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Carbon Management in Tropical and Sub-Tropical Terrestrial Systems

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Foreword

The book *Carbon Management in Tropical and Sub-tropical Terrestrial Systems* addresses a theme of global significance. Carbon (C), an important constituent of all ecosystems, is intricately interconnected with numerous ecosystem services for human wellbeing and nature conservation. Cycling of C is coupled with those of water (H_2O), nitrogen (N), phosphorus (P), sulphur (S) and other essential elements. It is the intensity and strength of the coupled cycling of C that is the source of ecosystem services including the net primary production, moderation of climate, renewability and filtration of water, activity and species diversity of biota, etc. Anthropogenic perturbation of the cycling of C, and weakening of its coupling with other elements (e.g. N, P) and water, can jeopardize ecosystem functioning. For example, depletion of the terrestrial stocks of C (comprising of those in vegetation and soil) can have a strong impact on soil quality and functionality. Consequently, the theme of soil C sequestration has received the attention of policy-makers. The year 2015 was declared by the United Nations as the year of soil, and the 2015–2024 decade has been declared by the International Union of Soil Sciences (IUSS) as the "Decade of Soil". In 2002, when the 17th World Congress of Soil Science (WCSS) was held in Bangkok, the IUSS worked with the Thai Government and declared 5 December as the World Soil Day (WSD). The WSD is celebrated on the birthday of the late king of Thailand – His Majesty King Bhumibol Adulyadej, the Rama IX of the Chakri dynasty. In cooperation with the IUSS, the WSD is also celebrated by the Food and Agriculture Organization (FAO) of the United Nations and other institutions throughout the world. In addition, the COP21, held in Paris in 2015, adopted a resolution of "4 per Thousand". It is a voluntary proposal of sequestering C in soils of the world to 40 cm depth at the rate of 0.4% (0.4% or 4‰) per year. The objective is to sequester carbon for advancing global food security, adapting and mitigating climate change and promoting other Sustainable Development Goals of the United Nations.

Therefore, this book is timely and highly pertinent because it addresses the theme of C sequestration in tropical and sub-tropical ecosystems. A majority of farmers and land managers in these regions are resource-poor and small land holders with farm size of less than 5 hectare and often as small as 0.5 hectare. Managed by extractive farming methods (e.g. residue removal, in-field burning, ploughing, flood-based irrigation, negative nutrient budget), soils of these farmers are strongly depleted of their soil organic carbon (SOC) content. Indeed, the SOC concentration in the root zone can be as low as 0.1% or less. Therefore, most soils have degraded physical, chemical, biological and ecological properties. Consequently, agronomic yields are low and stagnating, use efficiency of inputs (i.e. fertilizer, irrigation) is low, and the losses of water and nutrients (caused by erosion, leaching, volatilization) are high with severe adverse impacts on the environment. In addition, nutritional quality of the produce is also poor, and it has exacerbated the widespread problem of malnutrition because of severe degradation and depletion of soils.

It is widely recognized that the health of soil, plants, animals, people and ecosystems is one and indivisible. The concentration of SOC in the root zone, along with its quality and turnover, is a strong determinant of soil health, agronomic productivity, use efficiency of inputs and the environment. The latter includes adaptation and mitigation of anthropogenic climate change, water quality and renewability and aesthetic quality of the landscape.

This book is a pertinent reference material for researchers, students and practitioners in soil science, agronomy, ecology and sustainable management of natural resources with specific focus on the global issues such as food and nutritional security, adaptation and mitigation of climate change, quality, biodiversity and the Sustainable Development Goals of the United Nations.

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1 January 2019

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Preface

Terrestrial ecosystems are a significant carbon sink on Earth accounting for about 20–30% of the total anthropogenic carbon dioxide (CO_2) emissions to the atmosphere. When compared with oceans, it can be readily managed to either increase or decrease carbon sequestration by restoring or degrading vegetations available on lands. Any increase in concentration of radioactively active trace gases in the atmosphere is now recognized to modify global climate, affecting terrestrial ecosystems both functionally and structurally. The importance of soil as a sink and source of atmospheric carbon and the need for its additional sequestration in terrestrial agroecosystems through appropriate management are major issues among the scientific community and policy-makers to mitigate CO_2 enrichment in atmosphere. A land-use and management option that optimizes sustainable production and enhanced carbon sequestration in the soil is the need of the hour, particularly with reference to tropical and sub-tropical terrestrial systems, where the soil is hungry for carbon.

