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Identifying Climate-smart Soils in Sugarcane Growing Areas Using Soil Carbon Footprints

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Abstract

Sugarcane is an important cash crop in the country. Considering the potential of sugarcane, there is still an enormous scope to increase sugarcane productivity per unit area per unit time. This requires sugarcane-growing farmers to be ready to face new challenges like global warming and aberrant weather situations. This crop is grown in various states of India in different agroecological subregions, represented by soils containing divergent carbon pools. Carbon is stored in soil both in organic and inorganic forms through the process of sequestration. Soil acts both as a source and sink of carbon. With the global warming threat looming, soil carbon has been an important subject since it affects soil quality and productivity. It is, therefore, essential to have an understanding of soils that can withstand climate change and aberrant weather conditions. The climate-smart soils require global attention to preserve global and regional ecology in the sugarcane-growing areas for their sustenance, opening new opportunities for research and development. The present paper explores the extent of soil carbon footprints. It suggests identifying climate-smart soils used for growing sugarcane with a few parameters to maintain the country's overall soil carbon reserves.

Key words: Sugarcane, climate-smart soils, sustenance, opportunities, soil carbon footprints, sequestration.

Introduction

Sugarcane (*Saccharum spp.*) is a tropical plant grown as a cash crop worldwide. It is one of India's important commercial-led industrial crops, covering an area of nearly 5.8 million hectares (Mha). It has contributed significantly to the growth of Indian agriculture and the national gross domestic product (GDP). Sugarcane is India's prime sugar source. It occupies a prominent position in the Indian agricultural scenario because of its broader adoption in different agro-climatic conditions of the country. It has a significant role in the national economy and provides raw materials to sugar and over twenty-five other vital industries, producing alcohol, papers, chemicals, and cattle feed. Considering the potential of sugarcane, there is still an enormous scope to increase sugarcane productivity per unit area per unit time. This requires sugarcane-growing farmers to be ready to face new challenges like global warming and aberrant weather situations. This crop is grown in various states of India in divergent agroecological subregions, represented by soils containing different carbon pools, which are again linked with soil carbon sequestration and soil carbon footprints with particular reference to sugarcane crop.

Sugarcane is grown in different regions, varying from tropical to subtropical zones. The tropical region in India consists of Karnataka, Maharashtra, Madhya Pradesh, Andhra Pradesh, Tamil Nadu, Goa and Kerala. The sub-tropical region comprises Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal, Assam and the north-eastern states. Production and productivity of sugarcane are about 491 million metric tonnes (million MT) and 84 t ha^{-1}, respectively. Earlier, characterization and evaluation of some typical sugarcane growing soils of Jalgaon district, Maharashtra had been done (Prasad et al., 2007; Ashokkumar and Prasad, 2010). Further, other researchers had attempted to assess the fertility status of sugarcane-growing soils of Ahmadnagar and Latur districts (Patil and Sonar, 1994; More et al., 1994; Patil and Kharche. 2006; Manwar et al., 2015).

Sugarcane is the main sugar-producing crop that contributes nearly 95% to the total sugar pool at the global level. It is the prime source of sugar in India, also holding a prominent position as a commercial cash crop. It is grown over various soil conditions, *i.e.*, shallow to deep and coarse loamy to clay soils. Nowadays, sugarcane cultivation is one of the most profitable farming enterprises. Like other crops, sugarcane-growing soils also need an inventory. Judging by the value of soil resource inventory for increasing food production and conservation of natural resources (Eswaran and Gathrie, 1982; Bhattacharyya et al., 2014), a separate inventory of sugarcane-growing soils for India should be a research priority, as has been carried out by a few to develop site-specific sugarcane management strategies (Mahesh et al., 2019) using the pros and cons of economics (Tiwari, 2003; Jawanjal et al., 2015).

In the context of global warming and climate change, people only talk about carbon footprints regarding the above-ground footprints. Here is the evidence of

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soil carbon footprints related to underground soil activities mainly controlled by soil carbon sequestration. These soil carbon footprints could be a tool to identify climate-smart sugarcane-growing soils. The present paper shows the extent of soil carbon footprints. Also, it suggests methodologies for identifying climate-smart soils used for growing sugarcane with a few selected and interlinked parameters to maintain the country's overall soil carbon reserves.

Materials and Methods

The available literature was used to assess the limits of carbon sequestration, soil carbon footprints and climate-smart sugarcane soils (Ashokkumar and Prasad, 2010; Prasad et al., 2007; Jawanjal et al., 2015; Mahesh et al., 2019; Manwar et al., 2015; More et al., 1994; Bhattacharyya et al., 2008, 2017).

India contributes nearly 5.7% of the total global emissions [50 billion tonnes (Bt), CO_2 (eq.)] of greenhouse gases (GHGs) (Anonymous, 2019, 2021; Ritchie, 2020). Agriculture contributes globally 18.4% of the total GHG emissions (Ritchie, 2020); India's share is 4.4% of global agricultural GHG emissions (Anonymous, 2019, 2021; Ritchie, 2020) as illustrated in **Figure 1**. Within the overall contribution of agriculture towards GHG, agricultural soil contributes 4.1% of the global (50 Bt CO_2 eq.) C footprints (Ritchie et al., 2020). Below ground, total carbon footprints are nearly 817 billion MT and 27 billion MT of CO_2 equivalent in the world and India, respectively. Soil carbon footprints consist of organic and inorganic forms of carbon and are contributed by soil carbon sequestration.

Carbon sequestration refers to removing carbon, as CO_2, from the atmosphere by photosynthesis. Carbon storage indicates the amount of carbon locked in the woody materials above and below ground. Therefore, carbon sequestration is when CO_2 is removed from the atmosphere and held in solid or liquid form. Nearly 3.67 MT of CO_2 (1 MT carbon) is sequestered in soils as various pools by the clay colloids. Amorphous materials and free organic matter also contribute to soil carbon sequestration (SCS). SCS has a role in mitigating GHG emissions to reduce carbon footprints (CF) and hence demands attention from the planners to save this natural resource (soil) with particular reference to agriculture.

