Soil Organic Carbon Dynamics, Stabilization, and Environmental Implication

2

M. C. Manna and Avijit Ghosh

Abstract

Administering soil organic carbon (SOC) has now been acknowledged as the most essential aspect for managing the climate change, soil fertility as well as productivity. Various SOC pools and processes govern the SOC dynamics in varied agro-ecosystems. SOC dynamics in soil is manipulated by management practices, soil type, and climate. Perceptions of the different soil C pools and processes are of imperative significance prior to the execution and success of SOC management. Diverse agro-ecological approaches such as organic and integrated plant nutrition system have been proposed across different agroecologies to achieve a balanced SOC dynamics via suitable agro-management, though accepted with limited eagerness.

Keywords

Soil organic carbon · Carbon dynamics · SOC fractions · Global climate change · Carbon management

2.1 Introduction

Excluding carbonate rocks (inorganic carbon path), the soil represents the largest terrestrial stock of carbon (C), holding 1500 Pg (1 Pg $= 10^{15}$ g), which is approximately twice the amount held in the atmosphere and three times the amount held in

---

M. C. Manna (✉)
ICAR-Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India
e-mail: madhabcm@yahoo.com

A. Ghosh
ICAR-Indian Grassland and Fodder Research Institute, Jhansi, Uttar Pradesh, India

A. Rakshit et al. (eds.), *Soil Science: Fundamentals to Recent Advances*,
https://doi.org/10.1007/978-981-16-0917-6_2

the terrestrial vegetation. Soil inorganic carbon (SIC) pool contains 750–950 Pg C. Terrestrial vegetation is reported to contain 600 Pg C. Atmospheric concentration of carbon dioxide and other greenhouse gases are changing rapidly because of anthropogenic activities including fossil fuel combustion, deforestation, biomass burning, cement manufacturing, drainage of wetlands, and soil cultivation. The current level of carbon dioxide concentration in the atmosphere (which was at 370 ppm in 2004) is increasing at the rate of 1.5 ppm/year or 3.3 Pg C/year. Researchers predicted that unless necessary measures are taken immediately to reduce net emission of carbon dioxide, it may increase to 800–1000 ppm by the end of twenty-first century. Climatic sensitivity to atmospheric enrichment of carbon dioxide may be 1.5–4.5 °C rise in mean global temperature, with attendant increase in sea level. About 20% of the earth's land area is used for growing crops and thus farming practices have a major influence on C storage in the soil and its release into the atmosphere as CO_2. Within cropping/farming system, the equilibrium levels of soil organic carbon (SOC) can be related linearly to the amount of crop residue returned/applied to soil. The rate of accumulation of SOC depends on the extent to which the soil is already filled by SOC, i.e., the size and capacity of the reservoir. Mechanical disturbance of soil by tillage increases decomposition rate of SOC. Practices, which increase residue and/or plant growth result in enhancing SOC sequestration. The beneficial effect of SOC is more than improving soil quality and fertility.

Total geographical area of India is 328.7 million hectares (m ha) or about 2.5% of the total land area of the world. It is home to 1.1 billion or 16% of the world population. India is the second most populous country in the world. Principal land uses include 161.8 m ha of arable land (11.8% of the world) of which 57.0 m ha (21.3% of the world) is irrigated, 68.5 m ha of forest and woodland (1.6% of the world), 11.05 m ha of permanent pasture (0.3% of the world), and 7.95 m ha of permanent crops (6.0% of the world). The large land base, similar to that of the USA and China or Australia, has a potential to sequester C and enhance productivity while improving environmental quality. The Green Revolution of the 1970s needs to be revisited to enhance production once again and to address environmental issues of the twenty-first century including climate change. Organic carbon in soil play multi-functional role leading to reduction in productivity, enhance input use efficiency (e.g., fertilizer, irrigation), protect pollution of surface and ground water, and minimize emission of greenhouse gases (GHGs) from terrestrial and aquatic ecosystems into the atmosphere and help to improve the soil degradation (Swarup et al. 2000; Manna et al. 2018). Majority of carbon is held in the form of soil organic carbon, having a major influence on soil structure, water holding capacity, cation exchange capacity, etc.

Thus, in this paper, SOC dynamics, total carbon stocks, stabilization mechanism, and environmental quality have been discussed. Further, the C-sequestration mechanism, possible ways to enhance SOC has also been highlighted.

2.2 Soil Organic Pools and Dynamics

So far, literature on soil organic matter (SOM) changes in rainfed, semiarid, and sub-humid regions of India did not throw much light on the carbon functional pools, which are highly sensitive indicator of soil fertility and productivity. The distribution of soil organic matter into the following five functional pools may be made for its true representation (Parton et al. 1987).

Structural Litter Fraction This consists of straw, wood, stems, and related plant parts. The C:N ratio varies around 150:1. These are high in lignin.

Metabolic Pool Fraction It comprises plant leaves, bark, flower, fruits, and animal manure. The C:N ratio ranges from 10 to 25. This fraction contributes mineral nitrogen when it is decomposed.

Active Pool of Soil Carbon This is microbial biomass and their metabolites. The C:N ratio is around 5–15. This fraction contributes mineral nutrients and it gives life to the soil. Besides microbial biomass C (SMBC), light fraction of organic matter, water soluble carbon, and water soluble carbohydrates are also active pools of organic matter.

Slow Decomposable Soil Fraction This fraction is comparable to nature of composting materials having C:N ratio around 20:1. It makes temporary stable humus in soil, which is slowly decomposable.

Passive Soil Organic Fraction This is the highly recalcitrant organic matter with C:N ratio of 7:1 to 9:1. It is resistant to oxidation and is not readily involved in dynamic equilibrium with other types of organic fractions in soil. The specific relationship of management practices and biologically active soil organic matter with soil process is not well characterized. The structure of SOC sub-model is illustrated in century model (Fig. 2.1) (Parton et al. 1987).

This model includes respiratory C losses associated with dynamics of organic pools. Similarly, the N-sub models have the same basic structure of SOM and also include the flow of nutrients in different mineral forms. Moreover, SOC turnover is dependent on soil moisture, radiation, temperature, cropping, rooting, plant residue, etc. Combined effect of all these factors on the dynamics of SOM is not yet established in tropics. Studies therefore, need to be conducted to develop a model of SOM for rainfed cropping systems which will include different parameters such as physical properties of soil, nutrient status, light fraction of SOC, hot water soluble carbon, SMBC, activity of enzymes, etc. Such model may be of great practical importance from management point of view and as an indicator of soil quality.

