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Review/Overview

Climate–resilient agriculture and soil organic carbon

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ABSTRACT

The soil carbon (C) reservoir is an important component of the global C cycle. It comprises of soil organic C (SOC) and soil inorganic C (SIC). Soils of India are severely depleted of their SOC stock. Therefore, enhancing and maintaining SOC concentration to above the critical threshold (~1.5% in the 0-20cm depth) is essential to improving soil quality, increasing use efficiency of nutrients and water, minimizing vulnerability to extreme climatic events, decreasing susceptibility to erosion and other degradation processes, and sustaining agronomic production. Above all, recarbonization of the SOC stock is integral to any strategy towards adapting to and mitigating the abrupt climate change, advancing food security and improving the environment. The SOC stock is also important to provisioning of numerous ecosystem services (e.g., food security, water security). Thus, identification and adoption of recommended management practices (e.g., conservation agriculture, agroforestry, manuring and integrated nutrient management, diverse farming system) are important to C sequestration. The rate of SOC sequestration in cropland soils of India are low, but need to be credibly assessed for diverse soils and farming systems. Rate of formation of secondary carbonates for different practices and or leaching of bicarbonates in irrigated soils must be established. A way forward should consider: (i) improvement in education curricula at state agricultural universities to include courses on climate change, C sequestration etc.; (ii) establishment of National Climate-Resilient Agriculture Program (NACRAP), and (iii) development of mechanisms to compensate farmers and land managers through payments for ecosystems services (e.g., soil C sequestration).

Key words : Agricultural curricula, Erosion, Food security, Malnutrition, National Climate- Resilient Agriculture Program, Payments for ecosystem services, Soil C sequestration, Soil degradation, Soil quality,

With the anthropogenic global farming (IPCC 2013), land surface temperatures may be increasing more rapidly than over the ocean (Diffenbaugh and Field, 2013). The rapid rate of warming implies a major challenge for ecosystems to adjust with regards to land use and degradation and other biotic and abiotic stresses. Species and biodiversity will also be affected (Mortiz and Agudo, 2013), and may either decline or develop resilience. Global food insecurity, already affecting about 1 billion people, may be exacerbated. The abrupt climate change (ACC) could disrupt the progress towards a hunger-free world (Wheeler and Von Braun, 2013). Prevalence of drought and other extreme events can exacerbate food insecurity in several global hotspots (e.g., Sub-Saharan Africa, and South Asia), including India.

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India, with a land area of merely 2.4% of the world's, is a home to 15% of the global population (1.1 billion out of 7.3 billion). India is also rapidly urbanizing, with 7.3 million people moving into urban centers every year. Despite impressive achievements in agricultural production since 1950s, total food grain production can be easily doubled, from 257 million Mg to 550 million Mg (Table 1). Further, agronomic yields of major crops in India are much lower than the attainable yield and those obtained in other countries (Table 2). The yield gap can be filled through sustainable intensification and adoption of climate-resilient agriculture. More than 200 million people in India are food-insecure and about 50 million are prone to starvation (Table 3; FAO, 2002; Goyal, 2004; Chakravarty and Dand, 2005). Whereas, the cause of food insecurity is not necessarily the lack of supply nor the underproduction, soil degradation is an important factor affecting malnutrition and deficiency of essential micronutrients (Lal. 2009). In addition to inadequate calories intake (<2000 kcal/day) by food-insecure people, micronutrient deficiencies are

Table 1. Trends of food grain production in India over 60 years

Year	Production (10^6 Mg/yr)
1950-51	50.8
1960-61	82.0
1970-71	108.4
1980-81	129.6
1990-91	176.4
2000-2001	196.8
2011-2012	257
Potential	550

(Das, 2012; Ahmed and Haseen, 2012; FAO, 2011).

Table 3. Estimates of malnutrition in India

Year	Population (10^6)	
	Total	Malnourished
1979-1981	689	262
1990-1992	861	216
1998-2000	993	233
2010-2012	1100	~200

(Adopted and updated from Chakravarty and Dand, 2005; FAO, 2012)

important factors affecting health and wellbeing of those living below the poverty line and those consuming food grown on degraded and depleted soils.

Thus, the objective of this article is to deliberate the relationship between soil quality and carbon (C) sequestration, and discuss technological options and logistical challenges of recarbonization of the pedosphere. An attempt is also made towards establishing a link between soil quality and food security, with specific reference to the hidden hunger and malnutrition in India.

Soil quality and a healthy diet

In addition to adequate calories, a healthy diet must also provide about 50 nutrients comprising of vitamins, minerals, trace elements, amino acids, essential fatty acids, etc. (Welch and Grahm, 2005). A balanced diet must contain 7 macro-elements (Na, K, Ca, Mg, S, P Cl) and 17 micro-elements (Fe, Zn, Cu, Mn, I, F, B, Se, Mo, Ni, Cr, Si, As, Li, Sn, V, Co) (Welch and Grahm, 2004). These 24 elements must be available in adequate amount in soil, over and above the supply of macro (N, P, K, Ca, Mg) and micronutrients (e.g., Cu, Zn, Mo) needed for an optimal crop growth and yield. Thus, soil quality (physical, chemical, biological and ecological) must be optimal to sustain principal rhizospheric processes in relation to crop growth. Soil organic carbon (SOC) concentration, at an optimal level of 1.5% in the root zone, is an essential parameter affecting soil quality, rhizospheric processes, and ecosystem services essential to human wellbeing and environmental quality. Yet, SOC concentration in most agricultural soils of India is often <0.1% because of a widespread use of extractive and fertility-mining practices. Removal of crop residues for numerous competing uses (e.g., feed, fencing and construction materials, cooking fuel, open grazing), and inadequate application of organic and inorganic fertilizers are among major factors responsible for low SOC concentration. Use of animal dung as cooking fuel rather than as manure is also an important cause of the depletion of SOC pools in arable lands.

