nil
Crop residue application	Residues incorporated regularly	Rarely applied
Moisture conservation	Ridge furrows and bunding, and broad bed furrows are regularly used for soil moisture conservation[19]	Nil
Management	**Examples**	**Reference**
Out-of-box management		
Deep-rooted trees/cereals increase biomass and dissolve native soil carbonates	Cereals: grasses; trees: oranges, tea and rubber	1, 27–30
Split doses of FYM	FYM in two splits: one before rainfall and the other during the onset of winter in tropical India	12, 31, 32

Table 2. Conventional management interventions to influence soil organic and inorganic carbon storage and maintain balance between these two forms of carbon in the soil

Management interventions	Increased soil organic C	Reduced soil organic C loss	Reduced soil inorganic C levels
Crop rotation with leguminous species and increased crop residues	Yes	–	–
Crop cover	Yes	Yes	Yes
Manure and compost application	Yes	Yes	Yes
Rewetting organic (i.e. peat and muck) soils	–	Yes	–
Improved grazing land management	Yes	–	–

Sources: Refs 11, 14, 19. –, No information.

Thus, these areas offer a better scope for soil carbon sequestration. Assessing quantified values of soil carbon sequestration (CO_2 (eq.) t ha^{-1}), CSS were identified under a set of soil management practices in a given land-use system using business-as-usual (BAU) and the out-of-box management (OBM) interventions (Table 1).

Soil carbon sequestering management practices are divided into two broad categories. The first category includes traditional management systems that increase soil carbon with existing crops and management interventions. It may consist of conventional or BAU management practices (Table 2)[11,14,19]. The second category includes OBM or frontier technologies[11], which require more research and practical demonstrations before recommending for deployment at the field level. Interestingly, farmers are using management practices including choice of crops/trees (for example, oranges and pomegranates in the calcareous soils in semiarid and arid tracts of India) to ameliorate these soils to stop further degradation. Moreover, management practices including choice of crops/trees examples also show an increase in SOC using these deep-rooted crops (Table 1).

Management interventions on various land-use options will determine the extent of soil carbon sequestration. Such interventions could be BAU involving different levels of management (high and low) (Table 1), depending on the resource capability of the stakeholders. Management practices include appropriate crop rotation with leguminous intercropping, as well as broad-based furrow and green manuring (*Sesbania* sp., sun hemp) to increase organic carbon sequestration of the soil[21]. Plant/tree breeders should also work closely with soil experts to reduce the large gap between farmers' and achievable yields. This gap can be filled considerably by adopting a sustainable management approach to natural resources using sound agronomic principles and a broader understanding of the constraints and interactions of biotic and abiotic stresses in developing crop genetic bases to diversify production[22]. Management interventions should include frontier technologies involving OBM practices[11] (Table 1). Deep-rooted trees (for example, oranges) in a few sites under horticulture increase organic carbon sequestration of the soil. A considerable amount of inorganic carbon sequestration of the soil (as soil carbonates) causes chemical soil degradation. These soils can be reclaimed using OBM practices to improve urease and dehydrogenase activity[23]. Such practices can thus reduce inorganic carbon sequestration of the soil[12,24] (Table 1). Plant/tree breeders may be involved in developing such species of deep-rooted crops following a multi-disciplinary approach. These crops will ease the dissolution of the native soil carbonates through root exudates to reduce SIC.

Conclusion

Soil organic matter is controlled by inorganic substrates (78%) (precisely phyllosilicate minerals with higher surface area in the finer fractions). The black soils dominated by high-activity clay minerals (mostly smectites) show 2–3% SOC content in the first 0–30 cm soil depth. This indicates that the semiarid ecosystems dominated by black soils alone can boost the organic carbon sequestration in the soil with appropriate land management interventions[1].

SOC and SIC are the two important dynamic soil properties which depend on various factors. It is likely that soils falling below the suggested threshold values might have the capacity to qualify for CSS. However, it will require sound soil management. The present limit of threshold values is set for Indian soils, which may serve as a model to fix the limits for CSS elsewhere under similar bioclimatic and management conditions.

CSS must be protected, and the measures should be made available to the stakeholders. SOC is a boon, and SIC (PC) is a bane; therefore, proper management can help maintain CSS to improve farmers' livelihoods and sustain ecological balance. Such efforts require tropical soils to be kept constantly under vegetative cover[1].

Identifying CSS is an essential step towards saving soils from the effects of climate change. Moreover, a proper understanding of both organic and inorganic forms of soil carbon sequestration will help the planners choose the appropriate soil management[25] and identify different hotspots for soil nature conservation[5,26]. Such hotspots will also help monitor soil quality and health, affecting nearly three times more SOC sequestration in tropical semiarid India[1] and other similar parts of the world[27]. This might help assess the quantum of soil carbon credits the carbon farmers may achieve by maintaining their soils as climate-smart.

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