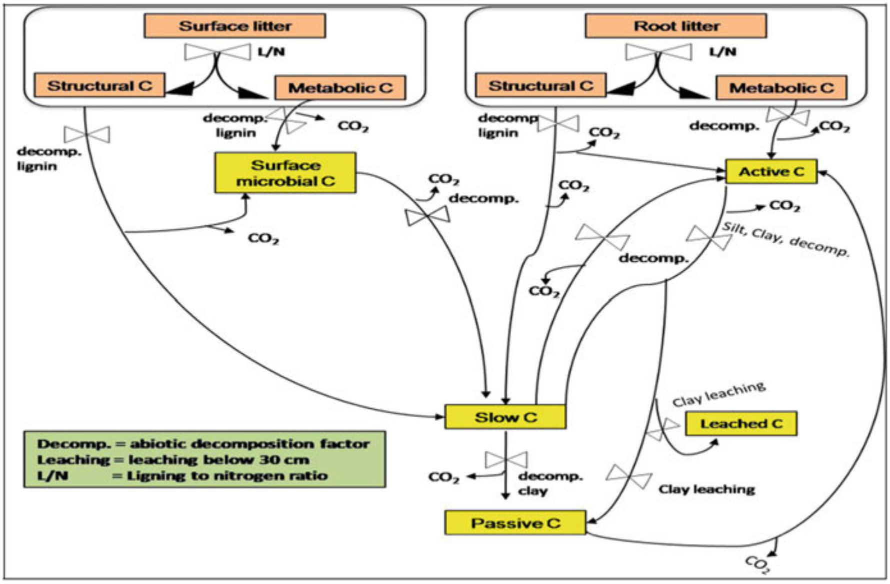

Fig. 2.1 Soil organic pool and dynamics in century model. Source: Parton et al. (1987)

2.3 Long-Term Application of Fertilizer and Manure on Active and Slow Pool of Carbon

Long-term application of NPK and NPK+FYM maintained or improved SOC content over initial values (Bhadoria et al. 2003; Manna et al. 2006; Joshi et al. 2017; Ghosh et al. 2019). Moreover, active fractions of SOC, viz., particulate organic carbon and hydrolysable carbohydrates, soil microbial biomass C and N were improved significantly with the application of NPK and NPK+FYM over control both in case of Alfisol, Inceptisol, and Vertisol (Table 2.1). The microbial biomass is considered a significant reservoir of plant nutrients, specially N and P and also active fraction of organic matter. The more labile component of soil organic matter fractions are soluble phase of carbon and carbohydrates acts as source of plant nutrients better than most other fractions (passive pool of carbon). The most important biological properties of organic matter are (1) its role as a reservoir of metabolizable energy for soil microbial and faunal activities, (2) its effects in stabilizing enzyme activities, and (3) its values as a source of plant nutrition through mineralization. Thus, important approach to characterize soil biological health may be presented by inherent fluxes at which the soil microbial biomass would transmit the organic and inorganic growth stimulants, including the nutrients supply to the growing crops. Little attention has been paid towards labile pools of carbon as compared to total organic carbon in most agricultural soils. Typically, organic matter levels decline rapidly when soil under native vegetation is converted to arable

Table 2.1 Long-term effects of manure and fertilizer application on active fractions of soil organic carbon under inceptisol (rice-wheat-jute, R-W-J and 30 years), vertisol (sorghum-wheat, S-W, 15 years), alfisol (soybean-wheat, soy-W, 30 years), and vertisol (soybean-wheat, soy-W, 39 years) system at 0–15 cm soil depth

Locations (cropping system)	Treatments	SMBC (mg kg^{-1})	SMBN (mg kg^{-1})	AHC (mg kg^{-1})	SOC (g kg^{-1})	%POM in SOC
Inceptisol (R-W-J, 30 year)	Control	169	11.4	526	5.4	10.6
	N	162	10.7	580	5.7	16.5
	NP	209	11.0	609	6.3	22.4
	NPK	327	15.2	689	7.4	20.0
	NPK + FYM	486	20.2	845	7.9	27.0
Vertisol (S-W, 15 year)	Control	201	8.6	462	3.5	10.3
	N	220	10.2	590	3.4	23.3
	NP	244	12.3	620	3.9	26.7
	NPK	382	13.3	725	4.2	30.1
	NPK + FYM	465	16.4	840	4.5	39.7
Alfisol (soy-W, 30 year)	Control	154	7.8	328	3.5	10.0
	N	185	6.7	368	3.4	9.8
	NP	201	9.6	442	4.2	14.7
	NPK	210	12.2	466	4.5	26.7
	NPK + FYM	265	14.5	517	4.7	31.2
Vertisol (soy-W, 39 year)	Control	156	26.1	250	6.3	10.0
	N	218	32.2	370	6.4	10.4
	NP	382	41.6	415	7.0	9.8
	NPK	559	46.3	443	8.6	11.0
	NPK + FYM	598	49.8	448	12.4	13.3

Source: Manna et al. (2006, 2007, 2013a, b) control (without fertilizer, manure, and lime): N: 100% recommended rate of nitrogen; NP recommended rate of nitrogen and phosphorus; NPK: 100% recommended dose of nitrogen, phosphorus, and potassium; NPK + FYM: 100% recommended rate of NPK and 10 Mg ha^{-1} year^{-1} FYM; *SMBC* soil microbial biomass carbon, *SMBN* soil microbial biomass nitrogen, *AHC* acid hydrolysable carbon, *SOC* soil organic carbon, and *POM* particulate organic matter

agriculture in the first 10–20 years and then stabilize at a new equilibrium level. Many factors contribute to loss of SOM levels such as lower allocation of carbon to the soil, removal or burning of crop residues, tillage induced aggregates disruption, more favorable condition for decomposition and greater losses of surface soil by water erosion. In agricultural soil, the light fraction typically contains 20–30% C and 5–20% N and 18–22% of total C and 1–16% of total N in the whole soil. Particulate organic matter (POM) contains 10–40% of total SOC and 13–40% of total N in the whole soil. The large POM maintains soil structure and macro-aggregation. The large amount of microbial community associated with the decomposing POM produces binding agent such as exo-cellular mucilaginous polysaccharides. It acts as a major food and energy for endogenic soil fauna. Thus, POM is associated with a multitude of soil process and functions and is therefore, a key attribute of soil quality. Acid hydrolysable carbohydrate (AHC) (32–37% of SOC) is a labile C fraction and has been found more rapidly in response to changes in management than SOC contents. The $KMnO_4$–oxidizable C fraction accounts for 5–30% of organic C. This oxidizable fraction usually is more sensitive to soil management than SOC. Long-term (39 years) application of balanced fertilizer either alone or in combination with manure has increased 3.2- to 3.6-fold of soil microbial biomass C, 1.8- to 2-fold of soil microbial biomass N, 1.8- to 2-fold of acid hydrolysable carbohydrates in Vertisol under soybean-wheat system as compared to fallow soil (Manna et al. 2013a, b). Over the years of cultivation of crops with application of balanced nutrients (NPK) maintained active fractions of C and N (Neogi 2014).

Thus, it is inferred from different long-term experiments that cultivation of double crops annually with imbalanced fertilization leads to greater nutrient loss that would have retain lesser amount of SOC and associate nutrients. Passive fraction of C and N pools are more resistant to decomposition and its mean residence time is about 500–1500 years. Long-term application of balanced fertilizer and manure significantly improved humic and fulvic acid fraction during 15–40 years in all the three soils (Inceptisol, Alfisol, and Vertisol) (Manna et al. 2007; Manna et al. 2013a, b; Joshi et al. 2017).