Nutrient mining on agricultural soils is a serious problem in India. Annual rate of soil N, P, K depletion is estimated at >80kg/ha for the states of Assam, Bihar, Haryana, Himachal Pradesh, Jammu and Kashmir, Jharkhand, Kerala, Rajsthan, Tamil Nadu and Tripura. Depletion of K_2O for major soils of northern India is estimated at 80kg/ha/yr (Roy, 2003). Nutrient mining directly impacts SOC stock and its quality. Repeated plowing, mixing O_2 in soil and increasing soil temperatures, exacerbate the rate of mineralization and deplete the SOC stock. Assuming crop uptake of N, at low agronomic yield and without any input of fertilizer or manure, is 60 kg/ha/year. With C:N ratio of about 16, the amount of SOC mineralized to release the amount of N removed by the crop is about 1000kg/ha. This is equivalent to 1725kg/ha of humus (C concentration of humus is about 58%). Being a light fraction (low density of ~ 0.6Mg/m^3) and concen-

Table 2. Trends in grain yields in India over 40 years and comparison with World's Highest Yields

Crop	Grain Yield (kg/ha)			World High Yield	
	1970-71	1990-91	2010-11	kg/ha	Country
Rice	1,123	1,740	2,240	10,800	Australia
Wheat	1,307	2,281	2,938	8,900	Holland
Pulses	524	578	689	2,800	China
Oilseeds	579	771	1,325	-	
Sugarcane	48,322	65,395	68,596	125,000	Peru
Tea	1,182	1,652	1,669	-	
Cotton	106	225	510 (1,600)	4,600	Israel

(http://en.wikipedia.org/wiki/Agriculture_in_India) trated in vicinity of the soil surface, SOC is also preferentially removed by erosional processes. The enrichment ratio of organic carbon in the soil being transported by erosion (water and wind) can be 5 to 10 (Lal, 1976). The problem of SOC depletion is exacerbated by accelerated erosion caused by water and wind. Removal of surface soil for brick making degrades soil quality and aggravates the problem of micronutrient deficiency. Land area affected by scalping of topsoil to 1-m depth for brick making is estimated at 0.5 to 0.7% of the cropland area per year in Hayana, Punjab and other regions in the Indo-Gangetic Plains.

Soil carbon stock

Earth is a major reservoir of C. The lithosphere (i.e., the geological strata) comprises of 75,004 Eg (Exagram = 10^{18}g = 1000 gigaton) of C or 99.938% of the total terrestrial C stock (Table 4). The non-geologic C component consists of 46.46 Eg or 0.062% of the total C stock. Of this ocean consists of 42Eg (Table 4). In contrast, the entire atmospheric reservoir contains merely 0.8Eg. Thus, even small changes in soil C stock can have a major impact on the atmospheric concentration of CO_2.The soil C stock affects and moderates numerous soil processes and functions (Fig. 1). Physical, Chemical, biological and ecological soil quality is strongly governed by SOC stock and its properties (Fig. 1).

Soil C occurs in two distinct forms: SOC and soil inorganic C (SIC). The SOC component comprises of highly reactive humus, and relatively inert charcoal, both of which are collectively termed “soil organic matter” (SOM). The SOM comprises the sum of all organic substances in the soil, including a mixture of plant and animal residues at various stages of decomposition, of substances synthesized microbiologically and /or chemically from the

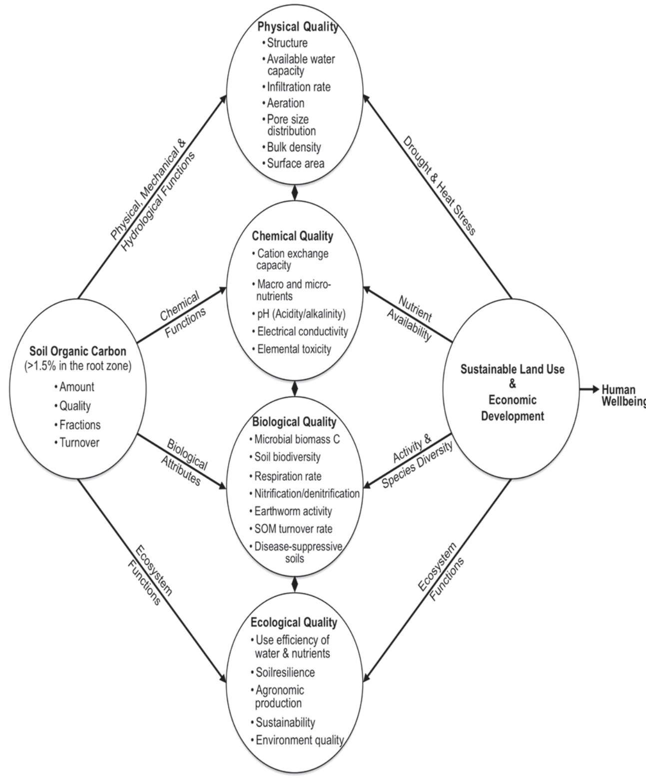

Fig. 1. Importance of soil organic matter in soil quality, sustainable development and human wellbeing.

