Santanu Kumar Bal · Joydeep Mukherjee
Burhan Uddin Choudhury
Ashok Kumar Dhawan *Editors*

Advances in Crop Environment Interaction

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Preface

Agriculture is facing multifaceted threats from unpredictable weather variability, frequent drought occurrence, irrigation water scarcity, degradation of soil resources, and environmental health. These stresses result in modification of plant physiology to impart responses to the changing abiotic and biotic environments, only at the cost of decline in the ability of plant productivity. Given these facts, assessing the status of natural resource base and understanding the soil-plant-environmental interaction mechanisms for devising adaptation and mitigation approaches are of great and imminent challenges for all of us. In this context, it is essential to understand potential applications of modern tools and existing coping mechanisms and their integration to develop advanced mitigation strategies. In a broader perspective, the proposed book deals with crop environment interactions in the pretext of changing climatic conditions.

This book tries to bring answers in four major theme areas such as the following:

Understanding the mechanism of carbon dynamics in soil-plant-environmental continuum, greenhouse gas fluxes in agriculture systems, soil properties influenced by climate change, and carbon sequestration processes
Mitigation and management of photothermal environment for improving crop productivity, soil health under variable climate, agro-ecosystem evapotranspiration losses through biophysical controls, and heat stress in field crops and its management
Studying the impact of climate change on biotic environments, insect-pest interaction, manifestation of diseases, and adaptation strategies for island agro-ecosystem
Innovative approaches for assessing stress impacts in crops such as crop modeling, remote sensing, and spectral stress indices.

This book is a collection of contribution from the authoritative experts in their respective fields, provides a perspective to young researchers and opens up new avenues of work in the respective fields, and will be useful for different stakeholders, including postgraduate students and other academicians as well.

We are extremely thankful to all the contributors for their efforts in providing comprehensive and coherent reviews. We are also thankful to Indian Ecological Society for providing language editing services. We sincerely appreciate Team Springer especially RaagaiPriya ChandraSekaran and Aakanksha Tyagi for providing technical support in this publication.

Hyderabad, India

Santanu Kumar Bal
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Part I

Understanding the Process of Interaction

Carbon Dynamics in Soil-Plant-Environment System on Climate Change Perspective: Special Reference to Rice

1

P. Bhattacharyya, P. K. Dash, C. K. Swain, A. K. Nayak, D. Chatterjee,
S. R. Padhy, R. Saha, and D. Barman

Abstract

Carbon is the backbone of life. It is present in the atmosphere, oceans, soils and earth's crust and basically divided into five pools. In this chapter, we have tried to find a link of carbon dynamics in soil-plant-environment system and climate change by keeping in mind the major food crop of India, rice. Climate changes have direct as well as indirect influence on dynamics of soil organic carbon (SOC) and its degradation kinetics that contribute to global warming. In future climatic scenario, there is an opportunity to increase carbon assimilation and carbohydrate accumulation in rice under elevated carbon dioxide (CO_2) environment. Again, temperature moderates the carbohydrate allocation in plant and significantly affects the growth of crop. Moreover, under changing climatic scenario, methane emission may become an important driver because of higher belowground carbon allocation. Therefore, enhancing carbon sequestration, growing of rice with low carbon footprint and soil management for controlling different pools of SOC could be some of the emerging approaches which are discussed thoroughly in this chapter.

Keywords

Climate change · C dynamics · C sequestration · Rice ecosystem

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1.1 Introduction

In last four decades, concern of global carbon (C) cycle increased dramatically because of significant anthropogenic effect on changes in C cycle. Moreover, the topic received higher importance when researches showed that ice core and ocean core sediments have much higher carbon dioxide (CO_2) concentrations than previous times. Spikes also found in core samples CO_2 concentrations which have not been recorded since the last 650,000 years. Global CO_2 concentrations have increased by 37%, from ~275 ppm in the preindustrial era (1000–1750 AD) (Nieder and Benbi 2008) to 395 ppm in 2017. Anthropogenic activities like fossil fuel burning and land use change contributed heavily to C release to the atmosphere. The primary components of ecosystem CO_2 exchange and global C cycle could be listed as oceans, soils, fossil fuels and vegetation. Photosynthesis, respiration, organic C decomposition and mass transfer between air and water are the major pathways through which C is introduced and or removed from atmosphere. Carbon accounts for around 40% of dry biomass in Earth's crust (Houghton 2007) and 0.27% of the mass of elements. In vegetation, forests are one of the biggest reservoir of C as trees hold a larger amount of C per unit area. The oceans have nearly 50 times more C than the atmosphere (approximately 38,000 Pg C; Lal 2003). Majority of those are present in intermediate-deep waters, and around 700–1000 Pg C in the surface ocean have direct contact with atmosphere (Nieder and Benbi 2008). Ocean sediments contained about 6000 Pg of reactive C, important in long-term C fluxes. The primary contributor of excess C in the atmosphere was fossil fuel burning, adding 8.5 Pg C to the cycle every year. Oceans, vegetation and soils were considered as net C sinks with 26.98, 22.22 and 1.59% C sequestration status, respectively. The remaining 50.79% of excess C from fossil fuel burning primarily is responsible for increasing atmospheric C by ~3.2 Pg per year (IPCC 2007, 2014).

On the other hand, soil C represents the largest C reservoir in terrestrial ecosystems (Houghton 2007). It is twice as large as the vegetation C reservoir and has relatively low residence time. Therefore, soil C is becoming the nodal point for scientific research in global C cycle. As annual exchanges of CO_2 from soils to atmosphere are slightly less than that of oceans-atmosphere, slight increases or decreases in net CO_2 exchanges from soils could have a significant effect on atmospheric CO_2 status (Amundson 2001). Soils have huge C sink potential and to mitigate climate change. The predicted C storage by 2050 across the Great Plains region in the central part of the United States is around 2.2–2.7 Pg C. Moreover, it was concluded that C sequestration primarily through increase in soil C and 47% of all land in Great Plains was considered agricultural land.