2.4 Slow Pool of Carbon

Both, in conventional tillage and zero tillage, fresh residue decompose and subsequently help developing different aggregate size classes (Fig. 2.2). However, in conventional tillage it decomposes much faster due to rapid oxidation in soil. In due course of time, the coarse fraction of interparticulate (iPOM) or heavy fraction of POM and fine iPOM or light fraction of POM are developed in the form of micro (53–253μm), followed by small-macro (250–2000 μm) and large macroaggregates (>2000 μm) aggregates. The time frame as mentioned in the figure indicated that the entire period for formation and disruption depends upon type and duration of tillage operation. In conventional tillage, the degradation of aggregates is more rapid than zero tillage operation. Thus, the practice of zero tillage may help to retain more POM in aggregates size classes than conventional tillage. Under intensive cultivation with multiple cropping systems, these carbon pools were significantly reduced due to reduction of large macroaggregates (>2 mm) and microaggregates (0.25 mm) that may reduce the heavy or light fraction of POM-C and POM-N, which resulted in low nutrient supplying capacity to soil (Manna et al. 2013a, b, Fig. 2.2). The application of recommended rate of NPK under soybean-wheat in Alfisol (30 years, Ranchi) and Vertisol (39 years, Jabalpur) and, rice-wheat in Vertisol (16 years, Raipur) improved the content of POMC and POMN by 5 to 38.6% and 5.2 to 28.5% compared to imbalanced N or NP treated soil (Manna et al. 2007; Joshi et al. 2017). The significant increase (48–72.4%) of mineral associated organic C and N (silt + clay

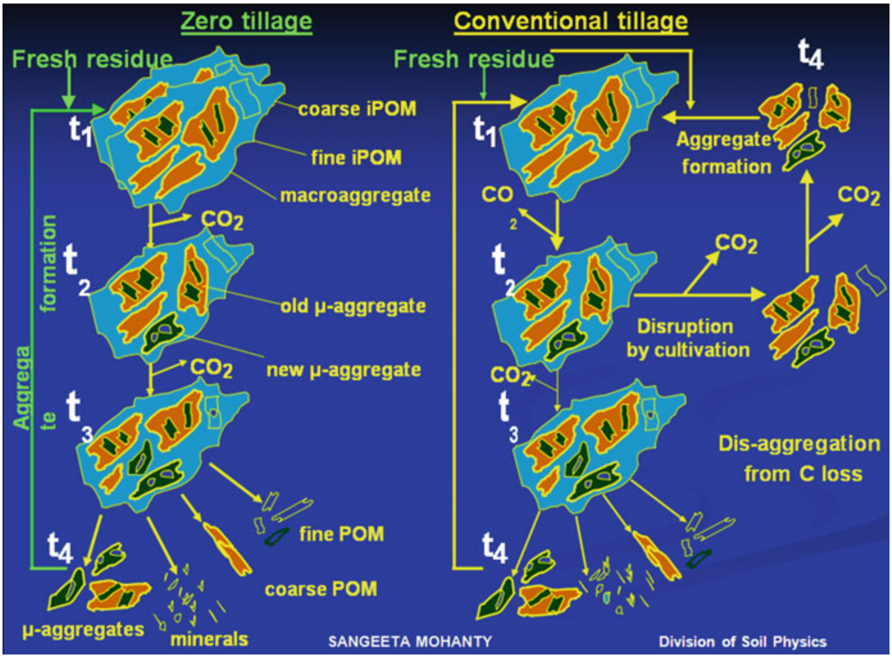

Fig. 2.2 Development and disintegration of soil aggregate's coarse and fine particulate organic matter in Zero–tillage and conventional tillage

Table 2.2 Long-term effect of manure and fertilizer application on C-mineralization rate (k) from aggregates of top soil layer (0–15 cm) in inceptisol

Treatment	0.25–2 mm k_c (mg kg^{-1} week^{-1})	0.053–0.25 mm k_c (mg kg^{-1} week^{-1})	<0.053 mm k_c (mg kg^{-1} week^{-1})
Control	0.022^{c}	0.040^{b}	0.030^{bc}
N	0.033^{c}	0.030^{b}	0.033^{bc}
NP	0.035^{c}	0.047^{b}	0.028^{bc}
NPK	0.051^{bc}	0.043^{b}	0.021^{c}
NPK + FYM	0.082^{a}	0.089^{a}	0.067^{a}

Computed through exponential model $C_t = \mathrm{Co}\ (1 - e\text{-kt})$. Means with similar lower-case letters within a column are not significantly different at $P < 0.05$ according to LSD test

fraction) was found under long-term application of N, N-P application as compared to fallow. These studies clearly indicated the less retention of labile pools of nutrients due to rapid cultivation, resulted in deterioration of soil quality in a long run. The rate of C-mineralization from different aggregates was studied from long-term nutrient management system. It was found that C-mineralization was greater in macroaggregates size classes than microaggregates and least was observed in mineral associates (Table 2.2). Application of NPK with FYM significantly improved C-mineralization from all size classes.

2.5 Passive Pools of Carbon

A significant variation in the passive fraction of C by nutrient management is limited thereby indicate that more time frames are required to effect a change of passive pools, i.e. humic and fulvic acid (Manna et al. 2006; Joshi et al. 2017). However, the C stabilization is significant under different long-term land use and management practices and a greater extend the turnover time is estimated in the range of 10–100 years in the intermediate pools.

2.6 Steady State of C and Turnover Period

The basic information on carbon steady state and turnover period under different long-term nutrient management and cropping system may help to better understand of carbon equilibrium or quasi equilibrium under different soils. To study the steady-state C and turnover period, the model was used to describe the relationship between total SOC and cropping year. The value of K indicates how rapidly the SOC changes towards a new equilibrium level as computed the following equation.

$$\mathrm{SOC}_t = \mathrm{SOC}_e + (\mathrm{SOC}_0 - \mathrm{SOC}_e)\ \exp\ (-\mathrm{kt})$$

where SOC_t is the value of SOC (g kg^{-1}) at time t; SOC_e is the value of SOC at equilibrium; SOC_0 is the value of SOC at $t = 0$ (4.6 g kg^{-1} for Vertisol and 7.12 g kg^{-1} for inceptisol); k is the exponential rate of variation (1/year) and t is the cropping year. Continuous application of 100% recommended rates of NPK plus FYM established a new equilibrium of SOC much earlier ($t_{1/2}$, 2.4 years in vertisol, 7.7 years in inceptisol and 2.1 years in alfisol) than imbalanced use of either N or NP fertilizer ($t_{1/2}$, 8.1–25.7 years in vertisol, 14.9–50.3 years in inceptisol and 2.1–2.8 years in alfisol). Thus, this basic information generated can be very well used to sustain the yield, assessing the soil quality and restoring the degraded soil as a result of over exploitation of natural resources (Table 2.3).