breakdown of products, and of the bodies of live microorganisms and small animals and their decomposing products (Schnitzer, 1991). Humus, a dark brown and black amorphous substance, has a large surface area, high exchange capacity, and large affinity for water and ions. Therefore, reduction in SOC stock (as is the case with most agricultural soils in India) leads to drastic decline in soil quality and its functions. In addition, SOC stock is a major source or sink of greenhouse gases (GHGs such as

Table 4. Estimates of global C reserves in geologic and non-geologic pools.

Reservoir	Amount (10^{18}g)	% of Total
I. Lithosphere	75,004	99.9
A. Carbonates	60,000	79.9
(i) Calcium Carbonate	35,000	46.6
(ii) Ca-Mg Carbonate	25,000	33.3
B. Geologic Carbon	15,004	19.9
(i) Sedimentary Carbon (e.g., graphite)	15,000	19.9
(ii) Fossil Fuels	4	0.005
II. *Non-Geological Carbon (Live Carbon)*	46.42	0.062
A. Oceanic (HCO_3 and CO_3)	42	0.056
B. Dead Surficial C (Humus)	3	0.004
C. Atmospheric CO_2	0.8	0.00095
D. All life	0.62	0.00076
GRAND TOTAL	75,050.42	100

(Adapted from Dunsmore,1992; Huigen and Comons, 2003; Lal, 2010)

CO_2 and CH_4), and can strongly influence the atmospheric chemistry. Use of nitrogeneous fertilizer, manure management and no-till farming can accentuate emission of N_2O from cropland soils (Ussiri and Lal, 2012).

The SIC component comprises of elemental C and carbonate-bearing minerals such as calcite, dolomite and gypsum. The SIC component is dominant, more so than the SOC, in soils of arid and semi-arid regions. It consists of two types of carbonates: primary and secondary. Primary or lithogenic carbonates are derived from the weathering of the parent material or carbonaceous rocks. In contrast, secondary or pedogenic carbonates are generated through the dissolution of atmospheric CO_2 to form weak carbonic acid, and its reaction with Ca^{2+} and Mg^{2+}brought in from outside the ecosystem (Huijgen and Comans, 2003; Dupre *et al.,* 2003); (Eq. 1, 2):

$$CO_2 + H_2O \leftrightarrow H_2CO_3^- \quad \text{... (Eq. 1)}$$

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3^+ + H_2O + CO_2 \quad \text{. (Eq. 2)}$$

Indeed, a small portion of the CO_2 produced in the soil by decomposition of SOM is diverted to formation of secondary carbonates. The process involves two additional biogeochemical reactions: (i) weathering of carbonates, and (ii) weathering of Ca/Mg bearing silicates (Dupre *et al.,* 2003) (Eq. 3, 4).

$$2CO_2 + 3H_2O + CaSiO_3 \rightarrow H_2SiO_4 + 2HCO_3^- + Ca^{2+} \quad ...(Eq. 3)$$

$$2HCO_3^- + Ca^{2+} \rightarrow CaCO_3 + H_2O + CO_2 \quad ...(Eq. 4)$$

It is important to note that CO_2 derived from carbonates does not imply C sequestration, and it simply transfers C from one location to another (Eq. 5, 6).

$$CaCO_2 + H_2O + CO_2 \rightarrow 2HCO_3^- + Ca^{2+} \quad ...(Eq. 5)$$

$$2HCO_3 + Ca^{2+} \rightarrow CaCO_3 + H_2O + CO_2 \quad ...(Eq. 6)$$

Secondary carbonates can occur in numerous forms including pseudomycelium, nodules, horizons, hardpans, laminar sheet or carbonate pendants (Landi *et al*., 2013). Precipitation of secondary carbonates in the sub-soil horizons in arid and semi-arid climates andcementation leads to formation of "caliche". Presence of vegetation and species composition can influence the rate of formation of secondary carbonates.

Short-term global carbon cycle

Two principal sources of anthropogenic emissions of CO_2 into the atmosphere are fossil fuel combustion and land use conversion. The era since 1750 is called "anthropocene" (Crutzen, 2002) because of human's impact in transforming Earth during this epochhas been as great as that of any geological force. In other words, this is the era in which human and our societies have become a global geophysical force (Steffen *et al.,* 2007). However, several ecologists and paleoclimatologists argue that anthropocene began with the dawn of settled agriculture (Kerr, 2004; Ruddiman, 2005; White, 2006) if not even earlier (Kerr, 2013; Mitchell *et al.,* 2013; Balter, 2013). Ruddiman argued that total CO_2 emission (through land use conversion, deforestation, cultivation of rice paddies and domestication of ruminants) since the pre-historic times to 1750 may have been as much as 320Pg (Pg = petagram = 10^{15}g = 1 gigaton). The global C budget since 1750 in Table 5 show cumulative emissions of 385 Pg from fossil fuel combustion and 205 Pg from land use conversion. Thus, total cumulative emissions from land use conversion (and agricultural activities) since the dawn of settled agriculture are estimated at 525 Pg compared with 385 Pg from fossil fuel combustion.