Soils have many essential life-supporting functions, of which growing plants and vegetation for food, fuel and fibre is important. Soils store carbon from the atmosphere to mitigate atmospheric greenhouse gas levels, filter contaminants to ensure clean drinking water to aquifers for posterity, provide habitat and maintain a microbial community and gene pool that decomposes and recycles dead organic matter and transforms nutrients into available forms for plants. These functions support many of the goods and services for social, economic and environmental benefits to humankind. They need to be protected and upkept from the increasing pressure of intensive use of land. In fact, the soil resources in tropical and sub-tropical areas are already showing signs of severe degradation and fatigue from human use and management. Soil degradation has been escalated during the past few decades with expansion of cultivation and urban dwelling for increasing human population. As a fallout of such degradation of soil, its carbon content gets lost through water, wind and other forms of erosion. This process is again accentuated by land conversion and associated increased emission of greenhouse gases out of recent phenomenon of burning of crop residues.

Soil management practices which can sequester carbon and reduce the risk of soil degradation in agroecosystems include conservation tillage in combination with planting of cover crops, green manure and hedgerows, organic residue management, mulch farming, water management, soil fertility management, introduction of agroecologically and physiologically adopted plant species, adapting crop rotation and cropping/farming systems, controlling grazing to sustainable levels and stabilization of slopes and terraces. These management practices should aim at optimizing CO_2 utilization by plants through photosynthesis to increase crop productivity and content of soil organic carbon. However, the ultimate aim should be to increase the labile fraction of soil organic carbon stored in stable micro-aggregates, reducing its accessibility for oxidation by microorganisms.

The objective of this book *Carbon Management in Tropical and Sub-tropical Terrestrial Systems* is to provide science-driven information for soil carbon management in the tropical and sub-tropical areas/countries in the context of global climate change and sustainable agricultural production. This publication includes 25 chapters grouped into five themes, namely, (I) impact of land-use management for regulating soil organic carbon (SOC) pools; (II) conservation agriculture and carbon sequestration, (III) soil physical and biological factors regulating SOC storage; (IV) carbon management in pastures, grasslands, forests and farming systems; and (V) frontier science regulating SOC storage. Researchers of national and international repute have contributed the chapters on soil carbon dynamics in different land-use and management systems, soil management for regulating carbon pools, soil management practices under the major crops and enhancing carbon sequestration: management options, conservation agriculture and carbon sequestration, soil physical parameters for regulating organic carbon pools, microorganisms regulating carbon cycle in tropical and sub-tropical soils, soil organic carbon stock and water management, grasslands as carbon sink, agroforestry for the enhancement of carbon sequestration, carbon sequestration potential of perennial horticultural and forage crops, developments in measurement and modelling of soil organic carbon dynamics and nanotechnology for improved carbon management in soil. Each chapter has been enriched with the current scientific and technical literatures on soil carbon management to provide updated information of high scientific and technical value.

The editorial team takes this opportunity to express their gratitude to all who have provided moral supports and shown their keen interest in bringing out this publication. The team also likes to convey its sincere gratitude and appreciations to all the distinguished authors and contributors for their dedication and commitments in writing their chapters. Special thanks are due to Professor Rattan Lal for his constant guidance and support in bringing out the book in global perspective and also for writing a thought-provoking Foreword for this book.

It is hoped that besides researchers and students of agricultural sciences, the publication will be useful to the policy-makers, planners, administrators and farmers. Last but not the least, the Springer team also deserves appreciation for their constant inspiration, guidance and cooperation in drafting the publication.

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Soil Carbon Management-Climate Change-Food Security Nexus: An Overview of the Book