The quantum of soil carbon, which can be sequestered is a moot question. So far, SOC in agricultural soils is concerned with the limit of organic carbon sequestration being reached till soils attain a near steady-state/QEV quasi-equilibrium value (QEV). Under natural vegetation/adopted system, carbon values in soil reach a near steady-state/QEV of organic carbon. SOC declines when forest lands are put to cultivation. Within a varied period, SOC stabilizes to reach a near steady-state/QEV in different systems, say, forest (500-100 years), agriculture and horticulture (5-50 years). In India, for Mollisols in the Bhimashankar Plateau, Pune, India maximum value of SOC QEV was 2-4% (Dickson and Grover, 1953; Jenny, 1950; Arrouays et al., 1995; Saikh et al., 1998; Naitam and Bhattacharyya, 2004;

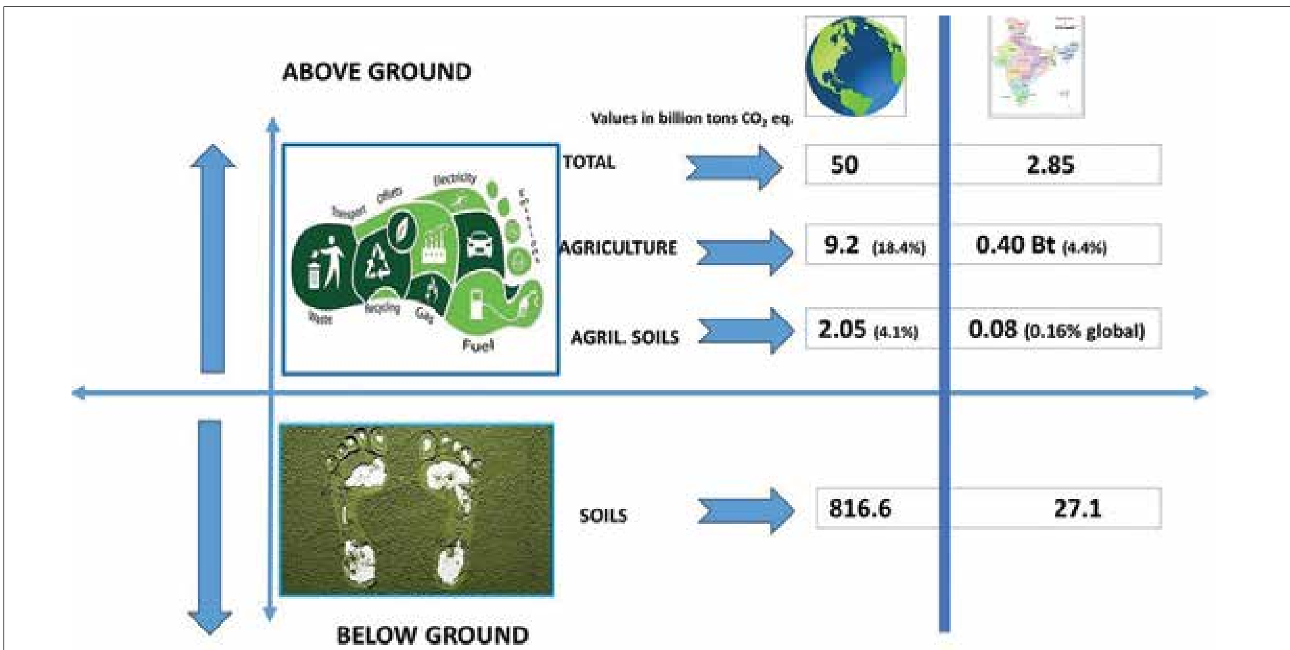

Figure 1. Carbon footprints above and below ground at global and Indian levels

Table 1. QEV of SOC in India's different geographic locations and bioclimatic systems

Systems	Soils	MAR* (mm)	QEV of SOC (%)	Duration (year)	References
Coastal Humid, India					
Teak (*Tectona grandis*)	Black (Vertic Haplustolls)	1423	3.5	Centuries	Bhattacharyya et al. 2006
Mango and cashew	Red and black	>3500	1.5-2.0	>45	Bhattacharyya et al. 2018a, b
Paddy	Red and black	>3500	1.0-1.2	>60	—-
Humid North Eastern Region					
Forest	Red (Typic Kandihumults)	1500	~2.2	Centuries	Bhattacharyya et al. 1996
Tea	Alluvial (Typic Dystrudepts)	1500	~1.2	~70	Bhattacharyya et al. 1996
Rubber	Red (Typic Dystrudepts)	1500	~1.3	~45	
Semiarid Tropics in Central and Peninsular India					
Teak	Black (Vertic Haplustepts)	1010	~1.0	500-1000	Dickson and Grover 1953; Jenny 1950; Naitam and Bhattacharyya, 2004
Cotton and pigeon pea	Black (Leptic Haplusterts)	1010	0.5	50	Naitam and Bhattacharyya, 2004

*MAR: mean annual rainfall

Bhattacharyya 2022a) as given in **Table 1**. For Histosols, the organic soils, it is still high and may reach more than 20% by weight (Soil Survey Staff, 2014).

Similar data for QEV of the soil inorganic carbon (SIC) is uncertain. But soil taxonomy suggests 15% or more (by weight, fine-earth fraction) $CaCO_3$ equivalent for qualifying a calcic horizon indicating reserves of high SIC. A few soils from the Indo-Gangetic Plains (IGP) in Uttar Pradesh and Bihar show 44-54% of $CaCO_3$ (Ray et al., 2014), suggesting half of the soils are calcareous. Such highly calcareous soils can sequester nearly 5 to 7% of SIC.

The SCS (t ha^{-1} CO_2 eq.) was estimated following this formula

SCSo (t ha^{-1} CO_2 eq.) = {[SOC*BD*0.3]*(44/12)*100}

SCSi (t ha^{-1} CO_2 eq.) = {[SIC*BD*0.3]*(44/12)*100}

where, SOC= Soil organic carbon in %; SIC= Soil inorganic carbon in %; BD= Bulk density, Mg m^{-3}; and 0.3= Soil depth in m. The factor 44/12 converts C into CO_2 equivalent.

Once SCS is estimated, we need to have limits of SCSo and SCSi to estimate soil carbon footprints with these assumptions.

i. SOC stock of the country should not be reduced and SIC stock should not increase.

ii. SOC stock of the country is 11.4 Pg at 0.3 m depth, which corresponds to SOC as 0.77%, BD as 1.5 Mg m^{-3} for India with an area of 328.7 Mha.

iii. To maintain this level of minimum SOC, the maximum SIC value should be fixed at 1.19%.

iv. SCSo and SCSi limits are >12.71 t ha^{-1} and <19.64 t ha^{-1}, respectively.

Below ground total carbon footprints are nearly 817 billion MT and 27.1 billion MT of CO_2 equivalent in the world and India, respectively. Soil carbon footprints are due to the sequestration of carbon in soils in both organic and inorganic forms (**Figure 1**). The climate-smart sugarcane soils (CSSS) are selected after assessing the soils in terms of SOC, SIC, BD values, SCSo (>12.71 t ha^{-1}) and SCSi limits (<19.64 t ha^{-1}) as shown (**Table 2**).