Being an ancient civilization and credited with domestication of several crops since 9 to 10 millennia ago, it is appropriate to obtain national (and regional for each biome or ecoregion) estimates of C emissions from land use conversion in India since the pre-historic era. A credible information on these estimates is important to developing national and regional strategies of adaptation to and mitigation of climate change, and obtaining estimates of the C-sink capacity through recarbonization of the terrestrial biosphere. Global estimates of anthropogenic emissions since 1750s are shown in Fig. 2 and Fig. 3. Similar

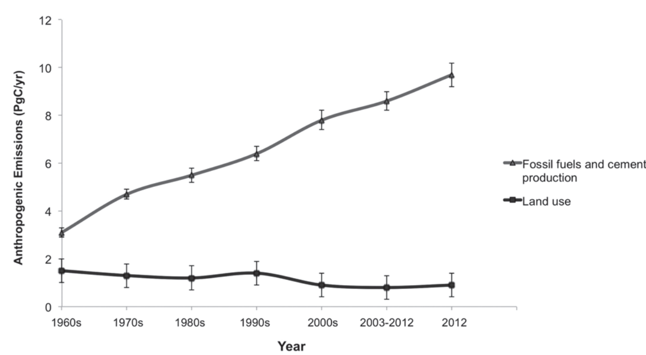

Fig. 2. Anthropogenic emissions of carbon since 1960s (Redrawn from Le Quéré *et al*., 2013).

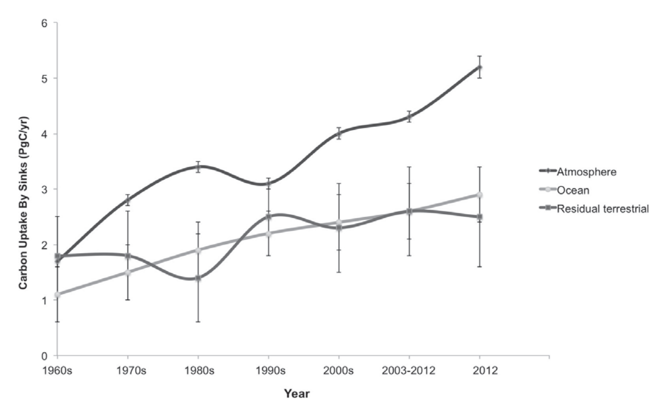

Fig. 3. Estimates of the uptake of anthropogenic emissions by three sinks (Redrawn from Le Quéré *et al.,* 2013).

estimate of anthropogenic emissions since 1950s are needed for India.

The short-term global C cycle (on a decadal scale, Fig.4) signifies the importance of the pedological C stocks and the key role of the net biome productivity (NBP) in moderating the atmospheric C pool. In accord with the data presented in Table 5, global estimates of the Residual Terrestrial C sink (180 ± 75Pg) since 1750 are greater than those of the oceanic uptake and account for ~30% of the total anthropogenic emissions. Thus, recarbonization of the terrestrial biosphere (Lal *et al.,* 2012), through sequestration of atmospheric CO_2 in plants and soils, is an important strategy of moderating the atmospheric concentration of GHGs while improving the environment and provisioning of numerous ecosystem services. Thus, credible estimates of the terrestrial C sink capacity are needed for India so that planning for a judicious landuse and soil/crop/ water management can be done and implemented at eco-regional and national scale. Estimates of the stock of SOC in soils of India of 24.3 Pg to 1-m depth (Gupta and Rao, 1984) and 9 Pg to 30–cm depth (Bhattachaya *et al.,* 2000) need to be updated for establishing a credible baseline.

Table 5. Global carbon budget since 1750

Parameters	Total Amount (Pg C)
I. Sources	
1. Fossil fuel combustion and cement production	385±20
2. Land use changes	205±70
Sub-Total	590±75
II. Sinks	
1. Atmosphere	245±5
2. Ocean	165±20
3. Residual terrestrial	180±75

(Adapted from Lé Quére *et al.,* 2013) Pre-historic emissions (Ruddiman, 2005) = 320P

Soil carbon sequestration

Terrestrial C sequestration is defined as the capture and secure storage of atmospheric C into biotic and pedologic