2.7 Carbon Stabilization

Carbon storage and sequestration in agricultural soils is considered to be an important issue. In agro-ecosystem research, it is possible to differentiate three levels of crop production: Potential, Attainable, and Actual (Rabbinge and van Ittersum 1994; van Ittersum and Rabbinge 1997). Similarly, carbon sequestration in agricultural soils has also three situations, i.e. potential, attainable, and actual (Fig. 2.3). The amount of carbon present in the soil is the function of land use change, soil type, climate (rainfall and temperature), and management practices. This is due to:

$$\text{Clay content} - \text{physically protected} = \text{Potential C}$$

Table 2.3 Initial status of organic-C and equilibrium values for different treatments after 15 years and 30 years of cultivation of 0–15 cm depth at Akola and Barrackpore, India

Akola (after 15 years of cultivation)						
Treatment	Initial SOC (g kg^{-1})	SOC_o mean (g kg^{-1})	Steady state (SOC) (g kg^{-1})	Loss rate (k, per year)	$t_{1/2}$ (year)	R^2
N	4.6	4.6 ± 0.329	3.5 ± 1.798	−0.027	24.7	0.93*
NP	4.6	4.7 ± 0.067	4.4 ± 0.429	−0.086	8.1	0.86*
NPK	4.6	4.8 ± 0.093	4.6 ± 0.267	−0.138	5.02	0.84*
NPK+ FYM	4.6	5.4 ± 0.147	5.3 ± 0.374	−0.291	2.4	0.42
Barrackpore (after 30 years of cultivation)						
N	7.12	4.9 ± 0.025	4.8 ± 0.018	−0.020	50.3	0.10
NP	7.12	4.9 ± 0.065	5.0 ± 0.022	−0.067	14.9	0.22
NPK	7.12	5.0 ± 0.038	5.1 ± 0.04	−0.095	10.7	0.39
NPK + FYM	7.12	5.4 ± 0.022	5.6 ± 0.017	−0.129	7.7	0.62^a

Source: Manna et al. (2013a, b)

*Value is significant at $P \leq 0.05$, ± standard error

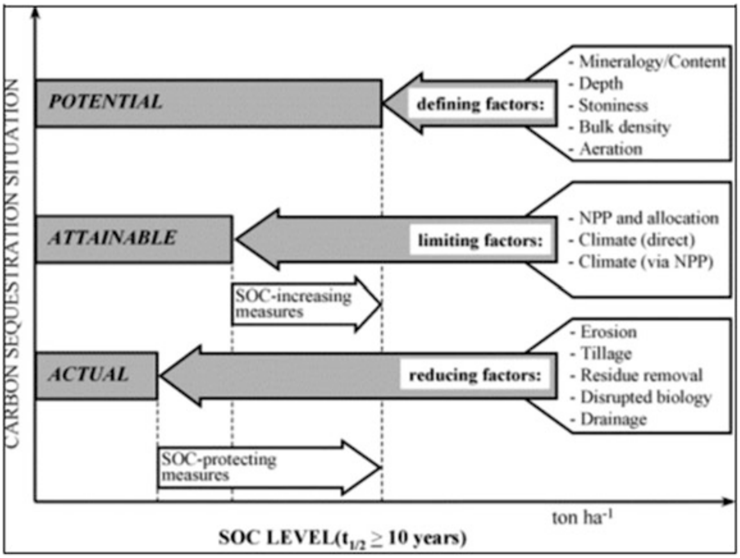

Fig. 2.3 Relationship between carbon sequestration situation and SOC level. Source: Adapted from Ingram and Fernandes (2001) and Manna et al. (2012)

$$\text{Climate} - \text{determines the net primary productivity} \\ = \text{Attainable C Management practices} = \text{Actual C}$$

Three terminologies are used in soil carbon sequestration study. They are $\text{SOC}_{\text{potential}}$, $\text{SOC}_{\text{attainable,}}$ and $\text{SOC}_{\text{actual}}$. The term "carbon sequestration potential," in particular, is used with different meanings; sometimes referring to what might be possible given a certain set of management conditions with little regard to soil factors which fundamentally determine carbon storage. Regardless of its potential, the amount of carbon a soil can actually hold is limited by factors such as rainfall, temperature, and sunlight and can be reduced further due to factors such as low nutrient availability, weed growth, and disease. The term "$\text{Attainable}_{\text{max}}$" is defined and is suggested as the preferred term for carbon sequestration in mineral soils, being more relevant to management than "potential" and thereby of greater practical value (Ingram and Fernandes 2001). The attainable soil C sink capacity is only 50–66% of the potential capacity (Lal 2004). $\text{SOC}_{\text{potential}}$ is the SOC level that could be achieved if there were no limitations on the system except soil type. Soil type has an influence because surfaces of clays and other minerals will influence how much organic C can be protected against decomposition. For a soil to actually attain $\text{SOC}_{\text{potential}}$, inputs of carbon from plant production must be sufficiently large to both fill the protective capacity of a soil and offset losses due to decomposition. Under dryland conditions (no irrigation) these factors will place a limit on the amount of residue that can be added to a soil such that attaining the $\text{SOC}_{\text{potential}}$ is not possible and a lower value defined as $\text{SOC}_{\text{attainable}}$ results. The value of $\text{SOC}_{\text{attainable}}$ is the realistically best case scenario for any production system. To achieve $\text{SOC}_{\text{attainable}}$, no constraints to productivity (e.g. low nutrient availability, weed growth, disease, subsoil constraints, etc.) must be present. Such situations virtually never exist and these constraints typically result in lower crop/pasture productivities than required to attain $\text{SOC}_{\text{attainable}}$. This second set of factors is referred to as reducing factors, which may well be under the control of farmers. Decreased productivity, induced by the reducing factors, leads to lower returns of organic carbon to soil and lower actual organic carbon contents ($\text{SOC}_{\text{actual}}$) (Baldock 2008).

It can be inferred that attainable level of organic carbon in Indian soils is generally limited by rainfall as we do not have much variation in mean annual temperature, although it may be limited in some areas and seasons. In this respect, use of simulation models like Roth-C and DSSAT-century could be the useful tool to determine the attainable level of soil organic carbon under different agro-ecological regions of the country. Using models to predict changes in organic soil carbon under different scenarios can provide an idea of the effects of different land uses and management practices, such as stubble burning, grazing pressure and fertiliser use. Models are able to estimate likely changes in organic soil carbon under a range of conditions, across a range of spatial scales and for much longer times than can be accommodated in experiments (Baldock 2008).

Regardless of potential, the amount of carbon a soil can actually hold is limited by factors such as climate, soil and can be reduced further due to factors such as nutrient availability, insect pest and disease incidence.