Results

Before arriving at CSSS using soil CF values, the following paragraphs detail soil carbon types, carbon

Table 2. Threshold limits of soil and soil carbon sequestration to identify CSSS

Soil Parameters	Threshold Limits
SOC (%), minimum	0.77
BD Mg m^{-3}, maximum	1.50
SIC (%), maximum	1.19
Soil Carbon Sequestration [CO_2 (eq.)] per unit area	**Threshold Limits**
SCSo t ha^{-1}	>12.71
SCSi t ha^{-1}	<19.64

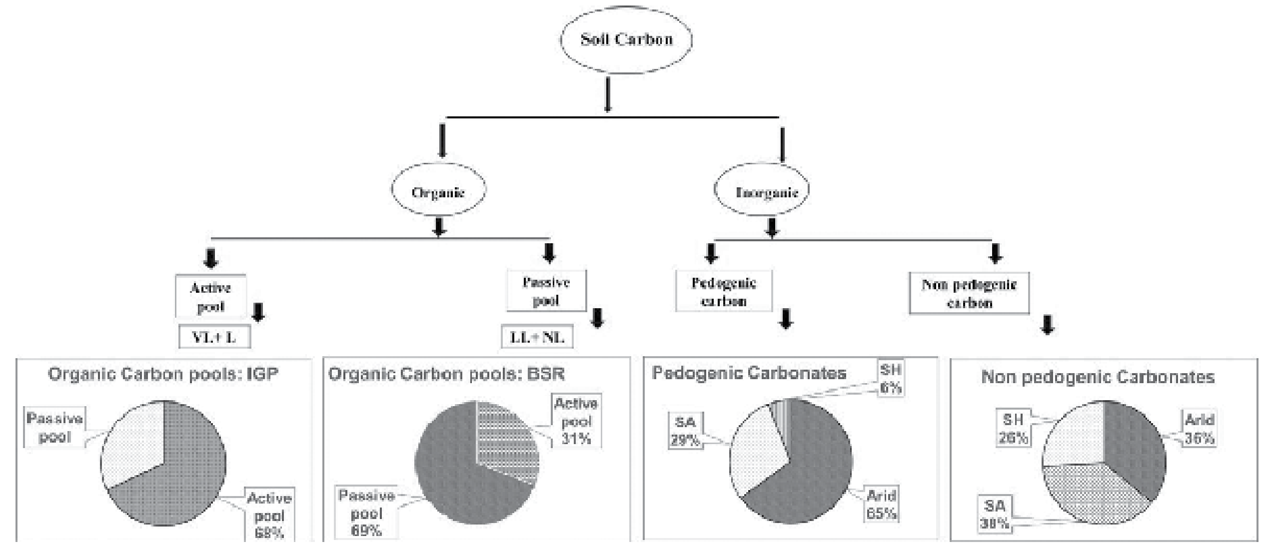

Figure 2. Organic and inorganic soil carbon, their fractions and types

sequestration as the causative factor of CFs and other factors affecting soil carbon footprints.

Types of Carbon in Soils

Carbon in soils is present in two types: SOC and SIC. SOC is separated into active (very labile-VL and labile-L, **Figure 2**) and passive pools (less labile- LL and non-labile-NL) (Chan et al., 2001; Mandal et al., 2008), which differ in their residence time. **Figure 2** also shows the organic and inorganic soil carbon, their fractions and types where VL – very labile: Organic C oxidizable by 12.0N H_2SO_4; L-labile: difference in C oxidizable by 18.0N and that by 12.0N H_2SO_4: LL-less labile: difference in C oxidizable by 24.0N and that by 18.0N H_2SO_4; NL-nonlabile: the difference between total C and oxidizable C by 24.0N H_2SO_4 (Chan et al., 2001; Majumder et al., 2008; Ghosh et al., 2010; Basak et al., 2021; Bharadwaj et al., 2019; Dutta et al.. 2015a, b, 2018)

Active C pool has a rapid turnover rate to effect very fast oxidation as CO_2 from soils to the atmosphere if not used by crops. This active pool has been the main source of nutrition influencing the quality and productivity of soils (Chivhane and Bhattacharyya, 2010; Mandal et al., 2008). Microbial activities slowly alter the passive pool of SOC. Due to its (passive pool) stable nature, this pool does not serve as a good indicator of soil quality. However, it does constitute significant SOC build-up.

The source of SIC is mainly through carbonates measured as $CaCO_3$ equivalent in soils (Jackson, 1973). Depending on the mode of formation of carbonates, SIC is grouped as pedogenic carbonates (PCs) and non-pedogenic carbonates (NPCs) (Pal et al., 2000). By and large, both these two forms of SIC dominate in drier bioclimatic systems (arid and semi-arid) (Srivastava et al., 2002). NPCs could be carbonates, could be geogenic with Fe-Mn-coated glaebules (common in black soils) and are older than white coloured PCs. NPCs are formed in a climate much wetter than the present dry climate. These two forms of inorganic carbon constitute the major SCSi source. Dissolution of soil carbonates could be a useful source of nutrition for plants and deep-rooted trees. The average values of NPCs in the wet climate are much higher than the PCs, suggesting the utility of NPCs in soils for land use planning (Bhattacharyya, 2021b) and thus helping provide soil ecosystem services to society.

Soil Carbon Footprints and Negative Emission Strategy

Soils act as a sink of CO_2 as a biological system. Therefore, it indirectly helps to negate atmospheric emissions (Paustian et al., 2019). Soils capture and store both organic and inorganic forms of carbon and thus act as a source and sink for atmospheric CO_2. Soils are important in enhancing carbon capture and storage (Bhattacharyya et al., 2008) and thus leaving signatures as carbon footprints. Soil preserves its carbon footprints in two different ways i.e. sequestering SCSo and ii) SCSi. Thus, soil carbon footprints below ground may be considered negative CFs, while carbon footprints aboveground are positive.

Increased SCSo in a few sites of the major food-growing zones in India namely the IGPs and black soil region (BSR) were reported (Bhattacharyya et al., 2007; Milne et al., 2007; Swarup and Wanjari, 2000); decreased SCSo is also not uncommon at places (Paustian et al., 1997; Bhattacharyya et al., 2014). Depending on the black cotton soils (BCS) and the land use, soils reach a QEV of SOC with time (Naitam and Bhattacharyya, 2004), as already mentioned. Soil carbon is a dynamic parameter and depends on managing resources (soil), and land use. Land resource managers and the stakeholders are responsible for following the appropriate management adversaries and the required intervention to maintain these dynamic properties under control. Soil substrate determines the saturation point of SCSo when other factors remain constant,. It is expected that smectite-dominant black soils should have a higher limit of SCSo (Bhattacharyya 2021a, b; Dalal and Carter, 2000), as discussed later.