It is also well recognized that SOC is the single most important indicator of soil quality assessment (Shukla et al. 2006). Soil quality refers to 'the capacity of a soil to function'. In agriculture, it signifies the capacity to sustain and/or enhance biomass production to provide healthy and inexpensive food and fibre to consumers. Therefore, not only the environmental point of view, SOC plays a dominant role in C cycling, soil health and production sustainability.

1.2 Carbon Cycling in Soil, Plant and Environment

Carbon is present in the atmosphere, oceans, soils and Earth's crust. It is present in the systems of plant, animal and any form of the living organism representing different C pools. Any movement of C among these pools is known as a flux. The combination of different C pools connected with the flux directions generates the carbon cycles (Fig. 1.1). The C in the atmosphere (as CO_2) is used by autotrophs in photosynthesis in the presence of sunlight and stabilized it in the form of glucose. This process transfers considerable proportion of C from atmospheric pool to biotic pool. Autotrophs like plants are consumed by animals. Over the time, these plants and animals die, respire and decay; the carbon will be released back to the atmosphere. In the same way many individual carbon cycles are linked among the pools, which integrally form global carbon cycle.

Global C pools are subdivided into five major pools (Fig. 1.2, Lal 2008a, b). Among them, oceanic pool is the largest (estimated as 38,153 Pg), in which surface ocean contributes 900 Pg, intermediate and deep ocean contributes 37,100 Pg, surface sediments contribute 150 Pg and marine biota contributes 3 Pg C. The second largest pool is the geological C pool which is estimated about 4130 Pg. This pool comprises fossil fuels of which 84.99% is coal, 5.57% is oil, 3.39% is gas and 6.05% is others (Lal 2008a, b). However, this C pool is reducing at the rate of 7.0 Pg

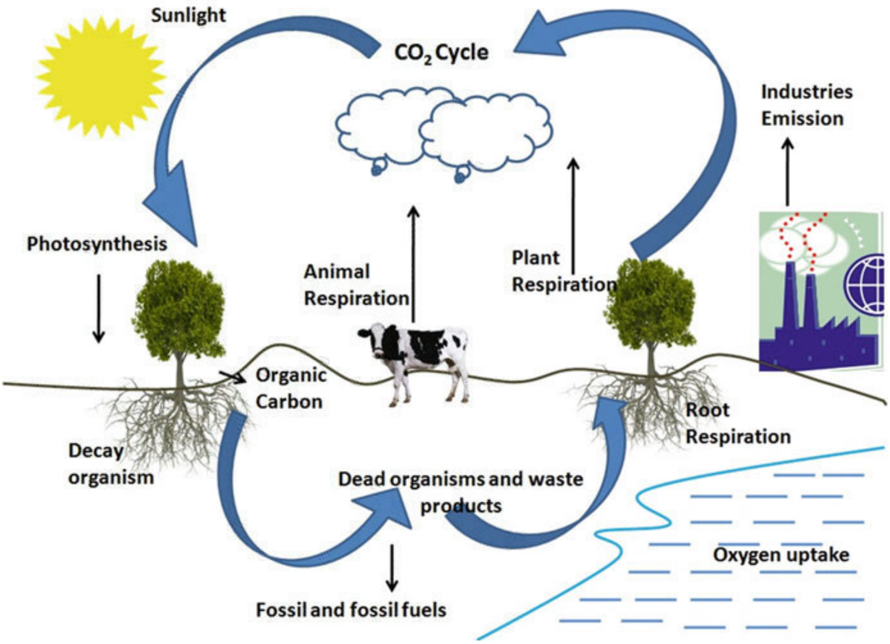

Fig. 1.1 Simplified carbon cycle in soil, plant and atmosphere

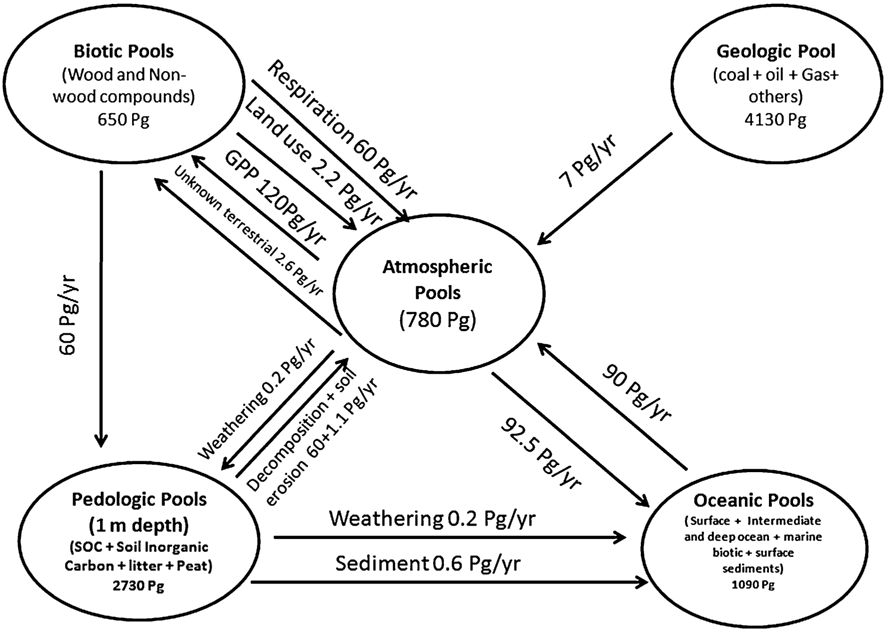

Fig. 1.2 Dynamics of global carbon pools (Note: Source, Lal 2008a, b)

