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Climate-smart Soils : A Suggestive Model of Tools for Carbon Benefits to Farmers

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Abstract

Soil carbon sequestration in organic and inorganic forms can be assessed to estimate soil carbon footprint (CFs). These footprints may be used to identify climate-smart soils (CSS) in different regions with different land uses. The CSS has been shown here as a tool to measure the quantity of carbon units the farmers can reap from farm activities. These carbon farmers can thus profit from their farms, creating a clean and sustainable environment to keep global warming at bay. This benefit will be an added advantage if such farmers maintain CSS in their farms using appropriate management practices with a blend of both organic and inorganic sources of plant nutrients. A suggestive model to link soil carbon sequestration, soil carbon footprints, climate-smart soils and carbon units is discussed.

Key words: Soil carbon sequestration, carbon footprints, climate-smart soils, carbon units

Introduction

Climate change is recognized as one of humanity's most significant challenges in the 21st century. The problem of climate change is a consequence of the greenhouse gases (GHGs) that maintain an average temperature of 15 ^{o}C on earth, allowing life to exist (Pachauri and Reisinger, 2007; Gorain et al., 2021). Carbon dioxide (CO_2) is the primary cause of the human-induced greenhouse effect, mainly from burning fossil fuels and deforestation. Another greenhouse gas, methane, comes from burning forests, ruminant livestock, rice paddies, farms and landfill gas. Other GHGs, such as nitrous oxide (NO_x) from fertilizers and some chemical processes, halocarbons from refrigerant gases and tropospheric ozone are released by the combustion of hydrocarbons (Benecke, 2009; Gorain et al., 2021).

Every country is spending a lot of time, energy, and money to solve one of the major international problems of climatic change threatening our existence. Considerable efforts are being made by governmental authorities, politicians, economists, non-governmental organizations (NGOs), and various others to address this issue. To produce a stringent plan of action for environmental protection, the Kyoto Protocol was organised in 1997, where stakeholders from across the globe brainstormed a mechanism whereby it was decided to incorporate carbon (main greenhouse gas) reduction endeavours with economic motives of enterprises to motivate sustainability efforts on their part. Under this arrangement, carbon, a gift of nature, has been converted to an economic commodity actively traded in carbon credits (Rajput and Chopra, 2014). Such a gift of nature and its economic benefits should also reach the stakeholders/carbon farmers engaged in farming.

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 (CCS) (Bhattacharyya et al., 2008) and thus leaving signatures as carbon footprints. Soil preserves its carbon footprints (soil carbon footprints: CFs) in two different ways viz sequestering i) organic carbon (SCSo) and ii) inorganic carbon (SCSi). Thus, CFs may be considered negative, while carbon footprints aboveground be positive CFs (Bhattacharyya, 2024, Bhattacharyya et al, 2024).

Soil organic carbon sequestration SCSo in a few sites of the major food-growing zones in India namely the Indo-Gangetic Plains (IGPs) and black soil region (BSR) were reported to increase (Bhattacharyya et al., 2007; Milne et al. 2007; Swarup and Wanjari, 2000) and decrease at some other places (Paustian et al., 1997; Bhattacharyya et al., 2014). Depending on the bio-climatic systems (BCS) and the land use, soils reach a quasi-equilibrium value (QEV) of SOC with time (Naitam and Bhattacharyya, 2004) which is important to assess the quantum of soil

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carbon sequestration.

Soil carbon is a dynamic parameter and depends on managing resources (soil) and land use. Land resource managers and the stakeholders are responsible for adopting the appropriate management practices and the required intervention to maintain the level of soil organic carbon substrate determines the saturation point of SCSo if other factors remain constant. The black soils are reported to have a higher limit of SCSo since these soils are dominated by smectite minerals with higher surface area, making them a better substrate for carbon sequestraation. (Bhattacharyya 2021a,b; Dalal and Carter, 2000).

Soil Carbon Footprints and Climate-Smart Soils

Estimating soil carbon sequestration provides the quantum of soil carbon footprints for identifying climate-smart soils (CSSs). The arid and semi-arid environments prevailing in central and southern peninsular India, dominated by black soils (Vertisols and their intergrades), are experiencing the global warming phenomenon which results in low soil organic carbon sequestration (SCSo) in these areas. Despite this, the total SCSo in these black soils is higher due to higher aerial extent, which naturally helps to garner more SCS. The SCS expressed per unit area [CO_2 (eq.) t ha^{-1}] is ideal for identifying climate-smart soils under appropriate soil/management practices in a given land use system. These CSSs should have high resilience to respond to various management interventions. The threshold values to identify CSSs are shown in **Table 1**.

