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Abstract

Soils act as a major sink and source of atmospheric CO_2 and therefore have a huge role to play in the carbon capture and storage (CCS) activity. The soils capture and store both organic (through photosynthesis of plants and then to soils as decomposed plant materials and roots) and inorganic carbon (through the formation of pedogenic calcium carbonates). The sequestration of organic and inorganic carbon in soils and its follow-up require basic information of CCS in the soils and their appropriate management techniques. The most prudent approach to estimate the role of soils as source and sink for carbon should require information on the spatial distribution of soil type, soil carbon (soil organic carbon, SOC and soil inorganic carbon, SIC) and the bulk density (BD). To estimate the CCS of soils in spatial domains, we have used the agroclimatic zones (ACZs), bioclimatic systems (BCS) of India and the agro-ecosubregions (AESRs) maps as base maps. These three approaches of land area delineations have been used for various purposes at the national and regional-level planning. We have shown the utility of these maps for prioritizing areas for C sequestration in soils through a set of thematic maps on carbon stock. It will make a dataset for developmental programmes at regional as well as national levels, to address the role of soils in capturing and storing elevated atmospheric CO_2 due to global climate change.

Keywords (separated by '-')	CCS - Carbon sequestration - Soils - Thematic maps

Chapter 4
Soil as Source and Sink for Atmospheric CO_2

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Abstract Soils act as a major sink and source of atmospheric CO_2 and therefore have a huge role to play in the carbon capture and storage (CCS) activity. The soils capture and store both organic (through photosynthesis of plants and then to soils as decomposed plant materials and roots) and inorganic carbon (through the formation of pedogenic calcium carbonates). The sequestration of organic and inorganic carbon in soils and its follow-up require basic information of CCS in the soils and their appropriate management techniques. The most prudent approach to estimate the role of soils as source and sink for carbon should require information on the spatial distribution of soil type, soil carbon (soil organic carbon, SOC and soil inorganic carbon, SIC) and the bulk density (BD). To estimate the CCS of soils in spatial domains, we have used the agroclimatic zones (ACZs), bioclimatic systems (BCS) of India and the agro-ecosubregions (AESRs) maps as base maps. These three approaches of land area delineations have been used for various purposes at the national and regional-level planning. We have shown the utility of these maps for prioritizing areas for C sequestration in soils through a set of thematic maps on carbon stock. It will make a dataset for developmental programmes at regional as well as national levels, to address the role of soils in capturing and storing elevated atmospheric CO_2 due to global climate change. AQ1

Keywords CCS · Carbon sequestration · Soils · Thematic maps

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M. Goel and M. Sudhakar (eds.), *Carbon Utilization*,
Green Energy and Technology, DOI 10.1007/978-981-10-3352-0_4

Layout: T1_Standard Book ID: 418313_1_En Book ISBN: 978-981-10-3351-3
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1 Introduction

Soil carbon (both soil organic carbon, SOC and soil inorganic carbon, SIC) is important as it determines ecosystem and agroecosystem functions, influencing soil fertility, its water-holding capacity and other soil parameters. It is also of global importance because of its role in the global carbon cycle and the part it plays in the mitigation of atmospheric levels of greenhouse gases (GHGs), with special reference to CO_2.

The soil plays an important role for atmospheric CO_2 sequestration (Batjes 2011; Powlson et al. 2011; Banwart et al. 2013; Bhattacharyya et al. 2014; van Noordwijk et al. 2014). AQ2 There has been a great deal of interest in mitigating the climate change due to global warming by sequestering and storing carbon in soil and its influence on soil quality and agricultural productivity (Powlson et al. 2011; Banwart et al. 2013; Bhattacharyya et al. 2014). Soils provide important ecosystem services at local as well as global levels and are the mainstay for crop production. Soils act both as sources and sinks for carbon (Bhattacharyya et al. 2008). With the challenge to feed a global population of 9 billion people by mid-century and beyond, it is essential to maintain the health and productivity of agricultural and rangeland soils (van Noordwijk et al. 2014). This can done by maintaining, and wherever necessary, increasing the soil organic carbon, especially in tropical soils. The carbon sequestration in soil has been used to describe the process of increasing organic carbon ~~stores~~ with appropriate land management interventions. The process could be natural and/or human-induced to harness CO_2 from the atmosphere and to store it in ocean or terrestrial environments (i.e. in vegetation, soils and sediments) and in geologic formations (USGS 2008; Powlson et al. 2011). The reduction of atmospheric CO_2 by sequestration has been reported to have a great potential for shifting greenhouse gas (GHG) emissions to mitigate climate change, and soil is considered as an ideal reservoir, can store organic carbon to a great extent (Wang et al. 2010).