year^{-1} by fossil fuel burning (Bandyopadhyay 2012). Pedologic pool is considered as the third largest, that is, around 2730 Pg up to 1 m depth. This pool includes four components: SOC (1550 Pg), soil inorganic carbon (SIC; 950 Pg), litter (40–80 Pg) and peat (150 Pg, Lal 2008a, b). The largest terrestrial C pool is SOC which plays a nodal role in C cycle and, thus, is considered as the most vital pool for global climate change. Carbon is taken out in the form of CO_2 from the atmosphere by plant during photosynthesis. The C, thus assimilated by plants, is transferred back to soil in the form of dead residues. Recycled residues act a substrate for soil biota which decomposes those and CO_2 and CH_4 become back to atmosphere through respiration. The SIC pool consists of calcite, dolomite and gypsum (carbonates of minerals), elemental C and also primary and secondary carbonates (Bandyopadhyay 2012). Atmospheric pool is the fourth largest pool (780 Pg) increasing at the rate of 4.1 Pg year^{-1}. The biotic pool is the least (500–650 Pg) among the global C pools. The terrestrial C pool is the sum of the pedologic and the biotic C pools. There is more interaction in between the terrestrial and the atmospheric pools (Fig. 1.2). The annual rate of global primary production (GPP) is 120 Pg, while the respiration is 60 Pg of C, land use conversion (1.1–2.2 Pg year^{-1}), decomposition (60 Pg year^{-1}) and soil erosion (1.1 Pg year^{-1}) are responsible for depletion of terrestrial C and at the same time enrichment of the atmospheric C pool. The fossil fuel (coal, oil, gas, etc.) combustion depletes the geologic C pool and enriches the atmospheric pool at the annual rate of 1.5–3.0 Pg carbon. However, the terrestrial C sink is increasing at the rate 2–4 Pg year^{-1} and might increase at 5 Pg year^{-1} by 2050 (Bandyopadhyay 2012).

1.3 Soil Carbon Dynamics

The easy approach to understand soil C dynamics is to understand the pools of organic C on the basis of susceptibility to microbial decomposition and their interactions. All the pools of soil C are present in dynamic equilibrium with different residence time. Their turnover rate depends on their chemical structure, environmental constraints and ambient physical conditions. A flow chart (Fig. 1.3) can precesily represents, such C pools in soil-plant system and their dynamics is presented in Fig. 1.3. Plant residues contain metabolic C, viz., proteins, sugar and starches are readily metabolized by microbes. And structural plant C, mostly present in lignin, cellulose, polyphenols and waxes are resistant to microbial decomposition. In general, an active, slow and passive fraction of organic C together represents total organic C pools in soil.

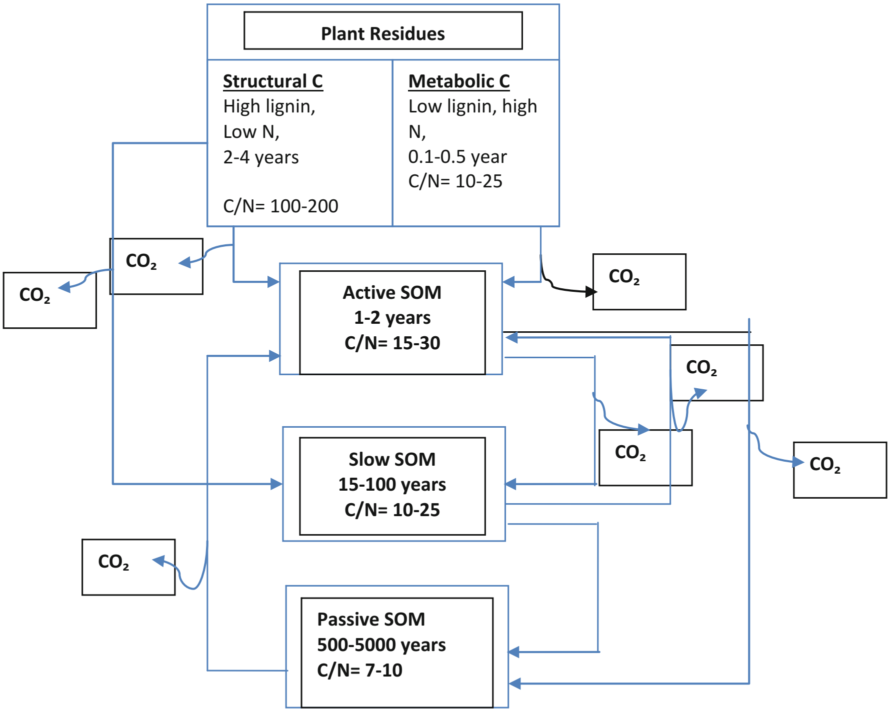

Fig. 1.3 Conceptual model of different pools of SOC and their interactions

1.3.1 Active Fractions/Pools of Soil Organic Carbon

Active pools of SOC represent the materials with a relatively high C/N ratio (~15–30) and short half-lives (few months to few years). Living biomass, fine particles of detritus, polysaccharides and few non-humic substances are the components of this pool. This provides readily available substrates for soil micro-organism and readily mineralizable nitrogen. Beneficial effects of these pools include structural stability of soil which leads to enhancement of water infiltration, easy tilling and reduced erosion. Although this fraction can be readily replenished by addition of organic matter and residues, this could easily be lost also through tillage and intensive cropping. It contributes about 10–20% to total organic C.