Measuring Soil Carbon Footprints: The methodology to estimate soil carbon sequestration (SCS) has been detailed earlier (Bhattacharyya et al., 2024; Bhattacharyya, 2024). The SCSo and SCSi were estimated following this formula:

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

Table 1. Threshold limits of soil and soil carbon sequestration to identify climate-smart soils

Soil Parameters	Threshold Limits
SOC (minimum) (%)	0.77
BD (maximum) M gm^{-3}	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

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 in Mg m^{-3}, 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.

a. SOC stock of the country should not be reduced while SIC stock should not increase.

b. SOC stock of the country is 11.4 Pg at 0.3 m depth, corresponding to SOC as 0.77%, and BD as 1.5 Mg m^{-3} for India with an area of 328.7 million ha.

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

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

Soil organic carbon may be determined by the Walkley and Black method (Walkley and Black, 1934) and be revised by the corrected Walkey Black Recovery Factor (WBRFc) (Bhattacharyya et al., 2015). Soil inorganic carbon (SIC) constitutes 12% of $CaCO_3$ equivalent in soils and may be determined following the standard method (Jackson, 1973). One hundred mesh air-dried soil samples are recommended for determining both SOC and SIC in the laboratory. Bulk density may be determined by the field/moist method (McIntyre, 1974; Klute, 1986). The soil parameters are to be monitored after 3-5 years for the areas used for agriculture. This duration will vary depending on other land uses, history, and soil types.

Conserving Climate Smart Soils: The climate-smart soils need to be preserved. These are important soils that are braving the brunt of climate change and providing all the ecosystem services to humankind (Bhattacharyya 2022; Paustian et al., 2016). These soils require appropriate management practices to keep them healthy to maintain climate-smart status. These practices might include management approaches such as business as usual (BAU) and out of box management (OBM). The BAU management practices may have two different levels of management, viz. high and low. High-level 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 (BBF) for soil

Table 2. Type of managements and their levels for increased soil organic carbon footprints to identify climate-smart soils (Source: Bhattacharyya (2024); Bhattacharyya et al., 2024)

Management		Fertilization	Manure	Legumes and others as intercrop	Residue applications	Moisture conservation
Type	Levels					
Business as usual	High management	Higher N, P and K fertilizer applications	Regular applications with farm yard manures conservation	Very common	Regular residue incorporation for soil moisture	Ridge furrows, bunding broad bed furrows are regularly used
	Low management	N, P and K fertilizer applications at relatively low rate	Rarely applied	Almost nil	Rarely applied	Nil
	Types	**Examples**	**Suggestion**	**References**		
Out of Box management	Crop choice	Cereals	Grasses	Bhattacharyya et al., 2004, Glover et al., 2010; Pimentel et al., 2012, Crews and Ramsey, 2017; Culman et al., 2013		
	Manures	Splitting doses of manures	FYM in two splits before rains and onset of winter in tropical India	Jadhao et al., 2019, 2020; Bhattacharyya et al., 2022		

moisture conservation. These are mainly at a minimum level at the low-level management types and must be brought to high-level management to qualify the soils as climate-smart.

Out-of-box management practices include adopting deep-rooted trees/cereals. The cereals may consist of a few species of grasses, while the trees might include oranges, tea, and rubber, among other options. Splitting manurial doses might help build up more SOC instead of a single dose of manures. This is more so in India's arid and semiarid tracts since higher atmospheric temperatures prevailing in these areas add to the problem of global warming, bringing more loss of SOC by volatilization. Therefore, FYM in two splits, one before rains and the other before the onset of winter in tropical India, may help increase the SCSo. This will help soils in arid and semi-arid areas attain climate-smart status **(Table 2)**.

Increasing the organic content of soil is beneficial to offset GHG emissions through sequestration. The addition of organic matter into the soil regularly with better management practices can increase the amount of carbon in the soil.

Carbon Markets: The carbon markets serve as platforms for the exchange of carbon credits. Companies or individuals can counterbalance their GHG emissions by procuring carbon credits from entities engaged in emission reduction or removal activities. Each tradable carbon credit signifies one tonne of CO_2 or an equivalent volume of other GHGs that have been diminished, sequestered, or avoided. Once a credit is utilized to offset emissions, it transforms into an offset and is no longer available for trading. Broadly, two types of carbon markets are there: compliance and voluntary. Compliance markets arise in response to national, regional, or international policy or regulatory mandates. In contrast, voluntary carbon markets operate voluntarily, encompassing the issuance, purchase, and sale of carbon credits on national and international scales (https://climatepromise.undp.org).