Historical agricultural production as well as its ongoing intensification worldwide has intensely impacted global carbon, water and nutrient cycles. And as such, both land-use changes to agriculture and agricultural production continue to contribute significantly to the increase in atmospheric carbon dioxide (CO_2), accounting for as much as 24% of the global greenhouse gas (GHG) emissions. Soils, however, can act as both sources and sinks of carbon, depending upon management, biomass input levels, microclimatic conditions and bioclimatic change. Substantially, more carbon is stored in the world's soils than is present in the atmosphere. The global soil carbon (C) pool to 1-metre depth, estimated at 2500 Pg C, of which about 1500 Pg C is soil organic carbon (SOC), is about 3.2 times the size of the atmospheric pool and 4 times that of the biotic pool. A widespread body of research has shown that land management practices can increase soil carbon stocks in agricultural lands with agronomic practices including the addition of organic manures, cover cropping, crop diversification, mulching, conservation tillage, fertility management, agroforestry and rotational grazing. There is general agreement that the technical potential for sequestration of carbon in soil is significant, and some consensus on the magnitude of that potential is arrived. On this basis, the 4p1000 initiative on soil for food security and climate14, officially launched by the French Ministry of Agriculture at the United Nations Framework Convention on Climate Change: Conference of the Parties (UNFCCC COP 21) in Paris, aims to sequester approximately 3.5Gt C annually in soils. Tropical and sub-tropical croplands in particular will be important in this effort, as these lands have inherently low SOC content.

There is a growing realization that facets of global changes (climate changes, changes in concentration of atmospheric constituent gases, land surface cover and biodiversity) are interlinked and strongly impact the livelihood and survival of the humankind. Since the mid-1990s, accelerated warming has been reported across the world. Temperatures are likely to rise in India by 3–4 °C by the twenty-first century (Pathak and Aggarwal 2012). The average temperatures have increased by 0.25 °C during the *kharif* and by 0.6 °C during the *rabi* season. Some reports suggest that the recent warming has potentially reduced crop yields by 6% in the *rabi* season (Peng et al.2004). The projected warming over the rainfed dry lands may exacerbate water scarcity, leading to a further loss in crop production (Funk et al. 2008).

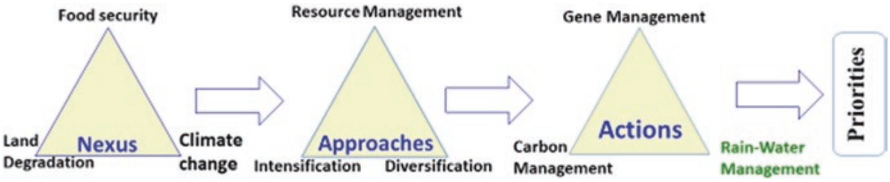

Fig. 1 Future research focus to tackle land degradation-climate change-food security nexus

Biomass production in tropical and sub-tropical regions of the world is mainly constrained by limited water availability and low nutrient supplying capacity of soils. Again, wilful and random intensification of agriculture with external inputs in these regions accentuates land and environmental degradation. Developing strategies for halting such land degradation and improving livelihoods of the poor of the region is an important issue that warrants urgent attention to achieve the Sustainable Development Goals. Based on remotely sensed NDVI data, Liu et al. (2015) estimated that 16% of the Indian territory (47 mha) showed a declining trend in NDVI between 1982 and 2006. Out of the area, 29 mha belongs to croplands and 12 mha to forest. The decline in canopy cover in croplands is a matter of serious concern, since it is associated with the on-going process of land degradation. Such degradation contributes to climate change through loss in biodiversity, SOC, soil moisture and biomass, etc. and brings a land degradation-climate change-food security nexus (Fig. 1). Poorly managed farms, degraded lands and natural resources are an ecological, social and economic liability. For the survival of civilizations, it is crucial that land degradation processes are attended, on a priority. One of the best ways of curbing such degradation is carbon sequestration in soils. In fact, sequestration of C has numerous co-benefits. Important among them are advancing food security, improving the environment, enhancing water quantity and quality, increasing biodiversity, etc. The future of SOC research requires through understanding of the linkages between land degradation, food security and climate change (Fig. 1). It also needs focussed strategies and approaches of resource management in order to make cohesiveness between intensification and diversification. Finally, action-oriented research for manipulation of crop genetics along with water and nutrient management need to be addressed.

This book has drawn together various perspectives on some of the key issues regarding carbon sequestration in soils of the tropical and sub-tropical regions for achieving sustainable production and neutrality in land degradation.