1.3.2 Passive Fractions/Pools of Soil Organic Carbon

Passive fraction of SOC represents the stable substances remaining in soil for hundreds to thousands years. The primary components of these fractions are humus, clay-humus complexes, humin and majority of humic acids. These pools accounts for 60–90% of the organic C in majority of soils and decompose very slowly. As an integral part it influences the colloidal properties of soil humus, cation exchange capacity and water holding capacity of soil.

1.3.3 Slow Fractions/Pools of Organic Carbon

Slow fraction of SOC has intermediate properties of active and passive C pools. These pools primarily include slowly decomposable and chemically resistant particles and finely divided plant tissues having high lignin content. Half-lives of these C pools are in decades. The slow fraction is an important source of available plant nutrients. It also provides the food source for steady metabolism of the autochthonous soil microbes.

1.4 Effects of Soil Management on Active and Passive Fraction/Pools of SOC

Soil analytical methods only evaluate chemical or physical fractions of soil organic carbon that approximate the functionally defined fraction/pools: passive, slow and active. Conservation-oriented practices and conservation agriculture facilitate high proportion of active-fraction components as microbial biomass and oxidizable sugars. Despite the analytical difficulties, models which assume the existence of these three pools could able to explain and predict precise changes in SOC levels and associated soil properties. Researches on dynamics of SOC have proved that the different pools of SOC play quite different roles in the system and in C cycle. Soil management practices that cause only small changes in total organic carbon (TOC) often cause rather pronounced alteration in aggregate stability and nitrogen mineralization. This is because of greater sensitivity of active C pools than passive pools in soil to management practices.

1.5 Stability and Degradation Kinetics of Soil Organic Carbon

Stability and decomposition of soil organic matter (SOM) in general and SOC in particular depend primarily on chemical structure of SOC, ambient temperature and moisture conditions. The temperature sensitivity of global C stocks decomposition is the key issue of present day because of its influence on global carbon (C) cycle and climate change feedbacks. Stability of SOC varied among the ecologies. Upland soils having better drainage and aeration facilitate roots and fauna to penetrate deep into lower soil horizons and enhance mixing of mineral particles with SOC favourable for decomposition. Therefore, relatively low C densities are generally observed in upland mineral soils. On the other hand, decomposition rates much slower in wet and peatlands where anaerobic conditions prevail accumulate higher organic C on top of soil layers.

1.6 Drivers of Soil Organic Carbon Decomposition

Balance of inputs and outputs of C in belowground regulates the organic C stocks in soils. Leaf and root detritus are the primary inputs, whereas effluxes of CO_2 from soil surface are the dominant output. Other two important outputs are hydrological leaching of dissolved and particulate C compounds and CH_4 efflux. Rhizosphere respiration and microbial decomposition of SOC represent the majority of CO_2 production from soils. These processes are primarily temperature-dependent. Water status also considerably regulates root respiration and microbial decomposition. Hence, efflux of CO_2 from soils is mostly related to soil temperature and moisture in simulation models. The kinetics of enzymatic reactions and activation energies are also closely related to molecular structure of the SOC and ambient temperature. The temperature sensitivity of decomposition of SOC enhances with increasing molecular complexity of the substrate. Substrate concentrations and affinities of the enzymes to the substrates also modified the rate of reactions.

Soils contain different organic C compounds having their own different inherent kinetic properties. Plants along with detritus that undergo transformations by microbial decomposition produce a wide range of C substrates. Abiotic condensation reactions generate/synthesize new aromatic structures having larger molecular weights, insolubility, which affect the rate and efficacies of enzymatic degradation. Complex molecular structures are characterized by high activation energies, inherently high-temperature sensitivity and low decomposition rates. The 'intrinsic temperature sensitivity' of SOC primarily depends on inherent kinetic properties based on molecular structure and ambient temperature of the substrates.

However, physical or chemical exclusion of the organic C substrates from microsites of enzymatic reaction by environmental constraints causing substrate limitation to reaction. In those environmental constraints, the observed response of SOC to temperature is referred to as 'apparent temperature sensitivity', which may be much lower than that of intrinsic temperature sensitivity. Conversely, removal of 'environmental constraint to decomposition' leads to increase in substrate availability that could result in higher apparent temperature sensitivity than intrinsic temperature sensitivity of the substrate temporarily. The environmental constraints include physical, chemical protection, drought, flooding, freezing, etc.

1.6.1 Arrhenius Equation and Michaelis-Menten Kinetics

Temperature coefficient, Q_{10}, refers to the factor at which the rate of reaction increases with 10 °C rise in temperature as given by van't Hoff. Temperature sensitivity of soil respiration also could be explained by that. Relative reaction rates as a function of temperature (Arrhenius equation, Eq. 1.1):

$$k = \mathrm{A}\exp\left(-\mathrm{Ea}/(\mathrm{RT})\right) \tag{1.1}$$

where A is the frequency factor, k is the reaction rate constant, Ea is the activation energy in joules mole^{-1}, $\mathrm{R} = 8.314\ \mathrm{JK}^{-1}\ \mathrm{mol}^{-1}$ gas constant and T is the temperature.

Recalcitrant SOC with complex molecular attributes (adsorbed/complexed SOC) has high activation energies, low decomposition rates and 'inherently' high-temperature sensitivity. Activation energy is a function of ambient temperature and molecular characteristics of the organic C compound (Davidson and Janssens 2006). There is a declining relative increase in the fraction of molecules with sufficient energy to react with increasing temperature, which leads to decrease in the Q_{10} values (Davidson and Janssens 2006; Tjoelker et al. 2001). That is why the highest temperature sensitivities of SOC are observed in colder regions where C stocks are also found to be largest (Post et al. 1982; USDA 2000). The Arrhenius function also shows that the temperature sensitivity of decomposition increases with increasing stability of organic compounds because stabilized substrates are less reactive due to higher activation energies. This means that the stable pool is more temperature-sensitive than the labile pool, which is characterized by low activation energies.