Carbon Trading: Carbon trading may be used to control the emission of CO_2 by providing economic incentives by a central authority (Marcu, 2006; Gorain et al., 2021). Indian Government recently released the guidelines for voluntary carbon market in the agricultural sector (Anonymous, 2023a). The Paris Agreement, based on the Kyoto Protocol adopted in 2015, includes the provision for a carbon market under Article 6. Articles 6.2 and 6.4 define the established mechanism for the functioning of the carbon market to compensate for emissions. The

Government of India notified the carbon credit trading scheme to set up a carbon credit market for the agricultural sector. This is part of The Energy Conservation (Amendment) Bill 2022. An environmental activity generating Green credits may have climate co-benefits such as reduction or removal of carbon emissions. An activity generating Green Credits under Green Credit Programme may also get Carbon Credits from the same activity under carbon market. The policy for which is now in place for the benefit of farming community (Annonymous, 2023C, 2024).

Carbon Credits: The Clean Development Mechanism (CDM) is a flexible mechanism for sustainable development (Metz et al., 2007). The CDM allows different projects in the developing countries for gaining certified emission reduction (CER) credits. These CERs can be traded for the emission reduction targets of the developed nations under the Kyoto Protocol. The mechanism helps both parties control emission reduction targets (Shukla et al. 2014). Similarly, the green credit programme is implemented to leverage a competitive market-based approach for carbon trading.

Carbon sequestration, also known as carbon capture, is a technique for the long-term storage of CO_2 or other forms of carbon, which helps mitigate global warming, causing more than 33 billion tonnes of annual worldwide C emissions. Carbon can be stored in various ways viz. (i) terrestrial sequestration in plants and soils; (ii) geological sequestration (below soil layers); (iii) ocean sequestration (deep in the ocean); and (iv) solid material (still in development). Global climate change centres on various factors regarding C sequestration and sustainable development. Carbon sequestration involves the mitigation processes regarding baseline scenarios, best practices, emission reduction credits, targets, leakage and verification. Sustainable development requires adaptation through eradicating extreme poverty and hunger, resilient livelihoods, environmental sustainability, social development and equity.

The Kyoto Protocol suggested stabilising GHGs in the atmosphere at a level to prevent air pollution interference with the climate system. Thirty-eight developed nations are legally bound to reduce man-made GHGs by 5.2%. One hundred and thirty-four nations have their reduction targets in this Protocol. India signed and ratified the Protocol (2002) and maintained that the major responsibility of curbing emissions rests with the developed nations. Different Kyoto mechanisms are (a) clean development mechanisms (CDM); (b) emission trading; (c) joint implementation (JI); (d) development, application and diffusion of climate-friendly technologies; (v) research and systematic observation of climate; (vi) education, training and public awareness of climate change; and (vii) improvement of methodologies and GHG data inventorization.

Carbon trading involves buying and selling credits, which permit a company/entity to emit a certain amount of CO_2/ GHGs. This trading could be (i) emission trading, where a company can reduce its emissions by half the cost of allowance bought from another company. A company with higher expenditure for reduction of its emissions from different companies to save its emission cost and (ii) project-based, where government and the World Bank subsidized credit to the companies assessing the extent of CO_2 equivalent the companies save or reduce. This trading includes baseline credit and offset trading.

The carbon credit may be earned by the agricultural farmers in the Indian context in terms of money and/or other incentives, as shown in **Figure 1**, with negating carbon emissions by storing more organic carbon in soils. India is the largest beneficiary, with 31% of the total world carbon trade through a CDM. This might help to earn Rs.2,25,000 to Rs. 45,000 crore through the Indian companies to garner 10% of the global market in the initial year. And if that happens, annual CER revenues would range from US$ 10 to US $ 300 million for India. Cost components in carbon trading is shown in **Table 3**. It shows that certified emission reduction (CER) for above-ground C footprints and certified negative emission reduction (CEnR) for below-ground (soil) C footprints (Bhattacharyya et al. 2024); Bhattacharyya, 2024) are important right from validation and regular monitoring.

Rural India has the potential for carbon credit in biofuel and energy farming. India can tap US$ 52 billion global market of carbon trading through biofuels and plantations (*Jatropa*, *Pongamia*) of trees with oil-bearing seeds and other materials. Besides, integrated energy farming in fuel farming systems can be established on barren and wastelands. This will bring land degradation neutrality (Bhattacharyya, 2020), enabling farms to earn carbon credits by maintaining CSSs (Bhattacharyya, 2024). Forest cultivation, thereby offering economic rewards for carbon storage to the farms, could effectively conserve and recoup lost carbon in degraded lands.