Soil Carbon Footprints in Different Bio-climatic Systems

The climate is one of the important factors controlling soil carbon sequestration. The SCSo follows the trend of arid cold (Ac) <arid hot (Ac) <coastal (C) <subhumid (SH) < humid-per humid H-SH) <semi-arid (SA). The scenario for the soil SCSi is slightly different; it follows the trend of coastal < humid-per humid < subhumid < arid cold < semi-arid < arid hot. Absolute estimates of soil carbon sequestration are area-dependent, making semi-arid BCS a higher contributor for SCSo even though most of the soils in dry areas contain low organic carbon (Bhattacharyya, 2023). This is true for BCS and estimating soil carbon sequestration for an individual soil site. This anomaly was removed by expressing the estimates per unit area. Such a method shows that H-PH and C, BCS store five times more SCSo than the total SCSo (46 t ha^{-1}). This is in line with the general understanding and observation of more SCS in higher rainfall areas. The SCSi shows that arid hot bio-climate stores a considerably high amount of SIC per unit area and constitutes seven times more than the total (37 t ha^{-1}). Inorganic carbon footprints in these dryland soils are larger than those of organic carbon. The details of SCS in various bioclimatic systems, rate of SCSo and SCSi and their relative proportions are given in **Figure 3a, b, c and d**.

Soil Carbon Footprints and Ecosystem Services

Soil carbon footprints are governed by SCS, which in

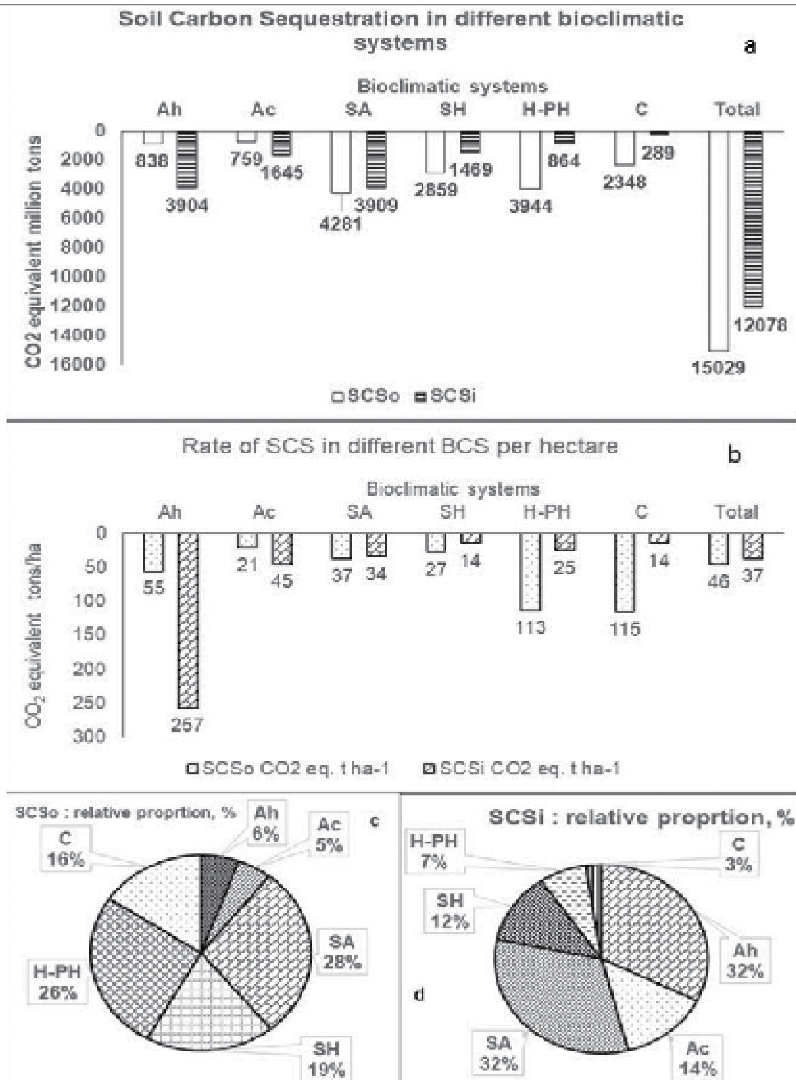

Figure 3. SCS in different bioclimatic systems (a); rate of SCS in different BCS (b); SCSo and SCSi, and their relative proportions (c&d) (Source: Revised from Bhattacharyya et al., 2017)

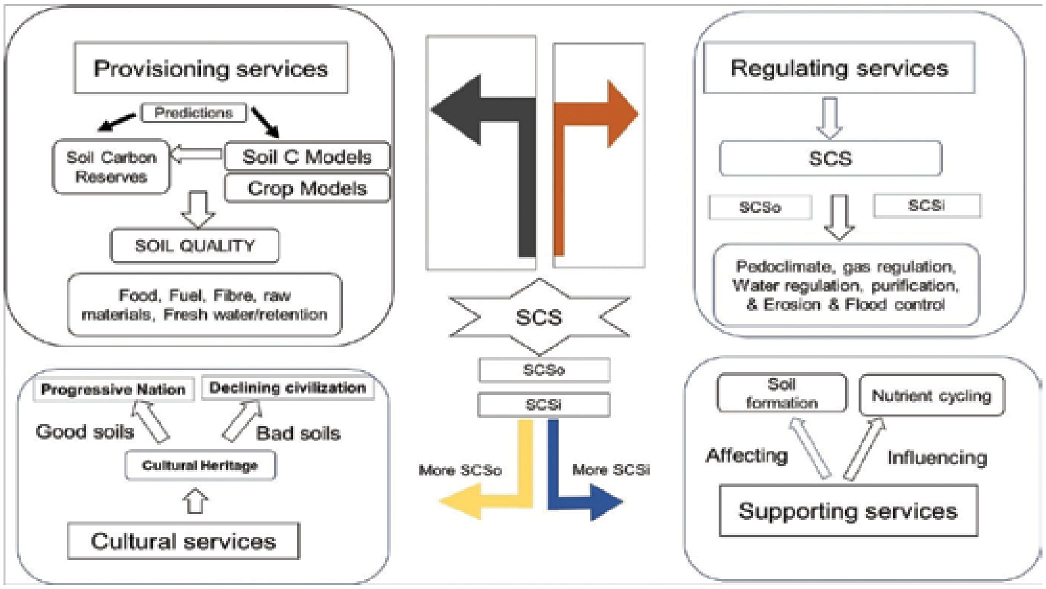

Figure 4. Soil carbon sequestration in SCSo and SCSi and their influence on various ecosystem services

turn provides provisioning, regulating, cultural, and supporting ecosystem services (**Figure 4**). Soil carbon regulates services in terms of sequestration of both (SCSo) and SCSi. Provisioning services centre on soil quality, requiring knowledge of SCS. This helps in assessing crop performance and to reschedule resource management. SCS can, therefore, influence food, fuel, fibre, raw materials and fresh water retention. SCS also supports ecosystem services, including soil formation and nutrient recycling. The progress of a nation and declining civilization are the results of poor soil/land quality. SCS dictates both. Thus, SCSo and SCSi shall maintain the cultural heritage of mankind since soils can memorize and store past events (Bhattacharyya, 2021b).