The application of Arrhenius kinetics is limited under conditions of low substrate availability. As described by Michaelis-Menten kinetics (Eq. 1.2), the reaction rates are further modified by substrate concentrations [S] and affinities of the enzymes for the substrates Km:

$$k = \mathrm{Vmax}^{*}\,[\mathrm{S}]/(\mathrm{Km} + [\mathrm{S}]) \tag{1.2}$$

where k is the reaction rate; Vmax is the maximal rate of enzymatic activity at a given temperature; Km is the Michaelis-Menten constant, representing the affinity of enzymes for the substrates expressed as substrate concentration at which the reaction rate equals Vmax/2; and [S] is the substrate availability (substrate concentration at active site of the enzyme).

Substrate availability is directly affected by stabilization of organic compounds (e.g. by interaction with mineral surfaces and metal ions, spatial inaccessibility due to aggregation and hydrophobicity (Sollins et al. 1996; Von Lützow et al. 2006)) or indirectly by external control factors (e.g. water, oxygen and nutrient supply, temperature, pH) that restrict decomposition. *In situ* temperature-insensitive processes such as seasonal litter fall, drying-rewetting and tillage alter the release of easily decomposable substrates.

1.6.2 Cancelling Effects

Michaelis-Menten constant becomes insignificant, and the temperature response of Vmax determines the decomposition rate when substrate is abundant and larger than Km and the temperature does not exceed the optimum temperature. However, Km becomes relevant when substrate availability is low, and the decomposition rate depends on the enzyme as well as on the substrate concentration. Temperature sensitivities of Vmax and Km can neutralize each other (Davidson et al. 2006), because those increase with temperature (Arrhenius 1889). This ‘cancelling effect’ is significant when substrate concentration is low or lower than Km and if both Km and Vmax have similar temperature sensitivities (Larionova et al. 2007). Respiration is controlled by temperature-sensitive processes which alleviate substrate limitation (e.g. decomposition of recalcitrant SOC pools) and produces available substrate when Vmax and Km cancel each other out.

The cancelling effect could be important for controlling the ‘actual’ in situ temperature sensitivity in soils as most soils are C-limited (Ekschmitt et al. 2005). However, cancelling effect is generally short-lived as the time delay between Vmax and Km changes is significant.

1.7 Plant Carbon: Partitioning and Allocation

Carbon allocation refers to the distribution of C (photosynthetic assimilates) throughout the plant body. Carbon allocation is an adaptive response to resource stress. The term C partitioning means the division of C (photosynthetic assimilates) into metabolic, structural or storage pools (Caraballo and Earnshaw 2014). In majority of cereals including rice, C partitioning occurs due to loading of sucrose (Suc) into the phloem, delivering it to sink tissues from source tissues (van Bel 2003). The gene ‘Suc transporters’ (*SUTs*) regulates the loading of sucrose into the phloem (Lalonde et al. 2004; Sauer 2007).

Under the elevated CO_2 environment, there is an increase in C and carbohydrate assimilation within the source, i.e. leaves of C_3 plants (like rice). The changes in CO_2 concentration also lead to changes in the partitioning of biomass between shoot and root. An experiment in open-top chambers showed CO_2 elevation (650 μmol Mol^{-1}) enhanced rice tillering in early vegetative stage, but panicle dry weight $plant^{-1}$ did not change at maturity. Root biomass was improved in elevated CO_2. In elevated CO_2, root/shoot ratio also increased at maturity, signifying higher C allocation to the belowground portion in rice under elevated CO_2 (Weihong and Dali 1998).

Temperature has significant influence on the development and growth of plants by changing the carbohydrate allocation within its different parts. Elevated temperatures significantly decreased carbohydrate assimilation within the source and sink parts of plants (Farrar and Williams 1991). Higher temperature would also trigger sucrose synthesis and decrease carbohydrate accumulation in leaf (Farrar and Williams 1991).

Experiments on the interaction between temperature and CO_2 showed an increase in biomass production in different C_3 grasses and rice at elevated temperatures and CO_2 (Lilley et al. 2001; Morgan et al. 2001; Roy et al. 2012). Moreover, regulation of photosynthesis, P uptake-utilization and sucrose-P synthase in rice were observed under elevated temperature and CO_2 (Sujatha et al. 2008; Bhattacharyya et al. 2013).

1.8 Environment Carbon

The net ecosystem exchange of CO_2 is the balance between fluxes of atmosphere and biosphere. It is associated with photosynthetic assimilation and respiratory effluxes from autotrophs and heterotrophs. The net budget between production and emission determines the nature of the system, whether a sink or a source of CO_2. However, meteorological variability and physiological activities of crop influence the temporal variations of ecosystem CO_2 exchange. Soil respiration is an integrated reporter of ecosystem functioning that represents the major pathway of C emission from terrestrial ecosystem (Mills et al. 2011). Soil respiration is critical as a small change of its rates could significantly regulate atmospheric CO_2 concentrations and soil C sequestration. Soil CO_2 emission integrates the components of soil CO_2 production, rhizospheric respiration as well as soil microbial respiration in soil-plant systems. Variations in soil respiration, i.e. soil CO_2 fluxes, are also influenced by agronomic practices. Agricultural operations affect soil CO_2 flux by altering soil environment like soil pH, temperature, moisture, aeration, C/N ratio of substances, etc. These have significant effect on soil microbial activities and SOC decomposition instrumental for transforming plant-derived C to SOC and CO_2.