India is one of the largest beneficiaries of carbon trading. The carbon credits are traded through multi-commodity exchange (MCX) only after the Foreign Contribution Regulation Act (FCRA) passes it. India's large number of sellers are searching for European market-based buyers. It requires an overall policy and legislative framework to govern these carbon trading issues. Credits from different sources are believed to be interdisciplinary/fungible (in Carbonspeak; Fungible means wherein an asset that can be exchanged for another asset with similar type and value). Carbon credits from various sources are not equivalent. For example, carbon sequestered in sinks is a different commodity from carbon saved by a technological breakthrough, which is again different from carbon saved by a change in society or lifestyle. The complexity of this is further increased since each source of GHGs requires specific legislation on supervision, requirements and agencies. Therefore, carbon market may not be forced into one market.

In this trade, soil carbon is gaining popularity as a credit, but it also faces many challenges, even in key markets. Soil carbon sequestration involves removing carbon from the atmosphere and storing it in soil. However, several factors required to be addressed to make soil carbon sequestration and the causative factors to make soil C credits popular, as has been initiated by the farmers in Australia and the United States of America (Anonymous, 2021).

In India and similar other countries with small land holdings, the SCSo, if estimated per unit area (ha), may benefit the small and marginal farmers. America might have created a gap in the voluntary market for natural climate solutions such as agriculture. If the potential of soil enrichment across the globe is increased by scaling up, the opportunity of this industry will be open. This will, in turn, benefit the soil, the atmosphere, the ecosystem, the economy, and the local communities simultaneously. The lack of transparency and standardization that hinders global carbon markets also affects the soil credit market. A standardized carbon market, making credits accessible to buyers, and addressing the right stakeholders are key to developing soil carbon markets (Anonymous, 2021).

The methods shown here in this article may be followed. This is a suggestive model which requires soil management protocol to help farmers earn credits if they preserve soils with more SOC and less SIC with a range of BD around 1.5 Mg m^{-3}. This might make the soil carbon credit accessible to Indian farmers with proper pricing structures. This might help planners sharpen the concept shown in **Figure 1**, encouraging farmers to maintain soil health for posterity.

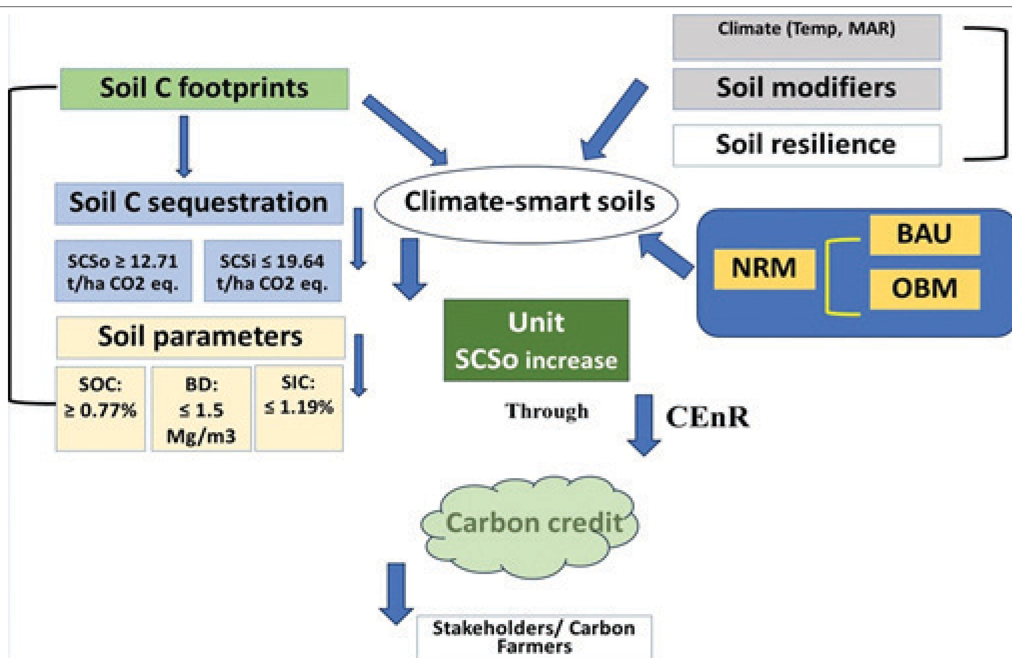

Figure 1. A suggested model to earn soil carbon credits by conserving climate-smart soils following suggested methodologies. (SOC: soil organic carbon; SIC: soil inorganic carbon; BD: soil bulk density; SCSo: soil organic carbon sequestration; SCSi: soil inorganic carbon sequestration; NRM: natural resource management; CEnR: Certified negative emission reduction (please see the text); BAU: business as usual; OBM: out of box management; Temp: atmospheric temperature; MAR: mean annual rainfall.