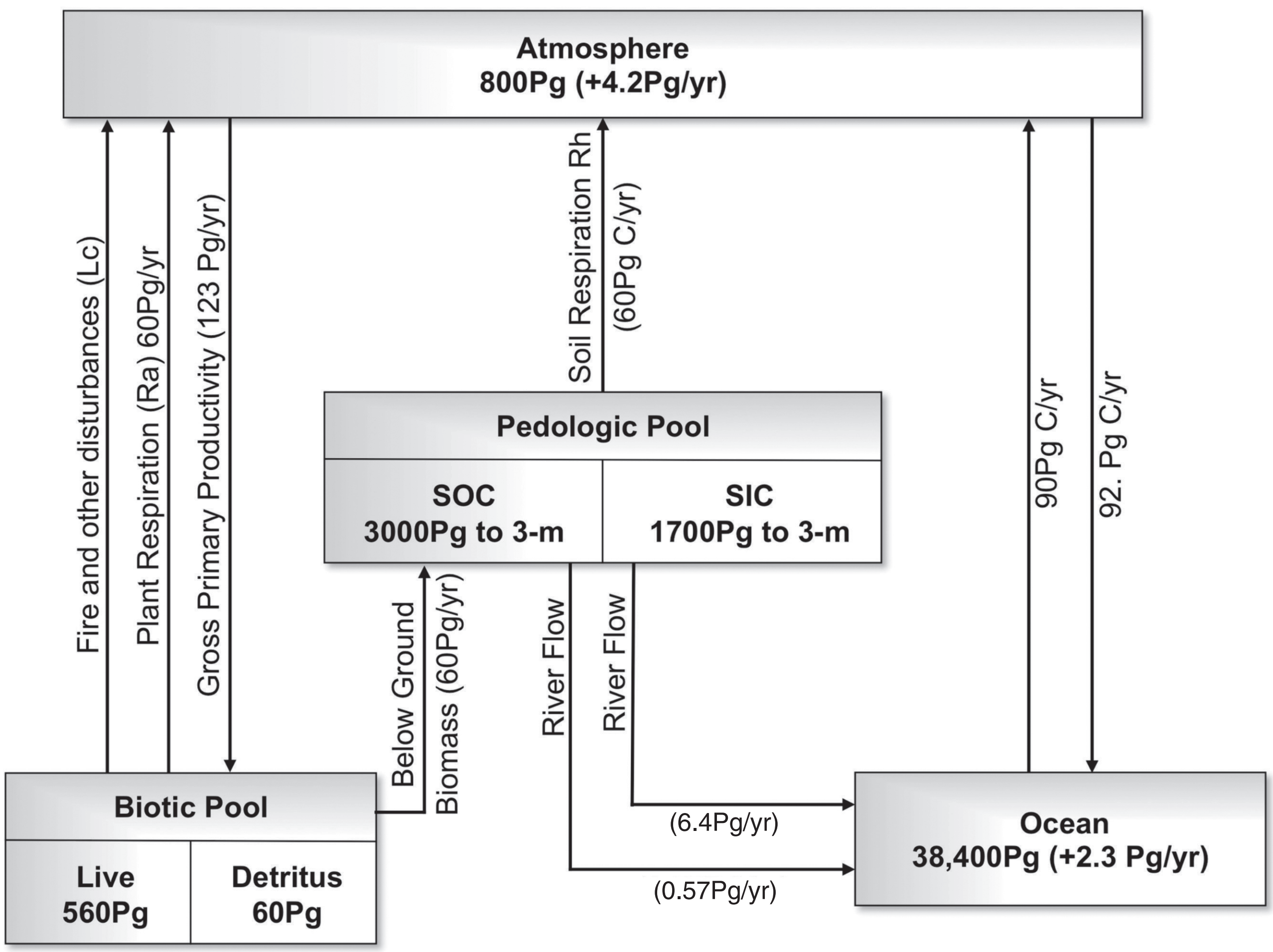

Fig. 4. The short-term global carbon cycle (Updated and redrawn from Nordt *et al.,* 2000; Dupré *et al*., 2003; Jansson *et al*., 2010; Lal, 2013) (NPP = GPP-Ra, NEP = NPP-Rh, NBP = NEP-Lc). The strategy is to maximize NBP and increase its mean residence time (MRT) in the atmosphere.

C reservoirs that would otherwise be emitted to or remain in the atmosphere (Lal, 2007). Soil C sequestration is defined as the process of transferring CO_2 from the atmosphere into the soil of a land unit through unit plants, plant residues and other organic solids, which are stored or retained in the unit as part of the soil organic matter (Olson, 2013). The definition by Olson is restricted to SOC sequestration. However, the soil C stock has two distinct components: SOC and SIC. Thus, a comprehensive definition of soil C sequestration must include accretion in both organic and inorganic components. Thus, soil C sequestration implies transfer of atmospheric CO_2 into the pedologic C stocks by increasing SOC and SIC components on a long-term basis by creating a positive ecosystem C budget through appropriate land use and judicious soil, vegetation, animal and water management systems. Basic principles and some technological options of SOC sequestration are outlined in Fig. 5. The goal is to maximize the net biome productivity (NBP) and increase its mean residence time (MRT). This can be done by adopting measures of "sustainable intensification" designed to producing more agronomic output with less input, decreasing environmental footprint, reducing losses of nutrients and water, and improving the use efficiency of input. A positive ecosystem C budget can be created through choice of site-specific management practices such as: tillage methods (conservation agriculture), water harvesting and recycling and converting blue water into green water, integrated nutrient management (INM) by combination of organic and inorganic fertilizers and recycling, erosion management, restoration of saline soils, improvement of soil structure, and recycling of biomass. Local adaptation and fine-tuning of these generic technologies is important to addressing the site-specific biophysical, economic, social and cultural factors.

It is important to recognize that there is neither a silver bullet nor a panacea. Each technological option must be assessed in terms of its trade offs, externalities, and hidden environmental and opportunity costs. The rate of SOC sequestration, through adoption of recommended management practices and in comparison with the baseline, may range from 50–500 kg/ha/yr for semi-arid tropics to 500–1,000 kg/ha/yr for humid temperate environment (Lal, 2004b, 2007). Some examples of research-based estimates of SOC sequestration for specific soils and cropping systems in India are shown in Table 4.