1.9 Methane Emissions from Rice Fields

Rice production systems are known to be an important anthropogenic source for CH_4 and contribute around 20 Tg CH_4 annually to global budget (Houghton 1996; IPCC 2014). Intensive rice cultivation in ecologically fragile ecosystem is anticipated to increase CH_4 emission in coming decades. *Rainfed* upland, *rainfed* lowland and irrigated land, representing about 15, 40 and 45% of total rice grown area in our country. Approximately, 48% of Indian rice area is irrigated. Flooded rice fields are the potent sources of CH_4 as well as can also act as sink for C (Bhattacharyya et al. 2014a, b). The source and sink capacity entirely depends on field management practices. Methane is predominantly emitted to the atmosphere through rice plant via aerenchyma pore spaces. Well-oriented aerenchyma tissues provide good conduit to CH_4 emission. Root exudation, nutrient supply and root oxidase activities also regulate the budget of CH_4 in rice field. Submergence/ flooding, methanogenic activities and C status of soils also affect the CH_4 emission from rice production systems.

1.10 Carbon Sequestration

Soil C sequestration primarily refers to accumulation/ transferring of atmospheric CO_2 into soil C pool with high residence time and storing it through judicious land management and cropping practices. The process of C sequestration involved both organic and inorganic C. Broadly, this is the process of transferring CO_2 from the atmosphere into the soil through crop residues, organic solids and other means in such a form so that it is not lost in short period of time.

1.11 Mechanism of Carbon Sequestration

1.11.1 Physical

The organic matter per se carbon may be protected from enzymatic degradation by sequestration within mineral mesopores (2–50 nm diameter), which is postulated under ‘mesopore protection hypothesis’ (Wang et al. 2003; Mayer et al. 2004). The tortuous porosity of mesopore hinders the oxygen to reach to the stored C, which may involve in low C accessibility to microorganisms and reduce microbial respiration.

Some short-range ordered minerals like allophane also protect C physically which is attributed to its peculiar structure analogous to a natural gel (Woignier et al. 2006). In the aggregates, SOC is also protected in microaggregates and mesoaggregates. Sometimes addition of OM decreases in permeability and few pore spaces being occupied by OM itself. Those subsequently facilitate the creation of inaccessible microporosity (Curry et al. 2007). Those physical protections of SOC prevent easy decomposition by inhibiting enzymatic breakdown (Rothman and Forney 2007).

1.11.2 Chemical

Chemical stabilization of SOC is related to the formation of organo-mineral (MIN-SOM) complexes (Basile-Doelsch et al. 2005; Mikutta et al. 2005; Broquen et al. 2005; Wiseman and Püttmann 2006) and organometallic (Al/Fe-SOM) complexes formed with aluminium and iron ions (Wiseman and Püttmann 2006; Egli et al. 2008; Chatterjee et al. 2013). Sorption plays an important role in SOC protection (Wiseman and Püttmann 2006). The organo-mineral complex is produced by the large number of valence-unsatisfied hydroxyl groups of these Al, Si and Fe hydroxides, which have the ability to adsorb ions and compounds of opposite charge specifically (Shoji et al. 1993; Mikutta et al. 2005), and the mechanism is the linking of SOM to clay particle through polyvalent cations and represented as [(Clay–P–SOM)x]y, where x and y are whole integers depending upon the size of primary clay particles (Manjaiah et al. 2010). Some other mechanisms like ligand exchange, coulombic attraction, van der Waals forces, polyvalent cation bridging with or without mediation by hydration water or hydrogen bonding, water bridging, etc. are also involved (Theng et al. 1986; Theng and Tate 1989). Both organo-mineral and organometallic complexes are very stable C reservoirs. This is primarily due to the toxic effect that aluminium has on soil microbes and also allow limited accessibility to enzymes, that protects the organic compounds from mineralization, by making the mean residence time of organic C very high (Basile-Doelsch et al. 2005).

1.12 Soil Processes Affecting C Sequestration

1.12.1 Aggregation

An aggregate consists of an assemblage of a number of primary particles (sand, silt and clay) into a secondary unit. Soil aggregates are formed by the combination of mineral particles with either organic or inorganic binding agents or both, which are the secondary soil particles (Bronick and Lal 2005). The formation of soil aggregates involves several factors such as microorganisms, vegetation, soil fauna, clay-clay interactions, clay-organic interaction and impact of cations (Baver and Gardner 1972). Stable microaggregates increased by the production of organo-mineral complexes, which encapsulates C and protects it against microbial activities (Kumar et al. 2013).

1.12.2 Secondary Carbonates Formation

In this process, the atmospheric CO_2 is chemically transformed into mineral carbonates like $CaCO_3$, $MgCO_3$ and other minerals which are geologically and thermodynamically stable (Lal 2008a, b). This process involved two stages, i.e. scrubbing and mineral carbonation. In scrubbing process, first CO_2 is absorbed in an amine or carbonate solvent. Then pure CO_2 gas is re-precipitated through

Table 1.1 Estimate of C sequestration through formation of secondary carbonates

Eco region	Land area (billion ha)	Potential rate (kg ha^{-1} year^{-1})	Total potential (Pg C year^{-1})
Arid	2.55	0–1	0–0.0026
Semiarid	2.31	3–114	0.0069–0.2633
Subhumid	1.30	1–124	0.0013–0.1599

mineral carbonation through heating the CO_2-rich amine. Finally stable rock carbonates are formed in which CO_2 is sequestered forever. For example, the formation of magnesite ($MgCO_3$), olivine (Mg_2SiO_4) and serpentine ($Mg_3Si_2O_5(OH)_4$) through the aqueous mineral carbonation reactions is as follows (Gerdemann et al. 2003). An estimate of C sequestration through formation of secondary carbonates is given in Table 1.1 (Rosenberg and Izaurralde 2013).