2.8 Impact of Organic Amendments Induced GHGs Emission and Management Practices for Mitigation

Global warming poses a major threat to the global environment and the major GHGs, the key contributor of global warming are originated from fossil fuel consumption (IPCC 2007; Pathak et al. 2009). Increased population and urbanization indicate rising shares of municipal solid waste (MSW), increase in food grain production generating plenty of crop residues, unscientific management of live stocks and poultry birds contributing considerable portion of CO_2, CH_4, and N_2O (Tables 2.4 and 2.5) in the atmosphere. The estimates of CO_2 emission from this untreated source may account for annual emission of approximately 5.2 and 155 Tg from MSW and animal waste and 198 Tg from crop residue manure (Table 2.4). MSW

Table 2.4 Potential of quantity of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emission from municipal waste and animal waste

	Total population ($\times 10^3$)	Total quantity of biosolid produce ($\times 10^3$) (Mg/year)	CO_2-C (Gg/year)	CH_4-CO_2-C eq (Gg/year)	N_2O-CO_2-C eq (Gg/year)
	261,790	12,995	5198	612	442.7
	Total population ($\times 10^3$)	Total quantity of manure produce ($\times 10^3$) (Mg/year)	CO_2-C (Gg/year)	CH_4-CO_2-C eq (Gg/year)	N_2O-CO_2-C eq (Gg/year)
Cattle	299,606	355,483	142,193	34,452	9732
Sheep and Goat	200,242	30,010	12,004	4514	5934
Horse and Ponies	625	317	127	37	10
Pig	10,294	2574	1030	377	509
Poultry	729,209	1028	411	92	88
Total animal + poultry	1,239,976	389,411	155,765	39,472	16,272
	Cattle	Sheep and goat	Horse and ponnies	Pig	Poultry
Manure weight (kg/year)	1186.5	150	506.7	250.1	1.4
Total C (%)	34.7	53.85	41.4	52.4	32.2
Total N (%)	0.5	3.25	0.5	3.3	1.4

Sources: All emission factors are adopted from IPCC (1996) and Manna et al. (2018)

Table 2.5 Potential of quantity of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emission from crop residue

Plant residue	Net area ($\times 10^3$) (ha/year)	Potential of residue ($\times 10^3$) (Mg/year)	TOC (%)	TN (%)	CO_2-C eq (Gg year)	CH_4-CO_2-C eq (Gg/year)	N_2O-CO_2-C eq (Gg/year)
Rice	42,750	210,480	45.3	0.61	841.9	26.631	7.81
Wheat	30,000	140,265	46.3	0.48	561.1	18.138	4.10
Sorghum	6210	15,840	44.8	0.52	63.4	1.982	0.50
Millet	7300	34,960	44.8	0.45	139.8	4.374	0.96
Maize	8670	100,170	52.5	0.52	400.7	14.688	3.17
Bengal gram	8520	11,479	47.8	0.8	45.9	1.533	0.56
Pigeon pea	3890	12,080	48.6	0.87	48.3	1.640	0.64
Lentil	1420	2260	45.9	1.21	9.0	0.290	0.17
Groundnut	4720	9400	41.9	1.6	37.6	1.100	0.91
Rapeseed	6290	16,060	45.9	0.67	64.2	2.059	0.65
Soybean	10,840	14,670	50	0.97	58.7	2.049	0.87
Sunflower	830	1620	39.7	0.53	6.5	0.180	0.05
Cotton	11,980	17,460	49.8	1	69.8	2.429	1.06
Sugarcane	5000	102,360	50.7	0.4	409.4	14.495	2.49
Potato	1990	34,912	45.8	0.52	139.6	4.466	1.10
				Total	2896.063	96.052	25.04

Sources: All emission factors are adopted from IPCC (1996), Manna et al. (2018)

generated in India is increasing at a rate of 1.33% annually (Shekdar 2009). It is estimated that overall N_2O losses from agriculture, animal, and municipal solid waste is about 45.73 Tg. The average per capita solid waste generation has been assessed to be 341 g of which 40% is biodegradable on dry weight basis and it shows that the estimates of GHG emissions from MSW was 5198 Gg CO_2, 612 Gg CH_4, and 442.7 Gg N_2O (Table 2.4) and GHG emissions from animal wastes in India was 155,765, 39,472, 16,272 Gg of CO_2, CH_4, and N_2O, respectively. During 2012, the contribution of crop residue towards GHG emission was 2,896,063 and 96,052 Gg of CO_2 and CH_4, respectively (Table 2.5).

Acceptability of mitigation options technologies need to be increased to reduce the net emissions of carbon dioxide, methane, and nitrous oxide. Nonetheless, the real challenge lies in the regional diversity of agricultural management practices which controls the rate of potential adoption of mitigation practices to accrue sustainable production and farmers benefit. Thus, the major challenge is how GHG emission can be reduced from agriculture, animal sector, and MSW management. Moreover, no quantitative information is still available on the total potential reduction in CO_2, CH_4, and N_2O emissions from existing croplands offsets by biofuel production. The emissions of CH_4 from composted farmyard manure and poultry manure-amended soils were very low. The practice of green manure application in rice field emitted lower CH_4 by methanogens than wheat straw as the easily biodegradable material content acted as with lower activation energy for microbes.

Application of surface mulching of straw during winter period reduced CH_4 emission compared to field incorporation. Composts consistently produced lower CH_4 emissions than fresh green manures or straws. Aerobic composting reduces readily decomposable carbon to CO_2 instead of CH_4. Low CH_4 production is highly influenced by inflow of oxygen and downward discharge of methanogenic substrate into the soil. In rice fields amended with biogas slurry emitted significantly less CH_4 than manure with wheat straw and in high-percolating site with rice field, CH_4 emission was extremely low. The main reason for low CH_4 emissions from rice fields in India is that the soils have very low organic C or receive very little organic amendments. Few measurements have been published for N_2O emissions from flooded rice soils amended with organic materials.

The existing information indicates that N_2O emissions from flooded soils with organic additions are similar to or less than the soils receiving chemical fertilizers, indicating that organic amendments do not appear to influence N_2O emissions very much. The dominant sources of N_2O in soils are biologically mediated reduction processes of nitrification and denitrification. In rice fields during periods of alternating wetting and drying N_2O occur as a result of nitrification–denitrification processes. Application of organic amendments like wheat straw, green manure coupled with nitrogenous fertilizer significantly reduced cumulative gaseous N losses.

High livestock density is always accompanied by production of a surplus of animal manure, representing a considerable pollution threat for the environment. Biogas is a smokeless fuel offering an excellent mitigation option for GHG emission from cattle dung cake, agricultural residues, and firewood, which are used as fuel in India.

2.9 Effect of Land Use and Management Practices on C-sequestration

Diversified cropping systems with better management substantially improved C-sequestration rate in semiarid-tropic soils of India (Manna et al. 2012). In vertisol, C-sequestration was maximum in castor + pigeon pea intercropping system (936 kg C ha^{-1} $year^{-1}$) followed by cotton/greengram + pigeon pea (885 kg C ha^{-1} $year^{-1}$), paddy-paddy system (861 kg ha^{-1} $year^{-1}$) then horticulture crop (citrus, 745 kg ha^{-1} $year^{-1}$) (Table 2.6).