Soil Carbon Footprints and Soil Substrate

Soil carbon footprints governed by carbon sequestration are regulated by soil substrate. Soil organic matter is controlled by inorganic substrates (78%) and precisely phyllosilicate minerals with higher surface area in the finer fractions (Batjes, 2001; Bhattacharyya and Pal, 2003). Both soil carbon footprints and sequestration are thus largely controlled by clays and clay minerals with higher surface areas; the amorphous materials and free organic matter contribute to the remaining portion (**Figure 5**).

The importance of surface charge density (SCD) determined by the nature of clay, surface area, charge

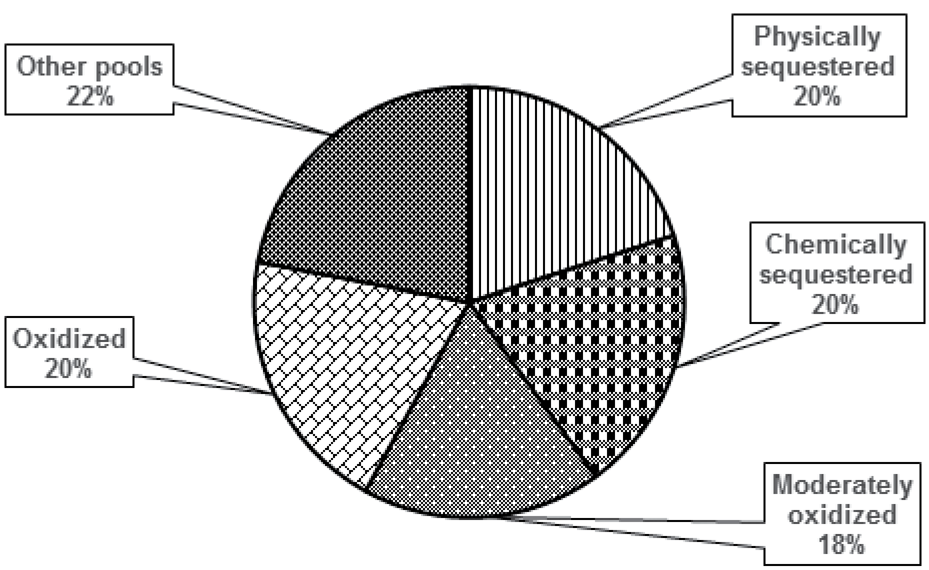

Figure 5. Soil substrate as a limiting factor for SCSo influencing soil carbon footprints (Source: Bhattacharyya, 2021b)

characteristics and cation exchange capacity, rainfall, and their combined influence indicates an inverse pyramid relation of content of SCS with soil as defined in **Figure 6a** (Bhattacharyya et al., 2015a). The capacity of soils to sequester carbon depends on the type of soils, drainage *i.e.* saturated hydraulic conductivity (SHC), sodium content in the form of exchangeable sodium per cent (ESP) of soil, and mean annual rainfall (MAR). Under Indian tropical conditions, a threshold limit of 900 mm MAR initiates the formation of soil carbonates (SIC) and increases SCSi as given in **Figure 6b** (Bhattacharyya 2022a).

The capacity of soil to sequester carbon to leave soil carbon footprints may indirectly be measured by their relative resistance to recovering organic carbon (OC), which is measured by standard procedure. The study to compare the recovery of OC by soils with similar clay mineral suite in the black soils in two important food-growing regions of India (IGP and BSR) made an interesting observation (Bhattacharyya et al., 2015b). Climatic parameters such as rainfall, and per cent recovery of organic matter from soils are inversely related to clay content as it influences corrected Walkley Black Recovery Factor (WBRFc)

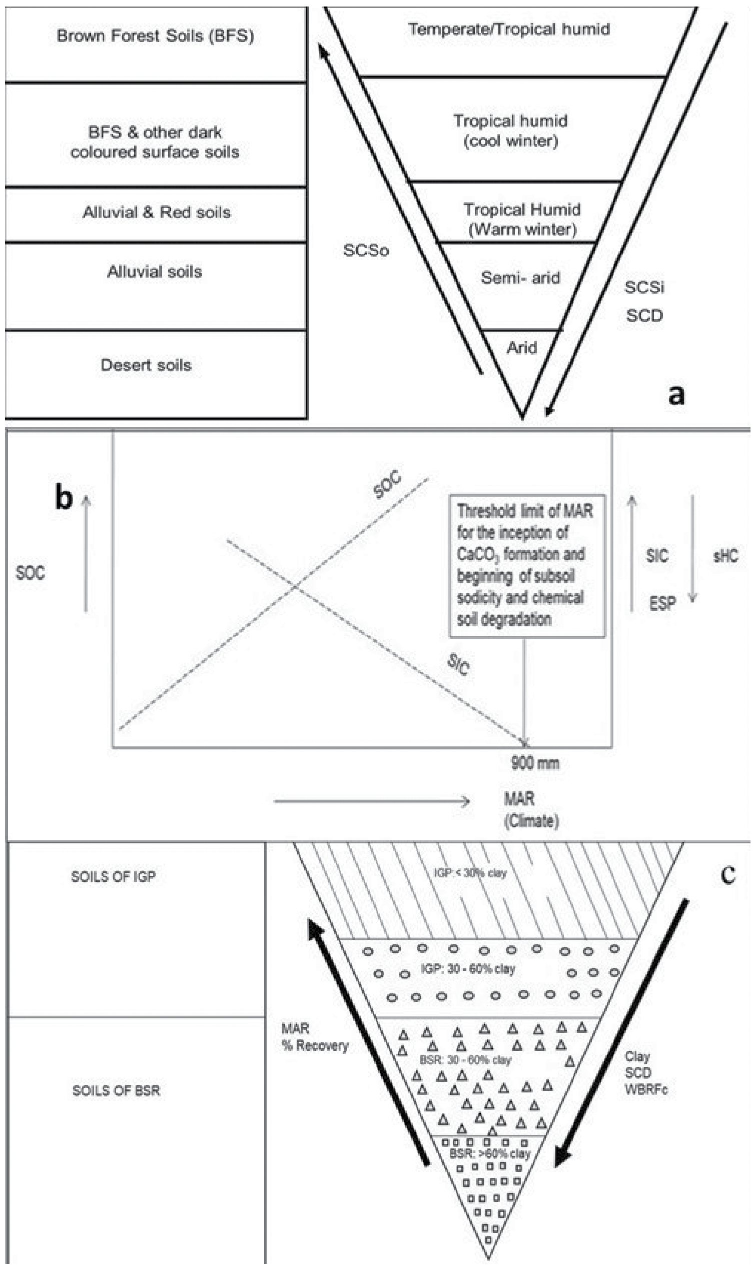

Figure 6 a). Soil organic and inorganic carbon and their relation with climate and soil properties to influence carbon footprints. b) Inverse pyramid relation of SCSo with bioclimatic system [controlled by climate (rainfall), temperature] and substrate quality (SCD, surface charge density). c) The relation between mean annual rainfall, clay content, % recovery of organic matter from the soil by chemical extractant, and corrected Walkley Black Recovery Factor in the soils of the Indo-Gangetic Plains and black soil region (Bhattacharyya et al., 2015 a,b).