Understanding of Basic SOC Pools and Dynamics in Tropical and Sub-tropical Environment

Sequestration of carbon in soil is governed by various edaphic, environmental and management factors; of them, soil aggregation and structure are important (Chap. 14 by Bandyppadhyay this volume). Kashyap et al. (2017) have indicated that nanomaterials due to their unique properties at nanoscale can enhance carbon stabilization and its sequestration in soil. In these chapters, the positive effects of nano-zeolite, nanoZnO particles and nano-Fe on aggregation and carbon build-up in agricultural soil have been documented (Aminiyan et al. 2015; Raliya et al. 2015; Tarafdar et al. 2013). Once C is sequestered in soils, it alters soil aggregation. The resulting aggregates, in turn, protect the C from microbial degradation within stable micro-aggregates (<250 mm), adsorbed on the inner surfaces of clays or chemically formed organo-mineral complexes (Lal 1997; Chap. 25 by Sangeeta et al. this volume). Additional research is, however, needed to elucidate the mechanisms of such nano-materials led SOC sequestration, its magnitude and economics. Also, cereals-based cropping system had low carbon storage compared to that of legume-based. It is highlighted that growing of bamboo, cane and rice or similar grass crops has significant potential of phytolith C bio-sequestration. In the case of rice, C content of phytolith varied from 1.4% to 3.37% in straw, from 1.13% to 2.27% in roots and from 2.13% to 6.3% in rice husk. In wheat and maize, the percent of PhytoOC is 0.16%, offering good opportunity to sequester C. It is estimated that growing high PhytoOC-yielding cultivars provides additional 1.0 million tonnes of carbon per year in these croplands (Chap. 3 by Kundu et al. this volume). This calls for a reorientation of crop breeding efforts for improving SOC sequestration. The usefulness of such sequestered C in maintaining ecosystem functions of soil is also studied.

Modelling C behaviour and its dynamics in soils is a tortuous exercise (Chap. 23 by Benbi and Nisar this volume). And till now, most of the C models to predict its pool and fluxes from soils are developed using studies concentrated mainly in temperate regions and with SOC in surface soils. Subsoil edaphic conditions, such as pH, oxygen concentration, microbial load and SOC distribution in pools, are different from those of surface soils and have hardly been considered in the existing widely used models. This is particularly true for models used in tropical and subtropical regions. Modified approach is needed to predict the turnover of organic C in subsoil up to 1.0 M of depth. Increasing C sequestration in subsoil profile may be possible by adopting deep-rooted perennials in the cropping systems.

Strategy to Create a Positive C Budget in Tropical and Subtropical Agroecosystems

The various chapters included in this publication have presented a wide range of topics including forestry, agroforestry, perennial horticulture and grasslands and the carbon stocks and C pools dynamics therein; effect of tillage and nutrients on SOC management; impact of amendments such as organics, nano-particles, etc. on carbon sequestration and crop productivity; etc. Soil carbon pool varied in the order of wet temperate forest (165.24 Mg ha^{-1}) > deciduous forest (138.64 Mg ha^{-1}) > tropical thorny forest (135.42 Mg ha^{-1}) > tropical riparian fringing forest (104.94 Mg ha^{-1}). Tropical thorny and riparian forest had more labile carbon fractions, whereas wet temperate forest had more non-labile carbon fractions (Sreekanth et al. 2013). Recently, Christopher Poeplau et al. (2018) have made a comprehensive method comparison for isolation of organic carbon fractions with varying turnover rates for a mechanistic understanding and modelling of soil organic matter decomposition and stabilization processes. They confirmed the importance of clay- and silt-sized particles (<50 μm) for SOC stabilization. At the same time, other groups have highlighted the brilliance of sesquioxides in storing a good amount of C in soils. Weighing the importance of soil components for C sequestration and its stabilization and prediction of its stocks over regions will be useful for judging soils as to their potential as a sink of C. How such potential of soils is changed over adoption of different management practices followed by farmers of tropical and sub-tropical regions needs to be assessed not only for upkeeping soil health but also curbing land degradation.

Sequestration of the atmospheric CO_2 in soil has long been considered as one of the potential strategies for mitigating global warming and improving soil health. Recent evidences show that conservation agriculture (CA) can reduce emissions of GHGs as well as sequester C in soils. Some of the management options associated with CA for increasing SOC sequestration includes (i) reduced tillage, (ii) cover crops, (iii) efficient nutrient management, (iv) efficient water management, (v) restoring degraded soils, (vi) practicing crop diversification, (vii) minimizing soil and water erosion, (viii) efficient pasture management, (ix) afforestation and efficient forest management, (x) efficient management of urban soils, etc. (Chap. 6 by Bhattacharya et al. this volume). Additionally, enhancing soil aggregation and structure for better retention of soil organic carbon (Chap. 24 by Pragati et al. this volume) is also an important management strategy to reduce CO_2 emissions from soils into the atmosphere.