Interestingly, carbon sequestration has always been referred to in the literature with respect to organic ~~carbon~~, despite the fact that both organic and inorganic forms of carbon are involved in C sequestration. The aspects related to the formation of pedogenic $CaCO_3$ (PC), as an example of inorganic C sequestration, have a direct bearing to soil health (Bhattacharyya et al. 2004, 2008), especially in low AQ3 quality, infertile soils in the semi-arid tropical (SAT) environments. Both vegetation and soils are the major sinks of atmospheric CO_2. Carbon stocks are not only critical for the soil to perform its productivity and environmental functions, but they also play an important role in the global C cycle. Soil C sequestration can improve soil quality and reduce the contribution of agriculture to CO_2 emissions.

As the tropics comprise approximately 40% of the land surface of the earth, more than one-third of the soils of the world represent tropical areas (Eswaran et al. 1992). The global extent of such soils suggests that agricultural management practices can be developed in India for enhancing crop productivity and maintaining soil health through C sequestration. These may also have application in similar soils occurring elsewhere in the tropical and subtropical parts of the world.

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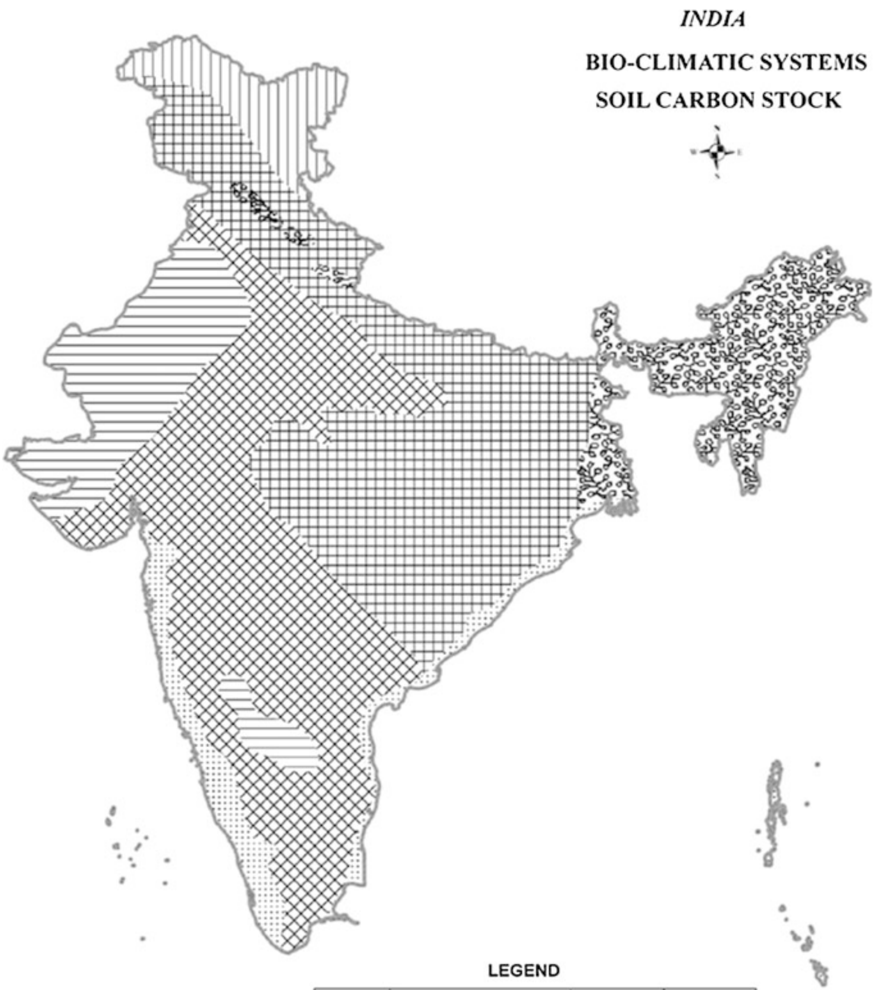
In this context, it was decided to prepare a synthesis on the potential of Indian soils to accumulate atmospheric CO_2 as evidenced by SOC and soil inorganic carbon (SIC) stocks. Moreover, the information on the factors and practices that favour C sequestration under diverse land use are put into context.