(Bhattacharyya et al., 2015a) as well as surface charge density in soils of the IGP and BSR.

The relative proportion of clay in soils of the IGP and BSR vary. Many black soils of the IGP contain < 30% clay, and a little less is occupied by those containing 30-60% clay. For BSR, most black soils fall within the range of 30-60% clay and a few with > 60% category. Recovery rate in these black soils with vertic (shrink-swell characteristics of black soils) properties may not be similar to soils other than black soils (**Figure 6c**). The quality of clay minerals with smectites as the dominant minerals are the main reason for holding organic matter tenaciously. Therefore, organic matter recovery from these clay-dominated soils is indirectly related to the amount of carbon stored. The charge characteristics of the smectites of these soils and the other soils might open up new vistas of clay research looking for an interface between pedology (soil taxonomy, mineralogy) and edaphology *i.e.* soil organic matter estimation, its sequestration and linking it to the amount of nitrogen for plant growth as given in **Figure 6c** (Bhattacharyya et al., 2015b). Soil substrate, therefore, significantly influences leaving carbon footprints (CFs).

Soil Carbon Footprints and Soil Modifiers

Soil modifiers such as, calcium-rich zeolites, non-pedogenic carbonates (NPCs), and gypsum help change soil physical, chemical and biological properties and influence soil parameters in a way that helps plants/trees to perform better (Bhattacharyya 2021a). These positive modifiers make soils crop-friendly, permitting a better soil environment for increased SCSo. Negative modifiers (pedogenic carbonates: and palygorskite) render soils poor in terms of SCSo and rich in SCSi, thus enhancing soil degradation (**Figure 7**). In both the cases, soil carbon footprints will be affected, making it challenging for natural resource managers.

Soil Carbon Footprints and Soil Resilience

Soil resilience is the pedo-edaphic environment's capacity to absorb a disturbance until it reaches the threshold limit of withstanding the changes. These changes might be natural or anthropogenic. Regarding SCS potential, it is important to assess the soil ecosystem's changes before they become irreparable. Soil has resilience and can return to normalcy (Holling, 1973; Folke et al., 2004; Walker et al., 2004; Bhattacharyya et al., 2016). Enhanced SCSo helps soils maintain quality and health, while SCSi impairs soil physical, chemical and microbiological activities. SCSo is considered a boon, and SCSi is a bane. Soil resilience has a tremendous influence on leaving carbon footprints.

Carbonate minerals initiate formation of SCSi in the subsurface and gradually engulf the entire soil depth. With high bulk density and poor drainage (low saturated hydraulic conductivity), these soils may become hard rock in the arid and semi-arid bioclimate. Such soils will make the land barren under business as usual (BAU) level of management (left of **Figure 8**). However, these soils show resilience under improved management intervention, which might soften the soils with more SCSo and less SCSi. This will make the land green to restore the soil ecosystem (right of **Figure 8**). These resilient soils should have a minimum threshold of SOC, SIC, and BD to help them qualify for climate-smart, as detailed later.

Soil Carbon Footprints and Climate-smart Sugarcane Soils

Soil carbon sequestration estimates provide the

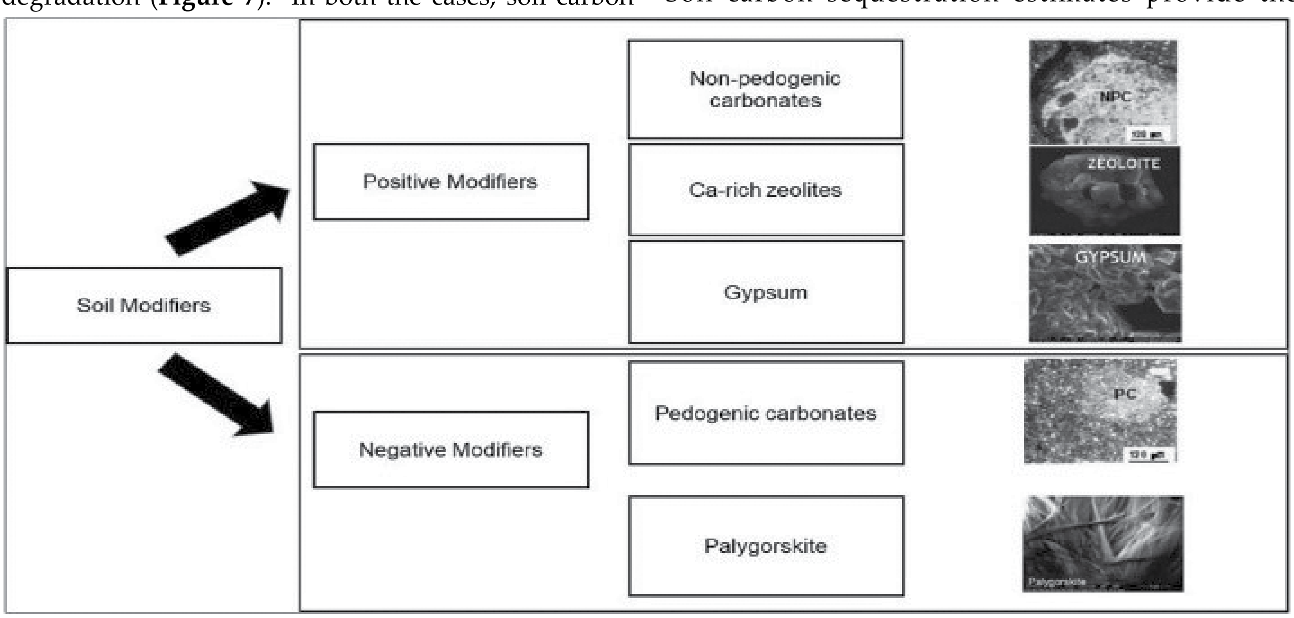

Figure 7. Various types of soil modifiers to control SCS and CFs (Source: Bhattacharyya, 2021a)