Strategies of enhancing formation of secondary carbonates are outlined in Fig. 6. In comparison with SOC, however, there are a fewer options of SIC sequestration as secondary carbonates. There are 2 types of secondary carbonates: biogenic and geogenic (Fig. 6). Formation of biogenic carbonates can be moderated through addition of manure and input of other sources of biomass-C, appropriate crop rotations, and afforestation by establishing site-specific tree species. In contrast, formation of geogenic carbonates involves using some options for accelerating silicate weathering (Eq. 3 and 4) through application of finely ground minerals (e.g., olivine). Addition of large quantities of lime, as in demolition sites, can also enhance formation of secondary carbonates. Leaching of bicarbonates with good quality irrigation water is another option in arid climates (Wilding, 1999). The rate of formation of secondary carbonates, in soils of arid and semi-arid climates is 2-4 kg/C/ha/yr (Lal *et al.*, 2000; Landi *et al.*,

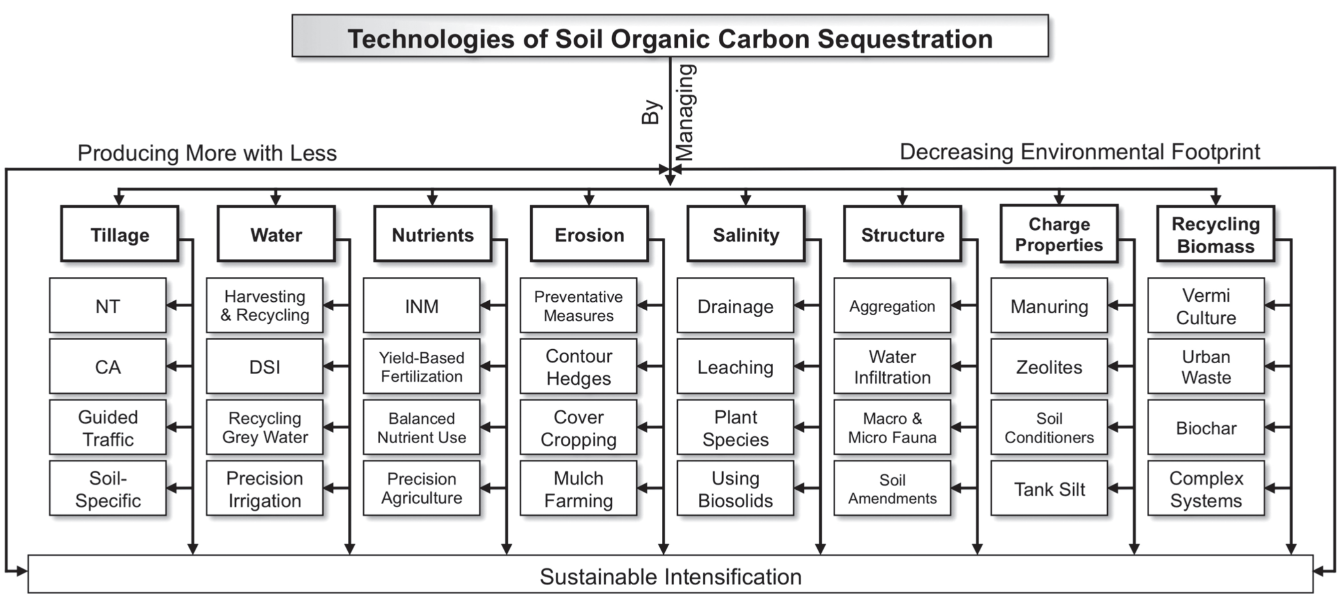

Fig. 5. Strategies of creating a positive soil organic carbon budget and sequestering carbon in soil.

2013; Pal *et al.,* 2012). The rates are generally high for the demolition sites and through leaching of bicarbonates.

Challenges of soil C sequestration in India

There are numerous co-benefits from recarbonization of the pedosphere. Important among these benefits are improving soil quality, increasing agronomic productivity and ensuring food security for growing and affluent population. An additional benefit lies in off-setting anthropogenic emissions by 40–50Tg C/yr (Lal, 2004a). While the abrupt climate change (ACC) cannot be entirely mitigated by soil C sequestration at global or Indian scale, the strategy of enhancing the soil C stock must be integrated to any agenda for improving the environment. Despite the finite capacity of soil C sinks to mitigate the ACC, it is important to realize that food insecurity and malnutrition cannot be alleviated without restoring SOC stocks to above the threshold or critical level (1.5% SOC in the root zone). Because of its long equilibrium time, it is pertinent to identify key SOC parameters (e.g., microbial biomass C, polyphenols, quinones, labile or passive compounds) relevant to soil quality and productivity (Janzen, 2004).

Despite the widespread recognition that restoration of SOC stock is important for a range of ecosystem services, there are numerous challenges to achieving the goal in India. For example, a widespread adoption of no-till farming or conservation agriculture necessitates the use of crop residue mulch. However, crop residues have numerous competing uses. There are also issues with perennial weeds, non- availability of a no-till seeder, and access to economic and environmentally benign herbicides and pesticides. There are similar trade-offs for other technological options (e.g., agroforestry, complex rotations, manuring). Thus, pros and cons (trade offs and externalities) of each option must be critically assessed under site-specific conditions with due consideration to biophysical, economic, social (gender) and cultural factors. In addition to croplands, afforestation of the Himalayan region would enhance SOC stock because of the large C sink capacity of forest soils (Singh and Rawat, 2013).