Table 3. Carbon trading and its cost components-existing and suggested

S. No.	Components
Existing cost components for CER (certified emission reduction)	
i.	Project details: documents
ii.	Validation of CER
iii.	Registration: First 15000 CER @ 0.1 US$; >15001 CER @ 0.2 US$
iv.	Monitoring of CER
v.	Verification of CER (3rd party)
vi.	Issuance cost: First 15000 CER @ 0.1 US$; >150001 CER @ 0.2 US$
vii.	Taxes (host country)
Suggested cost components for CEnR (certified negative emission reduction) *	
i.	Project details: Documents (farmers' field and other details)
ii.	Base Year of CEnR when started following standard methods (see methodology)
iii.	Registration to the SAUs/ICAR/ Extension Departments
iv.	Regular monitoring of CEnR following standard methods by SAUs/ICAR/ Extension Departments
v.	Verification of CEnR (3rd party)
vi.	Carbon credits to the farmers: Recommendation by the SAUs/ICAR/ Extension Departments
vii.	Benefits accrued to farmers online and / or other methods as per recommendation of SAUs/ICAR/ Extension Departments.
viii.	Reporting to the international authority about neutralising above-ground carbon footprints by CFs by the Indian farmers
ix.	Feedback by the farmers

*Also see Bhattacharyya et al., 2014; Bhattacharyya, 2024

Certified Emission Reduction, Proposed Certified Negative Emission Reduction and Carbon Credit Pricing

The Kyoto Protocol that provides for emissions reduction projects generates certified emission reduction (CER) credits for carbon trading. This is true for GHG emissions as carbon footprints aboveground. Soil carbon footprints, on the other hand, help mitigate GHG emissions since these are linked to a negative C emission strategy. Since soils act as a biological sink of CO_2, they indirectly help to negate atmospheric emissions (Paustian et al., 2019). Thus, soil carbon footprints may be considered negative. In contrast, carbon footprints aboveground are positive (Bhattacharyya, 2024, Bhattacharyya et al., 2024), and the efforts which help store more organic carbon in soils generate the proposed certified negative emission reduction (CEnR), may be used as carbon credits in carbon trading.

In addition to the nutrients made available from soil carbon, added through organic matter by FYM and other organic sources; farmers and other stakeholders may reap the benefits of increasing SCSo. A comprehensive assessment of soil health test was carried out using soil samples to generate data on soil physical, chemical and biological properties; fertilizer price was also considered for a few soil samples in the USA (McLain et al., 2021).

Role of Carbon in Climate Change: Soil carbon regulates services in terms of sequestration of both organic and inorganic forms. Provisioning services centre on soil quality, requiring knowledge of soil carbon reserves and predicting carbon stocks over the years. This helps in the prediction of crop yield. Both the forms of carbon in soils can help understand soil and land quality. Therefore, information on soil carbon will ultimately help influence food, fuel, fibre, raw materials, freshwater quality and its retention. Organic and inorganic carbon content also influence supporting services to affect soil formation and nutrient recycling. The progress of the nation and declining civilization are the results of poor soil/land quality. Soil carbon dictates both. Thus, soil carbon helps maintain cultural heritage and provide cultural services to humankind (Bhattacharyya, 2021b; Bhattacharyya et al., 2022) (**Figure 2)**.

Despite maintaining or increasing the SCSo for agricultural farmers, no benefits are provided as soil carbon credits. Maintaining SOC status indicates adopting proper management practices, keeping SIC and BD under control, aiding LDN, and increasing soil organic carbon footprint to keep global warming at bay (Bhattacharyya, 2024; Bhattacharyya et al., 2024). This helps natural systems like soils to maintain their status for providing ecosystem services to the humanity (**Figure 3**). Therefore, the farmers doing this job could benefit if suitable incentives are provided for maintaining natural resources like soils and thus maintaining the ecosystem for posterity. The following paragraph shows a link