It has been shown that among the different land-use systems, total C stock was highest in soils under forest followed by soils under fodder system, the cereal system – paddy, maize, cotton, redgram, intercrop, chilli and permanent fallow – and lowest in soils under castor system (Venkanna et al. 2014; Chap. 3 by Kundu et al. this volume). Ganeshamurthy et al. (this volume) in Chap. 20 has indicated that soils under perennial horticultural crops in tropical India, which cover an area of 12.1 million hectares (6.10 Mha fruits, 3.22 Mha plantation crops, 2.63 Mha spices and 0.14 Mha nuts) with an annual production of 214 million tonnes, is also a good sink for carbon. They further narrated that in horticultural systems, soil factors (soil moisture status, soil temperature, drainage, soil acidity, soil nutrient supply, soil clay content and mineralogical makeup) influence the microbe-mediated processes and organic matter behaviour in soils. Carbon sequestration potential in soils under some of the perennial horticultural crops is as follows: mango > cashew > rose > vegetable > medicinal and aromatic plants (Bhavya et al. 2017).

Carbon Sequestration Through Land Reclamation and Management

Improved soil management practices, such as growing of cover crops, sowing crops with conservation tillage, maintaining balanced level of soil fertility and converting marginal and degraded lands to restorative land uses, help in capturing and storing carbon in soils through a favourable impact on soil structure. A comprehensive database on C sequestration potential of various land reclamation options has been illustrated in chapter "Soil Management for Regulating C Pools: Perspective in Tropical and Sub-tropical Soils". Land reclamation through agroforestry has also been recognized as a good option. It accumulates C in the range of 0.29–15.21 Mg $ha^{-1}year^{-1}$. The amount can further be improved through imparting biochemical recalcitrance and physical protection and also by reducing C losses (Chap. 19 by Dhyani et al. this volume). Growing guinea grass, berseem and cowpea crops between main crop reduce fallow period, provide soil cover during peak summer months, reduce runoff and soil erosion and help in more C build-up.

Grazing Land Management

Carbon sequestration potential of grasslands is higher than that of cropland. The Indian mountainous line of more than 4500 km running from north-west to north-east provides an excellent space for the grasslands and can stock SOC at the rate of 37 Mg ha^{-1} at altitudes between 500 m and 1000 m. The rate is increased exponentially with altitude to 142.14 t ha^{-1}at altitude of above 2500 m (Chap. 17 by Pasricha and Ghosh this volume Chap. 18 by Mahanta et al. this volume). In Chapter "Soil Management for Regulating C Pools: Perspective in Tropical and Sub-tropical Soils", Debashis Mandal stated that transformation of degraded croplands to grassland can result in an annual increase of 3% or more SOC concentration (Conant et al. 2001). Through this conversion, C sequestration rate of 0.3–0.8 Mg ha^{-1} $year^{-1}$ was achieved in West Africa (Batjes 2001). Some researchers even reported a higher sequestration rate between 1.2 and 1.7 Mg ha^{-1} $year^{-1}$ in case of land conversion from degraded cultivated land to grassland (FAO 2004; Vagen et al. 2005). Rehabilitating degraded land converting to grassland is thus a good option for sequestration of carbon. Such effect of land-use change on C enrichment in soil was also observed in temperate climate wherein a 1.7 times higher SOC storage has been reported in agroforestry system than the croplands without trees (Chap. 22 by Rai et al. this volume).