1.12.3 Humification

Humification process refers to the alteration of residues of plant and animal origin into a stable and recalcitrant end product in the form of complex humic substance. Carbon is an important building block needed for this conversion, but simultaneously this process requires equivalent quantity of N, P, K, S and other nutrients. To sequester 10,000 kg of C in humus, there is a requirement of 833 kg of N, 200 kg of P and 143 kg of S (Himes 1998). Therefore, quality and fertility of soil and the interaction of soil with C inputs may strongly control the sequestration of C (Canadell et al. 1996). Thus, the application of organic manure and the land use system determine the amount of C stored in soils and the rate at which this storage could happen. If the applied organic matter contains less N, P and S per molecule of C, i.e. much higher C:N:P:S ratio, then there will be the requirement of additional mineral fertilizers which allow the formation of new fine fraction of soil organic matter that improves the humification efficiency of soil organic matter (Kirkby et al. 2013, 2014).

1.12.4 Translocation and Transportation

Translocation of eroded soil organic matter into the subsoil may promote carbon sequestration. Transport of soil organic matter-enriched sediments into protected areas of the landscape (like subsoil) and to depression sites and/or aquatic ecosystems protects the loss of carbon. Actually, a part of the translocated soil organic matter is buried and the rest is redistributed (Smith et al. 2001), which emitted into the atmosphere either as CO_2 through mineralization or as CH_4 by the process of methanogenesis (Alemu 2014). The deposition and burial of translocated soil organic matter are estimated to be 0.4–0.6 Gt C per year compared with 0.8–1.2 Gt C per year emitted into the atmosphere (Lal 2003).

1.12.5 Mineralization

Mineralization is a process in which the fixed atmospheric C in the form of organic matter is transformed into inorganic compounds mediated by the microorganism., hence reduces the chances of sequestrating more C in soil. However, this process should not be prevented artificially for reducing CO_2 emission in the atmosphere, because artificial limitation of the organic matter mineralization may lead to a shortage of nutrients and, thus, may decline the crop yield. Consequently, the photosynthetic binding of CO_2 may diminish (Janzen 2006). Therefore, a strategy aimed at increasing the stable pool of soil organic C seems to be more appropriate than a strategy aimed at limiting the C mineralization (Paustian et al. 2000).

1.12.6 Soil Erosion

Soil erosion negatively affects the carbon sequestration process. Through soil erosion induced processes, about 1.14 Pg of C are emitted annually into the atmosphere (Lal 2001). Soil erosion affects the C pool and fluxes because of several processes. It includes soil aggregate breakdown, exposure of C to climatic elements, organic matter mineralization in both disrupted aggregates and redistributed soil, transport of SOC-rich sediments into protected areas of the landscape and C sequestration with sediments in depositional sites as well as aquatic ecosystems (Alemu 2014) (Fig. 1.4).

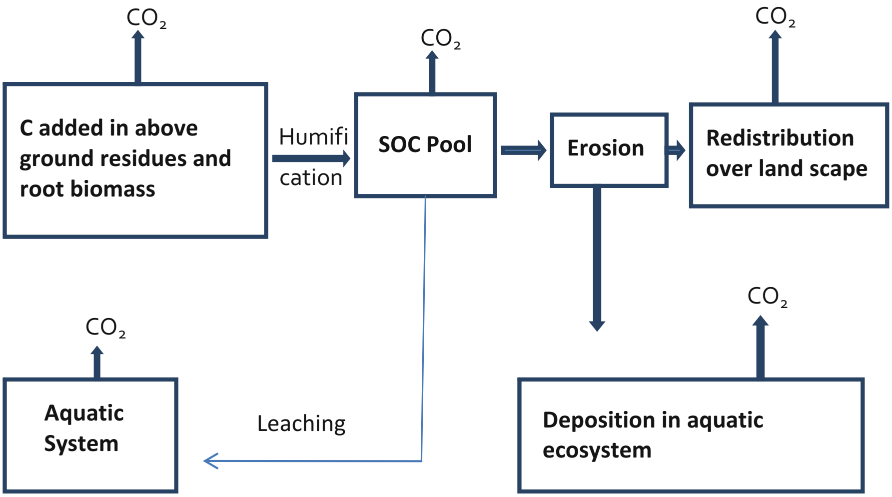

Fig. 1.4 Various soil mechanisms affecting carbon sequestration

1.13 Management for Carbon Sequestration

1.13.1 Biochar

An enormous amount of crop residues are being produced from the agricultural sector. The global estimate of crop residue production for cereal crops and 27 food crops are 2.8 and 3.8 Gt per year, respectively. In India, agro-residues are produced in a tune of about 435.98 million tonnes annually, among which 313.62 mt are in excess. However, those are partially utilized for various reasons (Murali et al. 2010) and 16% is burned (Streets et al. 2003). Accumulating residues can cause considerable crop management problems, and burning of these huge amounts of residues can even cause global warming. CO_2 is one of the most important greenhouse gases and as a result of biomass burning immediately releases CO_2 from nearly all carbon stored in the biomass. Increasing trend in environmental degradation is the concern, and at the same time, search for alternatives to crop residue burning is the need of the hour. Biochar is one of the solutions of this issue. Application of biochar in agriculture is a potential tool for C sequestration and sustainable soil management. In this process the biomass is transferred to an inactive C pool in biochar and redistributed to agricultural fields resulting in C sequestration, and at the same time agricultural productivity as well as environmental quality can be sustained and improved.

Biochar is rich in C, fine-grained porous products produced by thermochemical conversion process (pyrolysis) from the plant biomass at low temperatures (~350–600 °C) in an environment with absence of oxygen (Amonette and Joseph 2009). Biochar is also rich with hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and ash in a different proportion (Masek 2009). Due to the physical characteristics/quality of biochar like high porous structure, more surface area and higher water retention capacity, soil scientists recommend it as an important soil amendment.