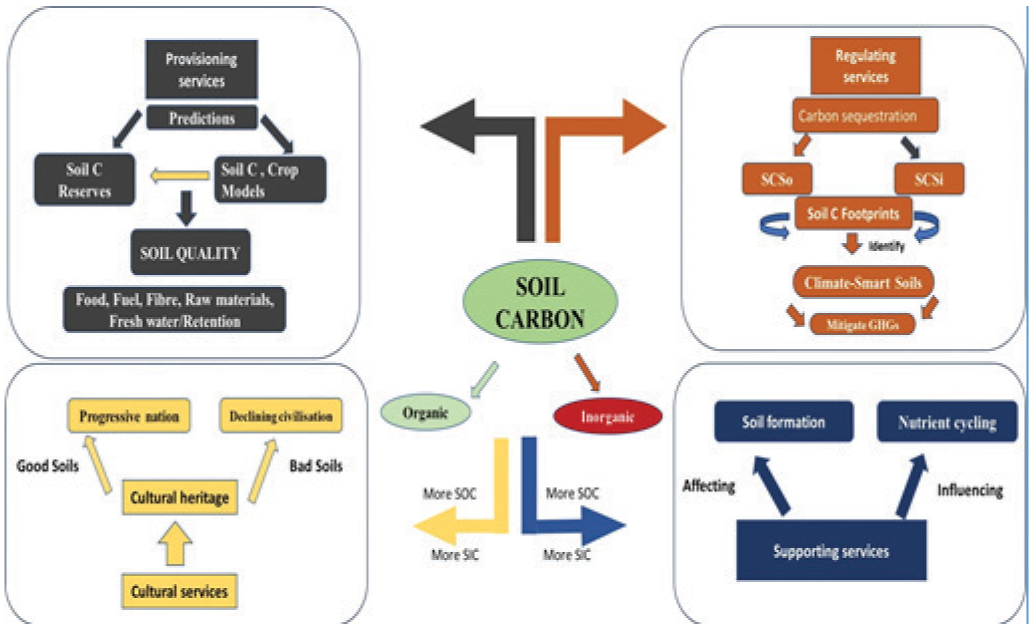

Figure 2. Soil organic and inorganic carbon, their reserves and prediction to influence ecosystem services; (Also see Bhattacharyya, 2021b).

between soil C management of the CSS and soil C benefits.

Fertilizers, along with FYM, help improve SCSo to increase soil organic matter (carbon). Generally accepted prices of fertilizers and manures are utilised to estimate the value of each nutrient (N, P, K) that makes up the soil organic carbon. The top 30 cm of one ha of soil with a bulk density of 1.5 Mg m^{-3} weighs 4500 tonnes. Therefore, 1% of soil organic matter (SOM) should weigh 45 tonnes per ha. Nitrogen (N) constitutes 5% SOM, and P and K each make up 0.5% of SOM, which shows that these three elements provide 2.25 tonnes of N and 0.225 tonnes each of P and K. The SOM has a 2% decomposition rate. Therefore, 0.045 tonnes of N and 0.0045 tonnes of P and K will be available to crops in one ha of land with in a depth of 30 cm per year **(Table 4)** (McLain et al., 2021).

The values of Rs.578, Rs.357, and Rs.255 for N, P, and K are obtained by multiplying tonnes of nutrients available ha^{-1} $year^{-1}$, signifying a total of Rs.1190 as the price of 1% soil organic matter from these nutrients from fertilizers. Similarly, Rs. 2250, Rs.563, and Rs.225 [total Rs. 3038 ha^{-1}] as 1% SOM price from N,P, and K and FYM (applied @ 1tha^{-1}) will be obtained in these values will increase when FYM is applied @ of either 5 or 10 tonnes ha^{-1} (**Table 4**). Therefore, the combined influence of fertilizers and FYM (@ 1t ha^{-1}) will be Rs.4228 to increase 1% SOM per ha per year.

Conclusions

It may be noted that doses of FYM will increase SOM content. However, the farmers require extra funds to apply increased doses of FYM. The increase of SOM may not improve crop yield, as shown in the LTFE datasets validated by different model evaluations (Bhattacharyya, 2022). Maintaining SOM levels using both fertilizers and FYM in the areas showing CSSs may bring the following benefits.

- Suppose farming *is not carried out* in CSS. In that case, the proposed increase of 1% SOM will enable soils to reach the threshold level of 0.77% SOC and BD and SIC are maintained at the required levels following the suggested levels of management interventions as given in (**Figure 1; Table 2**) (Bhattacharyya, 2024). This will increase the number of CSSs in the country and help mitigate GHG emissions (Bhattacharyya, 2024; Paustian et al., 2016).
- If farming *is carried out* in CSSs, then the proposed increase of 1% SOM will maintain the status of these soils as CSS provided BD and SIC are kept under control (**Figure 1; Table 1**).
- The carbon farmers may benefit of Rs. 4228 (with 1 t ha^{-1} FYM along with fertilizers; **Table 4**) as carbon $units^{-1}$ ha^{-1} $year^{-1}$ as soil organic matter with the following conditions.