A common practice that is followed by farmers of the SAT regions is to go in for deep tillage in peak summers and leave the field bare fallow before the onset of the monsoon rains. Adoption of such practices accelerate the loss of SOC due to both an increased mineralization of the SOC and erosion of sediments with runoff water (FAO and ITPS 2015), although mineralization of the SOC influences the biogeochemical nutrient cycles orchestrated by the soil microbial flora (Chap. 15 by Singh et al. this volume). Because of these, SOC is getting depleted at faster rates compared to its replenishment in SAT regions. However, processes of SOC loss/gain due to changing cultivation or management practices are usually slow unless the losses are linked to soil erosion. This is why cultivated or disturbed soils tend to lose SOC, whereas permanent grasslands and forests gain SOC over time (Jones et al. 2012). Again, bare fallows are neither conducive to any carbon build-up, nor in situ conservation of the summer monsoon rainfall, nor protect soils against erosive forces of the high-intensity rainfall. Therefore, the challenge for the SAT farmers is to close the summer window with some cover crops to conserve soils and rainwater. Kar (this volume) in Chap 16 has indicated that soil organic matter affects water retention in soils through greater structural effect close to field capacity than close to wilting point. This suggest that SOC amended surface soil layers are likely to possess increased capacity for absorption and conservation of rainwater into soil moisture which already has emerged as the most serious limitation to achieve the goal of global food security.

In 1960, Jenny and Raychaudhuri made a comprehensive study and showed that climate had the most impact on SOC reserve in Indian soils, although they did not make any estimate of its total carbon reserve. The first attempt for estimating OC stock was made by Gupta and Rao (1994) who pegged the SOC stocks of Indian soils at 24.3 Pg (1 Pg = 10^{15} g; billion tons). They considered 1-m depth surface of 48 Benchmark soil profiles for this assessment. A significant observation emerging from this study was that the salt-affected and other degraded soils having the least SOC had the maximum potential to sequester additional carbon if reclamation measures are initiated to rehabilitate them. Based on a detailed geographical distribution of soil series in the country and taking the soil depth further to 150 cm, Bhattacharyya et al. (2000a, b, 2008) estimated the SOC stocks of Indian soils at 63 Pg.

Increasing the SOC pool by 1 Mg C $ha^{-1}year^{-1}$ can enhance agronomic production in developing countries by 32 and 11 million tonnes per year in case of cereals and food legumes, respectively (Lal 2006). Such enhancement in SOC and the associated improvement in soil quality can be ensured by adopting resource conservation technologies. It is shown that no-till soils have a higher C stratification ratio over the other cultivated types [NT (2.11) >RT (1.77) >CT (1.53)] ensuring better soil quality and soil ecosystem functioning in the former (Chap. 16 by Hati et al. this volume. This gain in SOC in the top layers improves the ability of the soils to absorb and conserve rainwater in the SAT region. In fact, among the tillage practices, conservation agricultural practices and long-term recycling of crop residue support the natural systems by storage of more crop residues in soil. Adopting integrated nutrient management (INM) may improve carbon sequestration in soils by supplying N, P, S and other nutrients essential for humification process, and as such, optimally fertilized rice-wheat system was found to sequester more carbon compared to maize-wheat system (Kukal 2009). Furthermore, long-term fertilizer experiments in India also revealed that integrated or balanced nutrient management resulted in build-up organic carbon content of soils. Some major strategies for the enhancement of C sequestration potential in soils are thus no-till farming with crop residue mulch and cover cropping (conservation agriculture), an integrated nutrient management including the use of compost and manure and liberal use of biosolids (Chap. 9 by Sharma and Behera this volume, Chap. 10 Singh et al. this volume Chap. 13 by Bandyopadhyay et al. this volume). It is estimated that they could mitigate more than 50% of the total GHG emissions in India, but it all depends on the extent and speed of adoption of these measures by farmers which remain unsatisfactory (Chap. 23 by Benbi and Nisar this volume; Sapkota et al. 2018). The scale of soil carbon sequestration thus relies more on understanding the barriers and overcoming the constraints rather than on filling in the gap in our scientific and technical knowledge. However, sincere efforts are needed to be made in changing government policies to promote these technologies across the tropical and sub-tropical regions of the world in order to provide livelihood security to its teeming population.

Governance and Policy

Soil degradation with depleted soil C exacerbates challenges of livelihood of billions of people in tropical and sub-tropical regions of the world. At present, about 70% of the population in tropical region practice unsustainable cultivation that contributes to soil degradation. The main problem is that SOC sequestration does not have an immediate solution to food security. Farmers need the goods and services (provisioning services) that could immediately sustain their livelihood. Therefore, the presence of carbon markets and payments for ecosystem services may be an additional incentive for resource-poor farmers of tropical region while implementing soil rehabilitation and adoption of RMPs. Even with the large technical potential to sequester carbon in soils, there are often major limitations in achieving that potential in tropical countries and within specific farming systems. With any efforts to sustain prominent changes in practice, a significant understanding of sociocultural, political and socioeconomic contexts is required. Therefore, governance and policy play a very important role in implementing various strategies. Updating our understanding of the achievable potential for carbon sequestration in soils, and the practical implementation of improved soil management and farming practices aimed towards increasing SOC, offers a strategy for mitigation of climate change with potentially positive implications for food security and ecological resilience in the long term.