In addition to improvement of soil physical quality, it has high carbon sequestration potential, nearly 30–40% more than non-biochar materials (Lehmann and Rondon 2005). During the process of conversion of biomass to biochar, about 50% C contained in biomass is lost, leaving the stable biochar carbon, whereas almost 80–90% C content in non-biochar material in soils is lost in a period of 5–10 years depending on the quality of biomass and its exposure to the environment (Lehmann et al. 2006). However, non-judicious application of biochar in soils to increase terrestrial carbon sink may reduce soil productivity. Therefore application rate of biochar to get optimum crop response needs to be evaluated for long-term carbon sequestration management strategy. It has been observed that there is a straightforward relationship between crop yields and addition of biochar to the soil up to 50 MgC ha^{-1}, whereas the performance of crops may reduce at very high applications. But in most soil ecosystems, the performance of numerous plant species showed increasing trend even with 140 MgC ha^{-1} (Lehmann and Rondon 2005).

1.13.2 Conservation Agriculture

Conservation agriculture (CA) is an important model of sustainable agriculture which leads to profitable food production. This is also protecting and restoring the natural resources. Farmers are benefited with this technology because it increases crop yields and reduces production costs. It also has positive impacts on environment as well as society by enhancing food security, increasing soil fertility, improving water quality, reducing soil erosion and also helps in mitigation of climate change by increasing carbon sequestration. Conservation agriculture is a sustainable option for intensification as well as environmental protection as it is, in one hand less sensitive to climate and on the other provides resilience to the system.

Conservation agriculture is based on healthy functioning of the whole agro-ecosystem with a maximum attention and focus on the soil. The soil is not only a physical support to roots and plants but also a living entity with its physical, chemical and biological characteristics. The focus of CA is determinants of sustained productivity, which embraces the nutrient contents of the soil as well as its biological and structural status.

The main paradigm of CA is to convert an undisturbed or unhealthy soil to develop a fertile soil and produce healthier plants.

1.13.3 Principles of Conservation Agriculture

Conservation agriculture is a system which refers to reduce soil tilling as well as retaining the crop residues on the soil surface and maintaining the crop rotation.

The key elements which characterize CA include:

(a) Zero/minimal soil disturbance (no-tillage and direct sowing and direct placing of planting materials to soil)
(b) Permanent soil covers either by crop residues or by cover crops
(c) Crop diversification in sequence/associations through rotations

Conservation agriculture principles are converting a low-yielding, dry, rainfed conditions to high-yielding, irrigated conditions in a wide range of crop production systems. It also sustain biodiversity and natural biological processes both in above- and belowground soil surfaces. External inputs such as agrochemicals and plant nutrients of minerals or organic origin are applied without soil interventions such as mechanical tillage which are reduced to an absolute minimum or avoided optimally. In this way the soil qualities do not interfere with, or disrupt, the biological processes. CA facilitates good agronomy, such as timely operations, and improves overall land husbandry for rainfed and irrigated production. At the same time, CA complies with the generally accepted ideas of sustainability. The use of chemical fertilizer and pesticides, including herbicides, is also reduced in the long-term application. Depending on the agroecological location and management practices, it further helps in C sequestration in soil ranging from 0.2 to 1.0 t ha^{-1} $year^{-1}$. About 50% labour requirements are generally reduced which helps the farmers to save time, fuel and machinery costs.

1.13.4 Cover Crop and Residue Management

In organic agriculture, cover crops are incorporated by tillage. Incorporating of legumes enhanced productivity in wet season, and surface mulch in dry season was found effective. Mulching is helpful for in situ moisture conservation, weed suppression and nutrients mobilization both in organic and integrated nutrients management practices.

Crop residues directly effect on the evaporation of the water content from the soil surface and also the amount of water infiltrates into the soil. The organic residues incorporation significantly increases the crop yield with improvement in soil physical properties. It was reported that incorporation of locally available organic residues (*Ambrosia sp.*) continuously for 5 years in puddled rice could increase SOC by 21.1%. Apart from this it also increases the stability of microaggregates, moisture retention capacity and infiltration rate of the soil by 82.5, 10 and 31.3%, respectively (Saha and Mishra 2009).

1.14 Carbon Dynamics and Climate Change Feedback

Climate change affects SOC dynamics as well as its decomposition kinetics. Soil organic carbon decomposition that provide a feedback to the gaseous-C concentrations to the atmosphere contributes to the global warming. There are both direct and indirect effects of carbon dynamics to climate change feedback. Direct effects include temperature-mediated soil respiration, SOC decomposition leading to gaseous C emission, changes in precipitation and extreme climatic events.

As SOC decomposition rates and soil respiration are more sensitive to temperature than primary production it is predicted that climate change would increase the net transfer of C from soil to atmosphere, thereby creating a positive feedback to climate change. Growing stress tolerance species also contribute to a positive feedback to climate change. Increase of primary production (higher photosynthesis) and reduction of the length of growing season cause negative feedback to climate change by reducing the CO_2 emission to the atmosphere and absorbing more CO_2 from the atmosphere. The indirect effects which include positive feedbacks are (i) percolation and runoff losses of dissolved organic carbon (DOC) and (ii) higher root exudation that causes faster SOC decomposition through ‘priming effect’ and promotes methanogenesis and hence enhances the C losses from soil as methane. The indirect negative feedbacks include (i) increasing plant-microbial competition for nitrogen (N) that causes ecosystem C accumulation, (ii) increasing growth of mycorrhizal fungi causing C accumulation and (iii) stimulation of microbial biomass and immobilization of soil N causing limitation of N availability to plant and hence accumulation of C in soil. Another indirect effect on climate change (both positive and negative feedbacks) is through shifts in the functional composition and diversity of microbes and vegetation which occurs over longer time scales of decades and centuries.

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