Table 4. Value of soil organic matter in terms of fertilizer substitution

Fertilizer Source	Price of fertilizer/ FYM(Rs. t^{-1})* (I)	Nutrient in fertilizer/ FYM (%) (II)	Rs. t^{-1} of nutrient (III)	Available (t ha^{-1} $year^{-1}$) (IV)	Total value of % SOM (Rs.) (V = III * IV)
Urea (Rs.268 50 kg^{-1})	26800	46 N	12850	0.045	578
SSP Rs. 30 kg^{-1})	30000	16 P_2O_5	79375	0.0045	357
MOP (Rs.30 kg^{-1})	30000	60 K_2O	56667	0.0045	255
Total	1190				
Manure (as FYM)					
If 1 t ha^{-1} applied	2500	0.5 N	50000	0.045	2250
	2500	0.2 P_2O_5	125000	0.0045	563
	2500	0.5 K_2O	50000	0.0045	225
Total	3038				
Manure (as FYM)					
If 5 t ha^{-1} applied	2500	0.5 N	250000	0.045	11250
	2500	0.2 P_2O_5	625000	0.0045	2813
	2500	0.5 K_2O	250000	0.0045	1125
Total	15188				
Manure (as FYM)					
If 10 t ha^{-1} applied	2500	0.5 N	500000	0.045	22500
	2500	0.2 P_2O_5	1250000	0.0045	5625
	2500	0.5 K_2O	500000	0.0045	2250
Total	30375				

***Source: Anonymous, 2023b**

- i) The SOC, SIC and BD need to be monitored with careful laboratory analysis following the standard methods (Bhattacharyya, 2024).
- ii) To reach SOC quasi-equilibrium values as an indicator of stabilisation of SOC value, different duration has been suggested. Therefore, the natural resource managers monitoring the soils to provide benefit of carbon units to the farmers should know the land use history, duration of year and type of farming (agriculture or horticulture). Depending on soil types and the land use, soils reach a quasi-equilibrium value (QEV) of SOC with time (Naitam and Bhattacharyya, 2004). The duration may vary from 500-1000 years in a forest system, 30-50 years in an

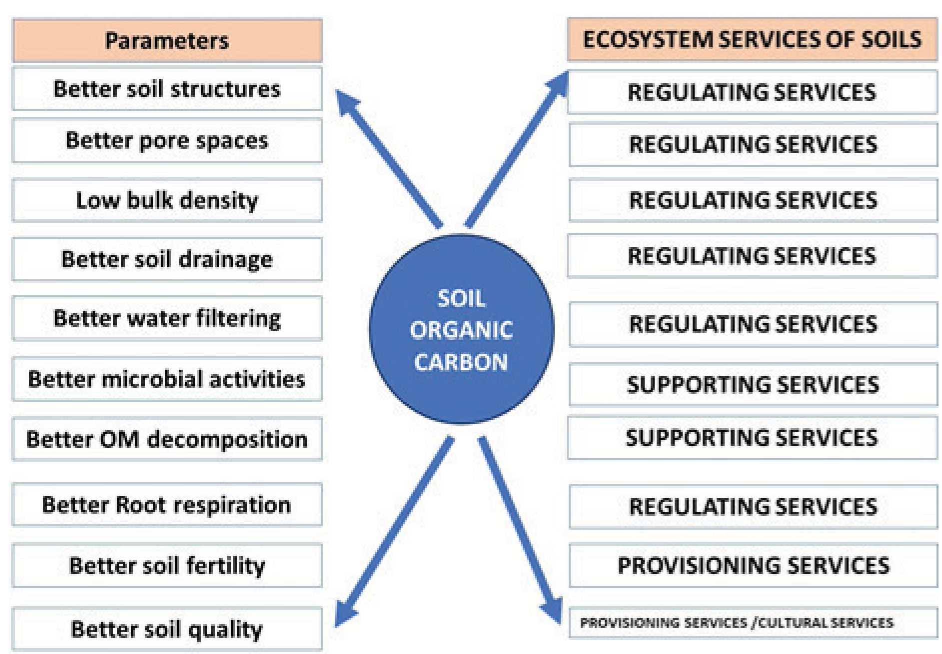

Figure 3. Various soil and other parameters and soil carbon show their relation with ecosystem services.