Following the conversion of cropland to forest and grassland across the Loess Plateau of China through their ambitious Grain for Green project, the average C sequestration rate that increased by 0.3 Mg ha^{-1} $year^{-1}$ in 16 years is an example of good governance and policy. Although the initial goal of the project was to control soil erosion, it has been remaining greatly influential in increasing both the rate and overall quantity of C sequestration in the soil. Interestingly, land converted to grassland had higher C sequestration rate than even forest and shrub land. All the examples narrated in this chapter clearly showed that rational and judicious soil management practices with suitable cropping systems enhanced C stocks in soils and thereby improved soil structure, curbing soil erosion and land degradation.

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Part I

Impact of Land Use Management for Regulating SOC Pools

1 Potential Soil Carbon Sequestration in Different Land Use and Management Systems in Peninsular India

Ch. Srinivasarao, K. L. Sharma, and Sumanta Kundu

Abstract

Information on dynamics of soil organic carbon (SOC) in agricultural soils is gaining importance because of its impacts on climate change and benefits for crop productivity. Conservation agriculture, application of residue and manures, appropriate cropping systems including legumes, green leaf manuring through leaves of N-fixing trees, conjunctive use of organic and chemical sources of nutrients, balanced fertilization, etc., play an important role in improving SOC. Besides management practices, soil types, parent material, clay content and other soil properties and climate are very important factors that determine carbon sequestration, CO_2 emissions and overall net carbon balance in soil. The Deccan Plateau in India has huge diversity in terms of climatic and edaphic conditions besides land use systems and soil management practices. Cropping systems like rice–maize, if continued for long term, may deplete SOC. Among other alternate land use systems, the highest SOC was observed in the agri-silviculture system followed by the silvi-pasture and agri-silvi-horti systems. Regular additions of nutrients through fertilizers along with organic manures are found necessary for carbon sequestration, particularly in soils with nutrient deficiencies. In this chapter, efforts have been made to collate the information on the effects of land uses and soil management on SOC stock. With the introduction of carbon trading, agroforestry systems may become more attractive. Research addressing both biophysical and socio-economic issues and identifying, developing and bringing out best management practices (BMPs) with reference to carbon sequestration and sustainable production needs to be intensified.

Keywords

Agroforestry systems · Best management practices · Carbon sequestration · Carbon stock · Semiarid tropics

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1.1 Introduction

Soil organic matter (SOM) is directly and positively related to soil fertility and agricultural productivity. There are many advantages of a high level of SOM, such as (i) reduced bulk density, (ii) increased aggregate stability, (iii) resistance to soil compaction, (iv) enhanced fertility, (v) reduced nutrient leaching, (vi) resistance to soil erosion, (vii) increased biological activity and (viii) reduction in emission of greenhouse gases. In most agricultural soils, organic matter is improved by leaving residues on the soil surface; carrying out crop rotations with pastures or perennials; incorporating cover crops into the cropping rotation or by adding organic residues such as animal manure, litter or sewage sludge (Krull et al. 2004).

The loss of SOM resulting from conversion of native vegetation to farmland has been extensively studied and is one of the best-documented ecosystem consequences of our agricultural activities (Paul et al. 1997). Agricultural activities have affected the quality and quantity of SOM on many different levels. The greatest loss of soil organic carbon (SOC) associated with agriculture occurs during the first 25 years of cultivation, with losses of 50% being common (Matson et al. 1997). It has been reported that in the Midwestern United States, the majority of soils converted from natural to agricultural systems have lost 30–50% of the original SOC level, or 4.4–7.2 Mg C ha^{-1} (Lal 2002). Agricultural practices contribute to the depletion of SOC through deforestation and biomass burning, drainage of wetlands, tillage, crop residue removal, summer fallow, cultivation, and overuse of pesticides and other chemicals. Cropland soils generally store less SOC than grazing land because cropland has greater disturbance from cultivation, lack of manure being returned to the system, has less root biomass and less biomass returned to the soil surface (Lal 2002). According to Matson et al. (1997), factors affecting soil C loss from agricultural soils include (i) climate and soil type, (ii) tillage intensity and depth, (iii) crop rotation decisions, (iv) amount of organic inputs, (v) amount of plant residue on the soil surface, (vi) quality of plant residues returned to the soil, (vii) soil biological activity, (viii) length and time of fallow and (ix) soil erosion.