The impact of long-term cultivation of crops in rotation and fertilizer and manure application on soil organic carbon stock, carbon sequestration rate, carbon sequestration efficiency have been computed in Inceptisol, Alfisol, and Vertisol (Manna et al. 2012). It was observed that the imbalanced fertilizer application (N and NP) was not encouraged for carbon sequestration rate and carbon sequestration efficiency in Inceptisol and Alfisol. However, treatment effect was prominently observed for

Table 2.6 Effect of different cropping system and management of C-sequestration rate in SAT benchmark soils of India

Location	Soil type	Cropping system	Study period	Sampling depth (cm)	Initial SOC $(\mathrm{Mg\ ha})^{-1}$	Final SOC $(\mathrm{Mg\ ha})^{-1}$	C-sequestrationrate $(\mathrm{kg\ ha\ year})^{-1}$
Madhya Pradesh	Typic haplustert (Kheri)	Paddy–wheat	1982–2002	0–30	19.8	22.5	135
Maharashtra	Typic haplustert (Linga)	Citrus	1982–2002	0–30	22.0	36.9	745
Maharashtra	Typic haplustert (Asra)	Cotton/greengram + pigeon pea	1982–2002	0–30	17.3	35.0	885
Gujarat	Typic haplustert (Semla)	Groundnut–wheat	1978–2002	0–30	27.3	31.9	209
Karnataka	Typic haplustert (Teligi)	Paddy–paddy	1974–2002	0–30	18.61	43.6	861
Karnataka	Typic haplustalf (Vijayapura)	Finger millet	1982–2002	0–30	19.3	21.9	130
Andhra Pradesh	Typic halplustalf (Kaukuntla)	Castor + pigeon pea	1978-2002	0–30	14.5	35.1	936

Sources: Manna and Rao (2012)

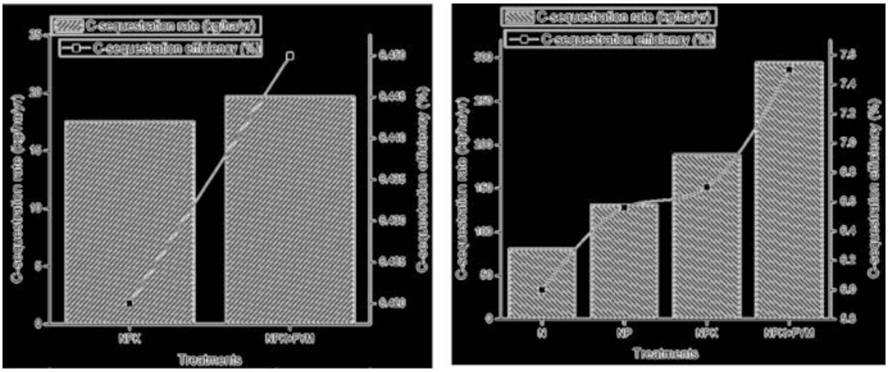

Fig. 2.4 Carbon sequestration rate and efficiency in (**a**) Inceptisol (**b**) Vertisol

C-sequestration efficiency and C-sequestration rate in Vertisol (Typic Haplustert) under sorghum-wheat system. Thus, SOC restoration process could be improved by a set of management practices in a long run. The results suggest that under high intensive cropping system recommended dose of inorganic NPK and NPK + FYM maintained soil quality parameters, which in turn supports better crop productivity and C-sequestration rate. In Inceptisol, the treatments with NPK and NPK + FYM showed lower carbon sequestration rate and it was varied from 17 to 22 kg/ha/year and C-sequestration efficiency was varied from 0.42 to 0.45% in these treatments (Fig. 2.4a). In Vertisol C-sequestration rate was varied from 75 to 300 kg/ha/year in N, NP, NPK, and NPK + FYM treatments (Fig. 2.4b) and C-sequestration efficiency varied from 5.8 to 7.5 % under sorghum-wheat system. The perusal of the graph signifies that carbon sequestration rate and efficiency depends on the type of soil and also cropping systems. It is clear that the C sequestration rate is higher in Vertisol than in Inceptisol. However, under high intensive cropping system recommended dose of inorganic NPK and NPK + FYM maintained soil quality parameters, which in turn supports better crop productivity and C-sequestration. The issue of climatic change and active and slow fractions of SOC and associate nutrients on productivity is needed more attention.

A significant build-up of SOC was found in 75% NPK+ FYM in soybean-wheat, sorghum-wheat, and soybean/sorghum-wheat system (Table 2.7). After 6 year of cultivation on an average SOC potential (CSP) was improved over initial SOC stocks from 2028 to 5292, 2028 to 4470, and 2343 to 5595 kg ha^{-1} at 0–30 cm in soybean-wheat, sorghum-wheat, and soybean + sorghum-wheat system, respectively. The SOC stocks in the plots of 0–15 cm depths in all these three systems were greater as compared to lower depth (15–30 cm). The C- sequestration rate (CSR) was greater in intercropping system followed by soybean-wheat system and sorghum-wheat system. Further it was observed that the C-sequestration potential was in the order: 75% NPK + FYM at 5 t ha^{-1} (F4) > 75% NPK + PC at 5 t ha^{-1} (F5) > 75% NPK + PM at 1.5 t ha^{-1} (F6) > 100% NPK (F3) > 75% NPK (F2) > control (F1).

Table 2.7 Effects of manures and fertilizer application on SOC stocks, C-sequestration potential (CSP) and C-sequestration rate (CSR) under different cropping systems

Treatments	SOC stock (kg ha^{-1}) after 6 year			CSP (kg ha^{-1})			CSR (kg ha^{-1} year^{-1})
	0–0.15 m	0.15–0.30 m	0–0.30 m	0–0.15 m	0.15–0.30 m	0–0.30 m	0–0.30 m
Soybean-wheat system							
F1	7776	6725	7250	−540	−205	−372	−62
F2	10,692	8610	9651	2376	1680	2028	338
F3	11,088	9240	10,164	2772	2310	2541	423
F4	13,860	11,970	12,915	5544	5040	5292	882
F5	13,662	11,550	12,606	5346	4620	4983	830
F6	11,880	11,130	11,505	3564	4200	3882	647
LSD ($P = 0.05$)	664.5	185.1	399.5				
Sorghum-wheat system							
F1	7736	6485	7110	−580	−445	−512	−85
F2	10,692	8610	9651	2376	1680	2028	338
F3	11,880	9030	10,455	3564	2100	2832	472
F4	13,266	10,920	12,093	4950	3990	4470	745
F5	12,078	9660	10,869	3762	2730	3246	541
F6	11,682	9660	10,671	3366	2730	3048	508
LSD ($P = 0.05$)	114.7	208.8	74.6				
Soybean + sorghum-wheat system							
F1	8526	7009	7767	210	79	144	24
F2	10,692	9240	9966	2376	2310	2343	390
F3	12,474	10,080	11,277	4158	3150	3654	609
F4	14,256	12,180	13,218	5940	5250	5595	932
F5	13,266	11,760	12,513	4950	4830	4890	815
F6	12,474	11,130	11,802	4158	4200	4179	696
LSD ($P = 0.05$)	168.5	237.8	138.6				

Control (F_1), 75% NPK (F_2), 100% NPK (F_2), 75% NPK + FYM at 5 t ha^{-1} (F_4), 75% NPK + PC at 5 t ha^{-1} (F_5), and 75% NPK + PM at 1.5 t ha^{-1} (F_6)

However, it was observed that the C-sequestration efficiency was greater in legume based cropping system and it was varied from 22.7 to 35.7% under soybean-wheat system followed by intercropping system (16.1–21.3%) and sorghum-wheat system (12.1–18.7%) (Fig. 2.5).