Payment for ecosystem services

Farmers and land managers, especially small landholders in developing countries, are often constrained by the lack of financial resources needed for adoption of RMPs to sequester C in depleted and degraded soils of agroecosystems. In general, a case is often made for providing subsidies to promote adoption of promising technologies (e.g., irrigation, fertilizers, seed drill). However, providing subsidies has its own limitations. It undermines initiative, promotes dependency, exacerbates corruption and, more importantly, undermines the true value of a finite but critical resource. Soil C is a precious resource. Thus, farmers must be rewarded appropriately and justly for soil C sequestration through payments for provisioning of ecosystem services. In this context, assessment of the societal value of soil C is essential to compensating farmers for the services provisioned to the world community. One of the reasons for severe depletion of SOC stock in soils of India and elsewhere in the developing countries is its being treated as a “global common”. Thus, the SOC stock has been prone to the tragedy of commons (Hardin, 1968).

Assessment of the societal value of soil C, and paymentsfor ecosystem services through transparent, just and fair procedures are crucial to restoring soil quality and improving the environment. The collapse of some voluntary markets for trading C credits is a classic example of the failure of a system because of undervaluing an essential commodity (e.g., soil C). The cost of geological sequestration of industrial CO_2 emissions by injecting into a geological strata is estimated at \$600 to \$800/Mg of CO_2 (Anonymous, 2012). In comparison, farmers are paid a nominal price, often less than US \$1/Mg of CO_2. Justify-

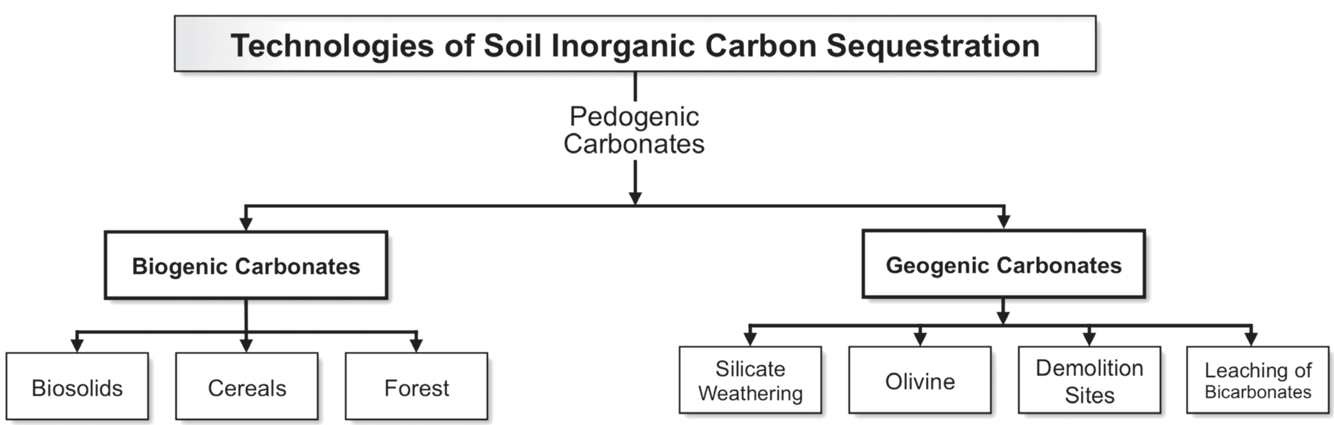

Fig. 6. Techniques of sequestering inorganic carbon in soils as pedogenic carbonates.

Table 6. Estimates of the rates of SOC sequestration in some ecoregion of India

Ecoregions		Farming System	Rate (Mg C/ha/yr)	Comments	Reference
Indogangetic Plains	i.	Rice-wheat	0.22-0.46	The rate improved with manuring.	Brar *et al.* (2013)
	ii.	Pulse-based	-	The SOC increased with pulses.	Venkatesh *et al.* (2013)
	Iii.	Rice-wheat	-	Benefits of organic manures.	Ghosh *et al.* (2013)
	iv.	IPCC Methodology in IGP	-	44.1 Tg over 20 years.	Grace *et al.* (2012)
	v.	Intensive agriculture	-	SOC improved with intensification	Benbi and Brar (2009)
Himalayan	i.	Tree-based	-	The SOC concentration increased with Eucalyptus> Acacia nilotica> Terminalia chebule> cropland.	Pal and Panwar (2013)
	ii.	Plantations	-	Ulma villosa has a high potential	Devi *et al.* (2013)
	iii.	Western Himalayas	-	The SOC buildup was temperate> lower alpine> upper alpine> subtropical	Singh *et al.* (2011)
	iv.	Rubber plantations in NE India	0.35-0.96	34 Mg C/ha over 20 years	Mandal and Islam (2011)
	v.	Chilapta Forest (WB)	-	S. Robusta, T. grandis	Jana *et al.* (2010)
	vi.	A. nilotica, D. sisou	-	Drought stress affect C sequestration	Singh *et al.* (2004)
	vii.	Land use	-	Forestry sector has a high potential	Bhadwal and Singh (2002)
Eastern India	i.	Silviculture on degraded lands	0.18-0.36	Slope aspect is a significant factor	Lenka *et al.* (2013)
	ii.	Hedgerows and grass filler	0.35-1.35	Soil and water conservation	Lenka *et al.* (2012)
	iii.	Afforestation	-	SOC increased with trees	Koul and Panwar (2012)
Semi-arid	i.	Groundwater (Alfisols)	0.57	Organics increased SOC	Srinivasarao *et al.* (2012)
	ii.	Soybean (Vertisols)	-	Soil type is important	Srinivasarao *et al.* (2009)
Diverse	i.	Cereals producing Phytolyths	-	87 Tg of Phyto C/yr	Rajendran *et al.* (2012)
Subtopical	i.	Cropping systems	-	Balanced fertilization and crop residue	Mandal *et al.* (2007)
	ii.	Maize-wheat-cow pea	0.73	Long-term manuring	Rudrappa *et al.* (2006)