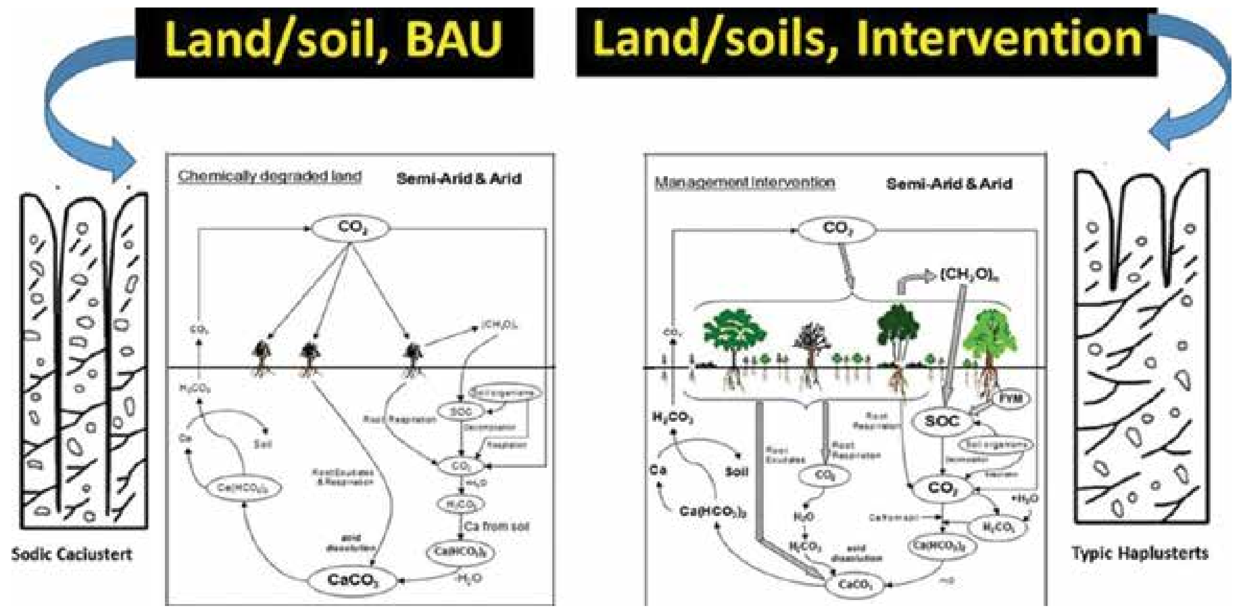

Figure 8. Chemically degraded land/soil (sodium-dominated black soils: Sodic Calciusterts) with low SCSo and high SCSi (Left, semi-arid and arid) in business as usual showing resilience due to management intervention with normal black soils (sodium dominated black soils: Typic Haplusterts) (right side). To keep soils /lands in good health, no parcel of it should be kept fallow.

quantum of soil carbon footprints useful for identifying climate-smart sugarcane soils (CSSS). The arid and semi-arid environments prevailing in central and southern peninsular India and a part of the IGP are used for growing sugarcane. These areas, especially the BSR, are experiencing the global warming phenomenon (Eswaran and Evan den Berg,1992), which is the major reason for low SCSo in these areas. Despite this, total SCSo in these BCS is higher due to higher aerial extent and always offers a better scope for SCS. SCS expressed per unit area [CO_2 (eq.) t ha^{-1}] is ideal for identifying CSSS under soil/management practices in a given land use system. The CSSS should have high resilience to respond to various management interventions. The threshold values to identify climate-smart soils are shown in **Table 2**.

Only a few could pass the test of being identified as CSSS out of the soils studied from the IGP, and BSR (Ashokkumar and Prasad 2010; Prasad et al., 2007; Jawanjal et al., 2015; Mahesh et al., 2019; Manwar et al., 2015; More et al., 1994). These soils are Damla Yamuna Nagar soils in Haryana and Tal soils from Bihar in the IGP, India. The soils from the BSR are Vadala Mahadev, Murud and Kolpa from Maharashtra (**Table 3**).

Examples of BSR and IGP soils used for growing sugarcane are shown in **Figure 9**, which satisfied the limits of SCSo as >12.71 t ha^{-1} and SCSi as <19.64 t ha^{-1}. The green line is the limit of organic carbon, and the red horizontal line is the inorganic carbon sequestration limit. These are only a few examples. Enthusiastic researchers can use this model

Table 3. Required parameters and their values for selected climate-smart sugarcane soils

Parameters	Tal soils	Damla, Yamuna Nagar soils	
IGP			
BD (Mg m^{-3})	1.3	1.3	
SOC (%)	0.8	0.8	
SIC (%)	0.0	0.0	
SCSo (t ha^{-1} CO_2 eq.)	13-15	13.6	
SCSi (t ha^{-1} CO_2 eq.)	0-6.9-15	0	
BSR			
	Vadala Mahadev soils	**Murud, Latur soils**	**Kolpa, Latur soils**
BD (Mg m^{-3})	1.6	1.4	1.5
SOC (%)	1.9	0.9	0.8
SIC (%)	0.03	0.7	0.2
SCSo (t ha^{-1} CO_2 eq.)	19	14.3	12.7
SCSi (t ha^{-1} CO_2 eq.)	0.5	12.5	4.2

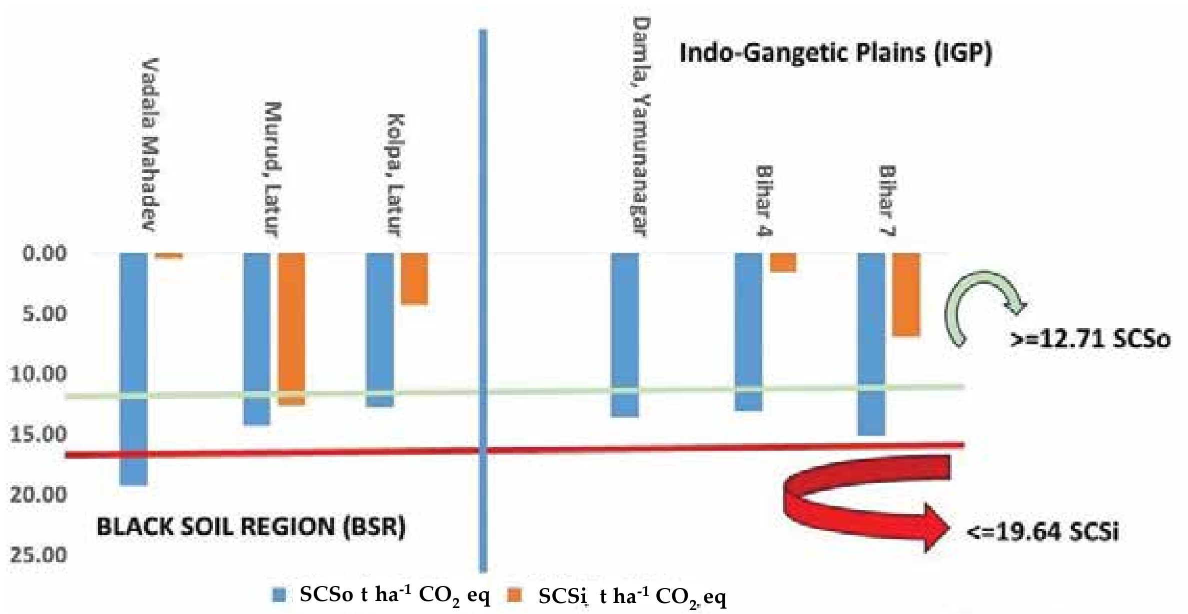

Figure 9. Climate-smart sugarcane soils in India: a few examples

understanding to identify more such soils from their database, not only from India but from other countries.