According to National Wasteland Development Board of India, the extent of degraded lands is around 158.06 million hectares (Table 2.8). It has been estimated that in India the forest cover has been depleted at the rate of 1.3 million ha^{-1} year^{-1} due to heavy pressures on forest lands for agricultural use and increased felling of trees to meet the requirements of the burgeoning human and animal population.

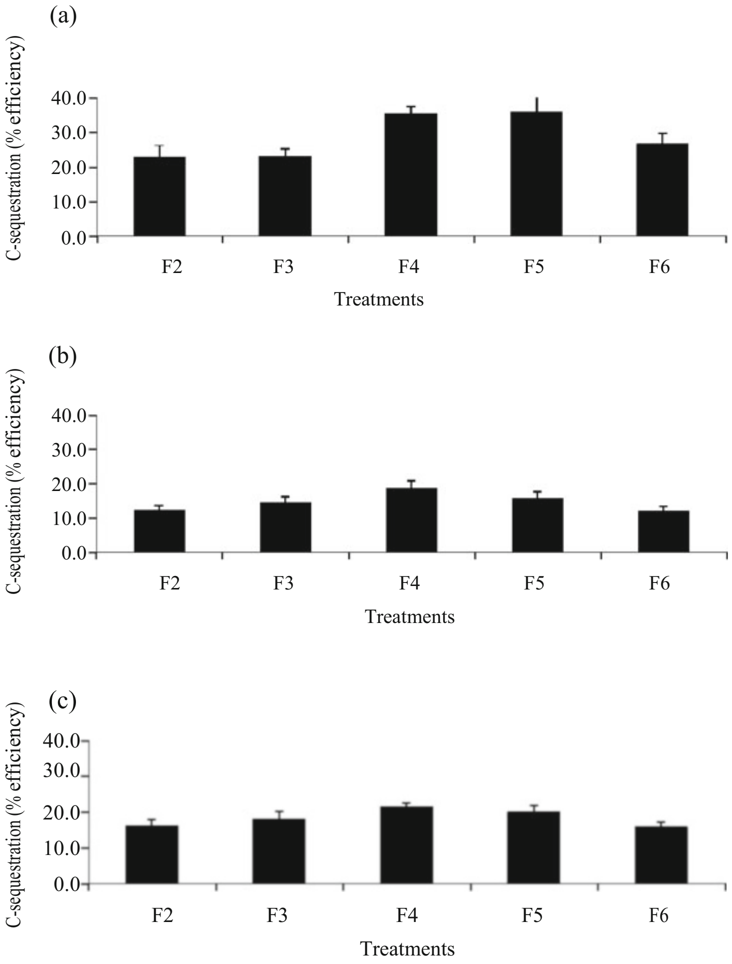

Fig. 2.5 Effects of fertilizer and manures on C-sequestration efficiency under three cropping systems (**a**) soybean-wheat, (**b**) sorghum-wheat, and (**c**) soybean + sorghum-wheat; error bars represents the standard error of mean; control (F_1), 75% NPK (F_2), 100% NPK (F_2), 75% NPK + FYM at 5 t ha^{-1} (F_4), 75% NPK + PC at 5 t ha^{-1} (F_5), and 75% NPK + PM at 1.5 t ha^{-1} (F_6)

Estimates of land areas affected by different soil degradation processes include 73.1 M ha by water erosion, 13 M ha by wind erosion, 3 M ha by fertility decline, 6 M ha by water logging, 7.5 M ha by salinization (Table 2.8). Such a deforestation trend in the world indicates that global climate will become warmer in the near future, due to increasing CO_2 concentration in the atmosphere. Many of these soils do not support any kind of vegetation except some perennial bushes and grass, which grow during the monsoon period. Wastelands, being extremely C depleted, have a relatively high potential for accumulating C in vegetation and soil if suitable trees and grass/crop species are grown, along with proper soil management practices.

Table 2.8 Categories of land under different types of wasteland in India

Number	Category	Ares (million hectares)
1	Water eroded	73.60
2	Degraded forest	40.00
3	Riverine	2.73
4	Ravines and gullies	3.97
5	Shifting cultivation	4.36
6	Sand dunes	7.00
7	Water logged	6.00
8	Saline/alkaline wasteland	7.50
9	Wind eroded	12.90
	Total	158.06

Source: Jha (1995)

Establishing permanent vegetative cover of trees and herbaceous plants on waste land will add to the SOC levels in the soil and reduce C loss through decomposition by moderating the temperature.

For example, one hectare of new forest will sequester about 6.2 tons of C annually, whereas 118 million ha wastelands as reported by Sehgal and Abrol (1994) have the potential to sequester nearly 1165 million tons of C annually. Lal (2004) computed carbon sequestration potential of Indian soils by assuming converting degraded soils to restorative land use and estimated total potential of 39 to 49 (44 ± 5) Tg C year^{-1}. According to him, Indian soils have considerable potential of terrestrial/soil carbon sequestration. They estimated the soil organic carbon (SOC) pool of 21 Pg to 30-cm depth and 63 Pg to 150-cm depth. The soil inorganic carbon (SIC) pool was estimated at 196 Pg to 1-m depth. The SOC concentration in most cultivated soils is less than 5 g/kg compared with 15–20 g kg^{-1} in uncultivated soils. Low SOC concentration in soil is attributed to plowing, removal of crop residues and other bio-solids and mining of soil fertility. Accelerated soil erosion by water leads to emission of 6 Tg C year^{-1}. Important strategies of soil C sequestration include restoration of degraded soils and adoption of recommended management practices (RMPs) of agricultural and forestry soils. Potential of soil C sequestration in India is estimated at 7–10 Tg C year^{-1} for restoration of degraded soils and ecosystems, 5–7 Tg C year^{-1} for erosion control, 6–7 Tg C year^{-1} for adoption of RMPs on agricultural soils, and 22–26 Tg C year^{-1} for secondary carbonates.