ing payments at a low value of soil C on the so-called "market dynamics, governed by the demand and supply of soil C" is being myopic. Sustainable management of natural resources is a long-term strategy, and restoration of soil quality must be based on assigning a just and a fair price to finite but essential natural resources (Lal *et al.,* 2013), which must be used, restored and judiciously managed in perpetuity.

A way forward

In addition to meeting the food demand of India and its increasingly affluent population, agriculture in India must also address many of today's major challenges such as climate change, water pollution and scarcity, dwindling biodiversity, degrading soils and increasing energy demand, urbanization and brick making, use of traditional biofuels, and sanitation. As an enterprise, agriculture must provide raw materials for agribusiness and industry, address regulatory issues while also raising the profile of the agricultural profession. A way forward must involve the following three among several potential strategies: improving curricula, developing a national program on climate-resilient agriculture through soil restoration and sustainable intensification, and creating a payment system for provisioning of ecosystem services.

Improve curricula: Agricultural curricula of state agricultural universities (SAUs) should be flexible, cross-disciplinary, demand-driven and yet provide skills through hands-on training and promote entrepreneurship. Rather than exam-centric, the curricula must be learning-centric with emphasis on self-study, group studies, assignments and case studies. Similar to the Land Grant Institutions (LGIs) of the USA, SAUs in India must also have a strong linkage between research, education and extension. The complementary research program must be characterized by originality, objectivity, accuracy, conservatism, reductionism, moral-neutrality, accountability, relevance, output/productivity-based and team-building approach. Private sector must play an important role in research and development, and in the curricula development. Basic principles of LGIs (e.g. openness, accessibility, competitiveness, productivity-based, evaluation of teachers' performance and service to people) are extremely pertinent to SAUs. Nonetheless, the LGI system must be appropriately adapted to the Indian conditions and to the specific needs of a highly diverse society. It is important to motivate students towards learning agriculture even in primary and secondary schools to train a cadre of academicians researchers, extensionists and practitioners qualified to address the emerging issues of climate change, soil/terrestrial C sequestration, resource degradation (soil, water), food security and malnutrition.

Develop a long-term program: Indian Council of Agricultural Research (ICAR) must establish National Climate-Resilient Agriculture Program (NACRAP). The NACRAP must be implemented on eco-regional basis and involve identification and adoption of land use and soil/water management practices which create positive soil/ecosystem C budget, restore degraded soils and desertified ecosystems, sustain productivity, and improve the environment (e.g., water and air quality). The NACRAP must produce report every 4 years, based on credible data on the state-of-soils, soil C stock, soil C sink capacity, the rate of C sequestration, relation between soil C concentration in the root zone, agronomic yield of principal crops (e.g., wheat, rice, maize, sorghum, millet, and pulses), the impact of climate change on agronomic production, and regional hotspots of climate change. Similar to IPCC, these reports must be based on well-planned activities of "Working Groups" comprising of inter-disciplinary teams of scientists and some learned farmers and land managers. The NACRAP should be jointly funded by ICAR, CSIR, and the private sector. Involvement of the private sector is extremely important.

Payments for Ecosystem Services: Government must adopt a bold and a visionary strategy of eliminating subsidies, but rewarding farmers through payments for ecosystem services provisioned through adoption of recommended management practices. Farmers should be rewarded through payments for ecosystem services such as soil C sequestration, reducing emissions (CH_4, N_2O) from farm operations, enhancing supply of renewable freshwater and improving water quality (Lal *et al.,* 2013).

CONCLUSION

Soils of agroecosystems of India are severely depleted of their organic carbon reserves. Depletion of the SOC pool is exacerbated by the widespread use of extractive and nutrient-mining practices (e.g., removal of crop residue, use of animal dung as fuel, open grazing). Sustainable intensification of agroecosystems is feasible only on soils containing SOC concentration at above the threshold level (1.5% in the 0-20cm depth). Priorities for immediate implementation include the following:

1. Identification and adoption of recommended managements practices of sustainable soil management.
2. Improvement of agricultural curricula to train students in climate change, soil quality, carbon management and sequestration, sustainable intensification, etc.
3. Creation of a National Climate-Resilient Agriculture Program (NACRAP) on eco-regional basis, and
4. Elimination of subsidies and rewarding farmers for provisioning of ecosystem services (e.g., soil C sequestration).

Agriculture in India must be given a high priority not only for advancing food security but also mitigating and adapting to climate change and improving the environment. As Dyson (2008) appropriately stated, "If we can control what the plants do with carbon, the fate of the carbon in the atmosphere is in our hands".

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