Conserving Climate Smart Sugarcane Soils

The climate smart sugarcane soils need to be preserved. These are important soils that are braving the brunt of climate change and providing all the ecosystem services we need (Bhattacharyya, 2022a), with special reference to sugarcane production. These soils require appropriate management practices which will keep them healthy and climate-smart. There could be two management approaches: BAU and out of box management (OBM).

Business as Usual Management Practices: The business as usual management practices could be of two types: high and low management. High management practices involve higher N, P and K fertilizer applications, regular farm yard manures (FYM) doses, legume intercropping wherever feasible, residue incorporations, ridge furrows, and bunding broad bed furrows for soil moisture conservation. These are mainly at a minimum level at the low management types and require to be brought to the level of high management to qualify soils as climate-smart.

Table 4. Management levels for increased soil organic carbon footprints to identify climate-smart soils

	Business as Usual (BAU)	
Management	**High management**	**Low management**
Fertilization	Higher N, P and K fertilizer applications	Higher N, P and K fertilizer applications at relatively low rate
Manure	Regular applications with farm yard manures	Rarely applied
Legumes as intercrop	Very common	Almost nil
Residue applications	Residues incorporated regularly	Rarely applied
Moisture conservation	Ridge furrows, bunding broad bed furrows are regularly used for soil moisture conservation	Nil
	Out of Box Management	
	Examples	**References**
Deep -rooted trees/cereals	Cereals: GrassesTrees: Oranges, tea, rubber	Bhattacharyya et al., 2004; Glover et al., 2010; Pimentel et al., 2012; Crews and Ramsey, 2017; Culman et al., 2013
Splitting doses of manures	FYM in two splits before rains and onset of winter in tropical India	Jadao et al., 2019,2020; Bhattacharyya et al., 2022b

Out of Box Management Practices: These might include deep-rooted trees/cereals; cereals may consist of a few species of grasses; trees (oranges, tea, rubber) may be options; and splitting doses of manures might help build more SOC to help. Qualifying soils as climate-smart, FYM in two splits before rains and the onset of winter in tropical India may be helpful (**Table 4**).

Conclusions

SOC and SIC are the two important dynamic soil properties and are dependent on various factors like bioclimate, substrate quality and level of management. It is pretty likely that the soils below the threshold values might have the capacity to qualify for climate-smart soils with higher level of soil management. The present values are set for Indian soils which may serve as a model understanding to fix the limits for CSS elsewhere in similar conditions. The CSS must be protected and the steps appropriate for such efforts should be made available to the stakeholders. SOC is a boon, and SIC is a bane. Therefore, a proper management balance might keep these soils as CSS to improve farmers' livelihoods and maintain ecological balance. This requires tropical soils to be kept constantly under vegetative cover. Since various factors control the CSS and thus require a perfect balance to maintain a see-saw relation **(Figure 10 a, b).**

Identifying CSS is an important step towards saving soils from climatic vagaries. Moreover, proper understanding of both the forms of soil carbon sequestration (SCSO, SCSi) shall help planners to set the target of appropriate soil management to save the planet for posterity. This might also open a new vista for managing climate-smart soils (Paustian et al., 2016; Bhattacharyya, 2024). Soil C footprints help to identify CSS for sugarcane. This model could be used for other crops in other areas too. Soil leaves carbon footprints in organic and inorganic forms and is related to carbon sequestration. Soil carbon footprints help mitigate GHG emissions since these are linked to a negative C emission strategy.

Identifying different CSSS shall help to find out hotspots for monitoring soil quality and health. The SOC sequestration, CSSS, and carbon units in soils are interlinked and inter-disciplinary subjects. This might be a beginning of another exercise to assess the quantum of soil carbon credits, the carbon farmers (engaged in field and horticulture crops) may achieve, by maintaining their soils as climate-smart (Bhattacharyya, 2024; Bhattacharyya et al., 2024).

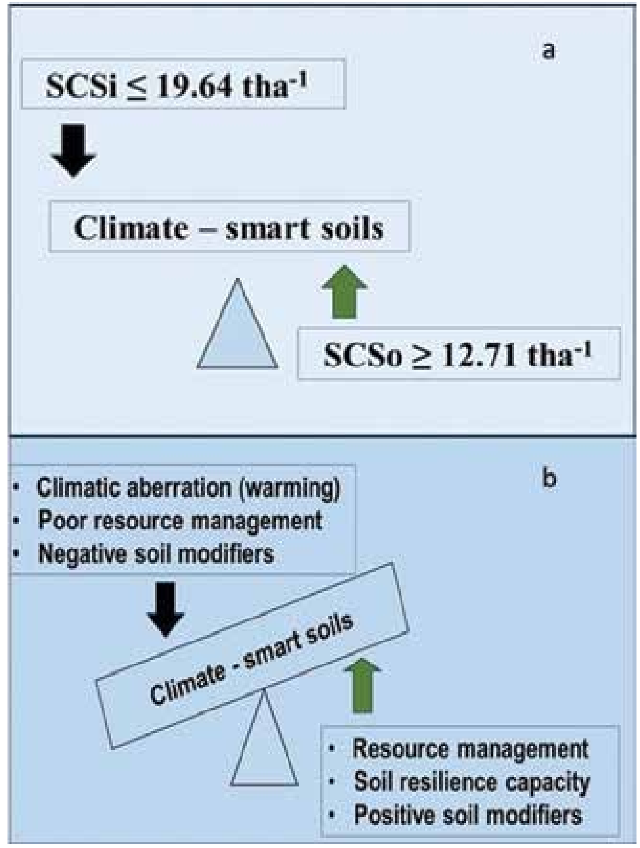

Figure 10. Climate-smart sugarcane soils a) need an exact balance of SCSo and SCSi threshold limits and b) have a see-saw relation with climate-smart sugarcane soils and other factors

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