2.10 Strategies to Enhance SOC

Strategies for enhancing the productivity of rainfed crops and cropping systems and storage of SOC on sustainable basis are as follows:

1. Correction of limiting nutrient(s) including micronutrients and site-specific nutrient management approach in rainfed areas can help in augmenting the productivity.
2. Inclusion of short duration legumes in cropping systems.
3. Green leaf manuring with the help of nitrogen fixing trees like Gliricidia and leucaena and off-season biomass generation and its incorporation.
4. Recycling and enhancing the quality of organic residues using effective composting methods.
5. Capitalization of the potential of microbes/bio-fertilizers.
6. Linking agricultural practices with short and long-term climatic forecast.
7. Adoption of site-specific soil and water conservation measures.
8. Appropriate crops and cropping systems for wider climatic and edaphic variability.
9. Enhancing the input use efficiency using the principle of precision agriculture.
10. Diversified farming systems for enhanced income and risk mitigation.
11. Ensuring credit, market access and crop insurance.
12. Controlling top soil erosion.
13. Conservation tillage (specially reduced and zero tillage) and surface residue management, mulching, etc.
14. Balanced and adequate fertilization and integrated nutrient use.
15. Carbon sequestration through agro-forestry tree species and its recycling by leaf litter fall.
16. Use of soil amendments.
17. Regular use of manures.

2.11 Future Research

Central questions that need to be addressed in the era of global warming revolves around (1) the temperature sensitivity of soil OM, especially the more recalcitrant pools; (2) the balance between increased carbon inputs to the soil from increased production and increased losses due to increased rates of decomposition; and (3) interactions between global warming and other aspects of global change including other climatic effects (e.g., changes in water balance), changes in atmospheric composition (e.g., increasing atmospheric CO_2 concentration) and land use change. A number of possible technologies to mitigate the worst impacts of climate change are available, mainly in managed systems. These technologies, which promote soil carbon stabilization and sequestration, will also help mitigate climate change itself (by reducing atmospheric CO_2 concentrations) and are cost competitive with mitigation options available in other sectors. Some warming will occur and it is important that humans adapt management practices to cope with this change, but soils also provide a great opportunity, along with a raft of other measures, to slow that rate of warming. Identifying the "win–win" options that deliver both adaptation and mitigation and finding ways to implement these measures, remains one of our greatest challenges for this century.

References

Baldock J (2008) Soil carbon in a carbon trading framework. Presentation to GRDC Soil Carbon Workshop, Melbourne July, 2008

Bhadoria PBS, Prakash YS, Kar S, Rakshit A (2003) Relative efficacy of organic manures on the performance of rice in a lateritic soil. Soil Use Manag 19:80–82

Ghosh A, Bhattacharyya R, Agarwal BK, Mahapatra P, Shahi DK, Singh G, Agnihorti R, Sawlani R, Sharma C (2019) Long-term fertilization effects on 13C natural abundance, soil aggregation and deep soil organic carbon sequestration in an Alfisol. Land Degrad Dev 30:391–405

Ingram JSI, Fernandes ECM (2001) Managing carbon sequestration in soils: concepts and terminology. Agric Ecosyst Environ 87:111–117

IPCC (1996) Intergovernmental Panel on Climate Change, climate change 1995, scientific technical report analyses, contribution of working group II to the second assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 880

IPCC (2007) The physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Jha LK (1995) Advances in agroforestry. Aph, New Delhi

Joshi SK, Bajpai RK, Kumar P, Tiwari A, Bachkaiya V, Manna MC, Sahu A, Bhattacharjya S, Rahman MM, Wanjari RH, Singh M (2017) Soil organic carbon dynamics in a Chhattisgarh vertisol after use of a rice–wheat system for 16 years. Agron J 109:2556–2569

Lal R (2004) Soil carbon sequestration in India. Clim Chang 65:277–296

Manna MC, Rao AS (2012) Impact of land use management on soil organic carbon dynamics. In: Singh AK, Ngachan SV, Munda GC, Mohapatra KP, Choudhury BU, Das A, Srinivasa RC, Patel DP, Rajkhowa DJ, Ramkrushna GI, Panwar AS (eds) Carbon management in agriculture for mitigating greenhouse effect. The Director, ICAR Research Complex of NEH region, Umiam, Meghalaya, India, pp 83–101

Manna MC, Swarup A, Wanjari RH, Singh YV, Ghosh PK, Singh KN, Tripathi AK, Saha MN (2006) Soil organic matter in a West Bengal inceptisol after 30 years of multiple cropping and fertilization. Soil Sci Soc Am J 70:121–129

Manna MC, Swarup A, Wanjari RH, Mishra B, Shahi DK (2007) Long-term fertilization, manure and liming effects on soil organic matter and crop yields. Soil Tillage Res 94:397–409

Manna MC et al (2012) Soil organic matter status under different agro-climatic regions of India. Sci Bull 2012:1–60

Manna MC, Bhattacharyya P, Adhya TK, Singh M, Wanjari RH, Ramana S, Tripathi AK, Singh KN, Reddy KS, Rao AS, Sisodia RS (2013a) Carbon fractions and productivity under changed climate scenario in soybean–wheat system. Field Crop Res 145:10–20

Manna MC, Kundu S, Mohanty M (2013b) Dynamics of soil carbon pools and carbon sequestration. In: IISS contribution in frontier areas of soil research. IISS, Bhopal, pp 47–64

Manna MC, Rahman MM, Naidu R, Sahu A, Bhattacharjya S, Wanjari RH, Patra AK, Chaudhari SK, Majumdar K, Khanna SS (2018) Bio-waste management in subtropical soils of India: future challenges and opportunities in agriculture. Adv Agron 152:87–148

Neogi S (2014) Soil respiration, labile carbon pools and enzyme activities as affected by tillage practices in a tropical rice–maize–cowpea cropping system. Environ Monit Assess 186:4223–4236

Parton WJ, Schimel DS, Cole CV, Ojima DS (1987) Analysis of factors controlling soil organic matter levels in Great Plains Grasslands 1. Soil Sci Soc Am J 51:1173–1179

Pathak H, Jain N, Bhatia A, Mohanty S, Gupta N (2009) Global warming mitigation potential of biogas plants in India. Environ Monit Assess 157:407–418

Rabbinge R, van Ittersum MK (1994) Tension between aggregation levels. In: Fresco LO, Stroosnijder L, Bouma J, van Keulen H (eds) The future of the land: mobilising and integrating knowledge from land use options. Wiley, Chichester

Sehgal JL, Abrol IP (1994) Soil degradation in India-status and impact. Oxford and IBH Publishing Co Pvt. Ltd, New Delhi

Shekdar AV (2009) Sustainable solid waste management: an integrated approach for Asian countries. Waste Manag 29(4):1438–1448

Swarup A, Manna MC, Singh GB, Lal R (2000) Impact of land use and management practices on organic carbon dynamics in soils of India. Glob Clim 2000:261–282

van Ittersum MK, Rabbinge R (1997) Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crop Res 52:197–208