2 Soil: Source and Sink of Carbon

Soil carbon (SOC ~~plus~~ SIC) is a major determinant of agroecosystem functions; it greatly influences soil fertility, water-holding capacity, and other soil quality parameters that influence overall productivity and sustainability. The main context for soil carbon management in tropical India is a relatively high amount of SOC (Jenny and Raychaudhuri 1960) (Table 1) and low amount of SIC, whereas soils in rest of the regions show a reverse trend (Bhattacharyya et al. 2000). The soils sequester both organic (through photosynthesis of plants and then to soils as decomposed plant materials and roots) and inorganic carbon (through the formation of pedogenic calcium carbonate) (Pal et al. 2000). The sequestration of organic and inorganic carbon in soils and its estimation requires basic information on the processes that determine the C sequestration of soils. The most prudent approach to estimate the role of soils as both C source and sink is to develop the spatial distribution of SOC and SIC in various agroclimatic zones, bioclimatic systems and agroecosystem sub-regions (Victoria et al. 2012; Batjes 2011; Bhattacharyya et al. 2008). Carbon as SOC and SIC storage has been reported to be related to climate (temperature and rainfall). The carbon storage values for different bioclimatic systems have been collated and are shown in Fig. 1.

Table 1 Soil carbon stocks in different bioclimatic systems of India (0–0.3 m soil depth)

Area million ha	SOC stock Pg	SIC stock Pg	Total C stock Pg	Carbon stock/million ha	
				SOC	SIC
Arid bioclimatic system					
52	1.0	1.7	2.7	0.019	0.033
Semi-arid bioclimatic system					
116.4	2.9	1.9	4.8	0.025	0.016
Sub-humid bioclimatic system					
105.0	2.5	0.3	2.8	0.024	0.003
Humid to per-humid bioclimatic system					
34.9	2.1	0.04	2.14	0.060	0.001
Coastal bioclimatic system					
20.4	1.3	0.07	1.37	0.064	0.003



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Symbols	Bio-climatic Systems	SOC stock (Pg)	SIC stock (Pg)
	Arid cold	0.60	0.70
	Arid hot	0.40	1.00
	Semi arid	2.90	1.90
	Sub humid	2.50	0.30
	Humid to per humid	2.10	0.04
	Coastal	1.30	0.07

Fig. 1 Carbon stocks in major bioclimatic systems in India (0–0.3 m soil depth). *SIC* soil inorganic carbon; *SOC* soil organic carbon (*source* Bhattacharyya et al. 2008)

The arid bioclimatic system is characterized by low annual rainfall (<500 mm) (Bhattacharjee et al. 1982) and does not support dense vegetation, resulting in low organic C status of the soils. This bioclimate is divided into cold and hot arid depending on atmospheric temperature (Bhattacharyya et al. 2000) and within the cold arid bio climate, the Ladakh plateau is colder than the northern Himalayas. Lower atmospheric temperature at the subzero levels that cause hyper-aridity does not support vegetation, which is in contrast to that found in the western region of the northern Himalayas. This is the reason for more SOC stock in the cold arid bioclimate (Table 1). Following U.S. soil taxonomy (Soil Survey Staff 2006), total SOC stock of Indian soils in the first 1.5 m depth is estimated at nearly 30 Pg, whereas that of SIC as nearly 34 Pg. The SOC and SIC stocks in five bioclimatic zones (Bhattacharyya et al. 2008) show that SOC stock is two and one-half times greater than the SIC stock in first 0–0.3 m soil depth. Although the presence of $CaCO_3$ in the humid and per-humid region is due to inheritance from strongly calcareous parent material, usually on young geomorphic surfaces (Velayutham et al. 2000), the SIC stock in dry bioclimates is relatively large (Bhattacharyya et al. 2008). The SIC stock increases with depth in all soil orders (except for the Ultisols) of dry climates, which cause more calcareousness in the subsoil (Pal et al. 2000).