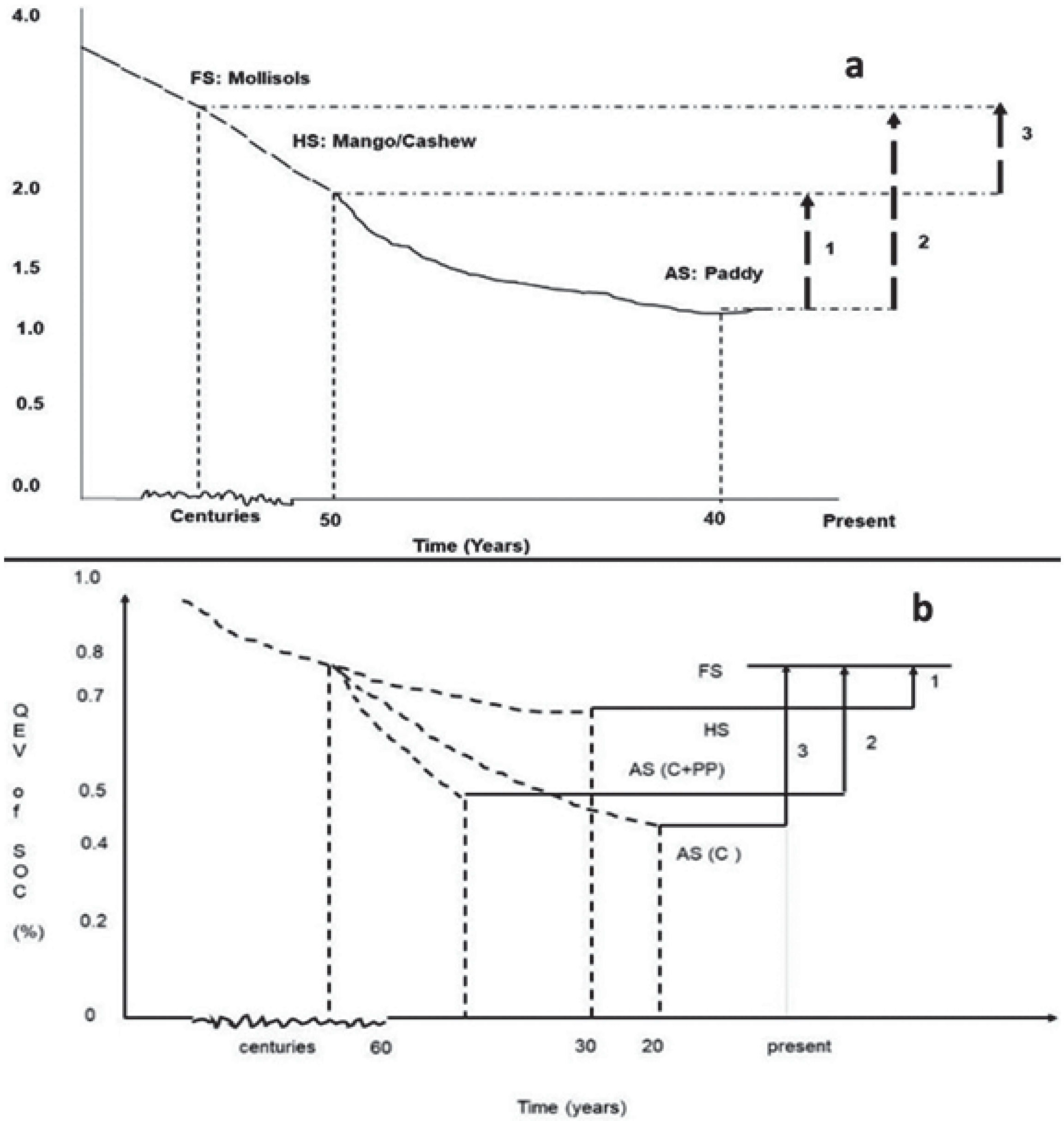

Figure 4 a, b. Quasi-equilibrium values (QEV) of soil organic carbon (SOC) in black soils vs. time under different systems in humid bioclimate showing their potential to increase QEV for greater SCSo (0-30 cm soil depth).

[FS: Forest system (Teak, Tectona grandis); HS: Horticultural system (Mango, and Cashew.); AS: Agricultural system (Paddy); 1, Scope for soils in AS (0.1%) to reach HS; 2, Scope for soils in AS to reach FS; 3, scope for soils in HS to reach FS]. g, QEV of SOC in black soils vs. time under different systems and their potential to increase QEV for greater SCSo (0.30-cm soil depth) in Semi-arid tropics. [FS: Forest system (Teak, Tectona grandis); HS: Horticultural system (Nagpur Orange, Citrus sp.); AS (C+PP): Agricultural system (Pigeon Pea, Cajanus cajan); AS (C): Agricultural system (Cotton, Gossypium sp.) 1, Scope for soils in HS to reach FS ; 2, Scope for soils in AS (C+PP) to reach FS; 3, scope for soils in AS (C) to reach FS].

agricultural system after forest cutting, and 5-15 years of other farm systems. The black soils (Vertisols and its intergrades) in the sub-humid tropics in India attain a QEV of 0.8 and 0.7% SOC over 30 years (horticultural) and centuries (forest) (Naitam and Bhattacharyya, 2004) (**Figure 4 a,b**).

- Soil organic matter/soil organic carbon has a considerable role in soil ecosystem services (**Figure 2**). Maintaining and/or improving the status of SOM of the CSSs will add value to ecosystem management. In the proposed estimation of the value of carbon units (**Table 4**), these aspects have not been added due to the absence of any reference. Future research may delve into linking ecosystem services and soil carbon units to bring it into the overall carbon trading to benefit the carbon farmers.

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