3 Prioritizing Areas for Carbon Sequestration in Soils

Carbon stock in soil depends largely on the aerial extent of the soils besides other factors such as carbon content, depth and bulk density (BD). Even with a relatively small carbon content (0.2–0.3%), the SOC stock of arid and semi-arid systems indicates a high value. This is due to a large area of the dry tracts. Therefore, the carbon stock per unit area (Pg/mha) should ideally be considered to identify the influence of soil and/or management parameters for carbon sequestration in the soils. A threshold value of 0.03 Pg SOC/mha has been found to be effective in finding out a system (agriculture, horticulture, forestry) which sequesters sizeable ~~quality~~ of organic carbon in the soils (Bhattacharyya et al. 2008).

Criteria such as SOC stock per unit area as well as point data for individual soils indicate that vast areas in the arid (AESR 3, part of ACZ 10), semi-arid and drier parts of the sub-humid bioclimatic systems (BCS) of the Indian subcontinent are low in SOC and high in SIC stock and thus should get priority for organic carbon management. The total prioritized area has been worked out as 155.8 m ha.

It has been reported that increase of OC enhances the substrate quality of soils. The dominant black soils (Vertisols and their associated red soils) in the semi-arid tropics (SAT) are rich in smectites (Pal et al. 2000) which results in improving substrate quality of soils resulting in 2–3% carbon sequestration (Bhattacharyya et al. 2006). In view of better substrate quality of these dominant soils in the arid (southern India, AESR 3), semi-arid and dry sub-humid tracts of the country, a modest SOC content of 2% gives an estimate of SOC stock as 14.02 Pg. This value is 3.7 times more than the existing SOC stock of the prioritized area (Bhattacharyya et al. 2008). The SOC stock has increased from 34 to 118% over a period of nearly 25 years in SAT due to adoption of the management intervention and the substrate quality (Bhattacharyya et al. 2007). Thus with appropriate management interventions in maintaining the capability of productive soils and also in improving the less productive soils, organic carbon storage capacity of Indian soils can be enhanced. Such management interventions have helped in the dissolution of native SIC ($CaCO_3$) due to increase in pCO_2 in the soil and contribute partly to the overall pool of SOC (Bhattacharyya et al. 2004).

4 Concluding Remarks

Although the unique role of soils as a potential sink in mitigating the effects of atmospheric CO_2 has been conceived, the present study indicates the sequestration of atmospheric CO_2 in the form of SIC (pedogenic carbonate) and its subsequent important role in enhancing SOC in the drier parts of the country through management interventions. The study also points out that the soil can act as a potential medium for CCS. This tool (thematic maps on soil C stock) may help planners in prioritizing C sequestration programmes in different dry BCS representing various ACZs and AESRs of the country.

Soils of the tropical Indian environments are endowed with diverse, generally good substrate quality, and they are under favourable environmental conditions, as is evident from their considerable potential to absorb atmospheric CO_2 as SOC. The formation of pedogenic $CaCO_3$ (as SIC) and its subsequent role in enhancing the potential of soils to sequester SOC in the drier regions of the country illustrates a unique process involved in sequestering atmospheric CO_2. Major soil types generally show resilience to spring back to normal productive state with appropriate management interventions by farming communities with the support from national and international institutions. These soils have provided a sustainable foundation for India's growing self-sufficiency in food production, and they generally maintain a positive organic C balance in the longer term. In view of a good potential for C sequestration by major zeolitic and nonzeolitic soils, the present SOC stock of about 30 Pg can be further increased under improved management of soil, water, crop and nutrients in various diverse production systems. These case studies indeed may serve as a model elsewhere under similar soil and climatic conditions in the tropical world to maintaining soil heath and productivity under climate change through C sequestration.

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