There are several reports of the influence of land uses on change in C pools in soil. Lal et al. (1998) comprehensively commented on the importance of land use in influencing the C pools in terrestrial ecosystem. It has been established that changes in land use contribute C to the atmosphere releasing it from biomass through burning or decomposition. Similarly, agricultural practices release C owing to increased rate of mineralization brought about by changes in soil moisture and temperature regimes. Lal et al. (1998) emphasized that for C sequestration with respect to land uses, two important aspects include management strategies and policy issues. Among the management strategies, important components include (i) land use and farming systems (arable pastoral, silviculture, mixed systems, non-agricultural uses, natural ecosystems and recreational land use); (ii) soil management (cultivation of land and tillage methods, residue recycling, soil fertility restoration, water management and erosion control); and (iii) plant types and animal waste management (improved cultivars, crop sequences, cover crops and deep-rooted grasses and animal waste handling).

Besides management strategies, policy consideration focusing on institutional support, incentives and rewards system are equally important.

1.2 Description of the Peninsular India

The peninsular India comprises peninsular plateau and peninsular plains. The Peninsular Plateau is a large plateau in India, making up most of the southern part of the country. It extends over eight Indian states and encloses a wide range of habitats, covering most of central and southern India. It is located between two mountain ranges – the Western Ghats and the Eastern Ghats. Each rises from its respective nearby coastal plain. They almost meet at the southern tip of India. The Deccan Plateau is separated from the Gangetic plain to the north by the Satpura and Vindhya Ranges, which form its northern boundary. The Western Ghats mountain range is very tall and blocks the moisture from the southwest monsoon from reaching the Deccan Plateau, so the region receives very little rainfall (World Wildlife Fund 2001).

This region consists of 35 districts of Andhra Pradesh, Karnataka and Tamil Nadu and covers 12% area of the country. These districts have been subdivided into six subzones. The dominant soils contribute 10%, 18% and 13% of the SOC, soil inorganic carbon (SIC) and total carbon (TC) stocks of the country, respectively. This region occupies nearly 45% area of the country and covers the semiarid tropics (SAT) of the Indian subcontinent. The black soils (Vertisols and their intergrades with some inclusions of Entisols) are dominant in SAT along with the associated red soils (Entisols and Alfisols). The carbon storage capacity of soils depends on the quality of soil substrate and its surface charge density (SCD). The increase of SOC again enhances the SCD of soils and the ratio of internal/external exchange sites. The soils in these hills and plateau are dominated by smectites and smectite–kaolinite minerals. This region is a reserve to maximum amount of carbon in soils, which could be due to large areal coverage as well as greater carbon sequestration potential of these soils (38%, 43% and 39% SOC, SIC and TC, respectively).

1.2.1 Climate

The climate of the region varies from semiarid in the north to tropical in most of the regions with clear wet and dry seasons. Rainfall occurs during the monsoon season from June to October, and March to June is very dry and hot, with temperatures regularly exceeding 40°C. It rains here only during some months. Comprising the northeastern part of the Deccan Plateau, the Telangana Plateau spreads over an area of about 148,000 km^2, a north–south length of about 770 km and an east–west width of about 515 km. The plateau is drained by the Godavari River taking a southeasterly course, the Krishna River, which divides the peneplain into two regions and the Penneru River flowing in a northerly direction.

1.3 Carbon Dynamics – Some Experimental Evidence

In general, information on the dynamics of organic carbon storage in agricultural soils is gaining increasing importance because of its impacts on climate change and benefits for crop productivity. Good farming practices have the potential to make agricultural lands or soils a net sink for C, thereby attenuating CO_2 load in the atmosphere. The SOC levels at a point of time reflect the long-term balance between additions of organic carbon from different sources and its losses through different pathways. As such, SOC is naturally variable across land use, soil types and climatic zones (Swarup et al. 2000). Following the adoption of large-scale intensive cropping, the long-term balance of SOC is disturbed, since on the one hand more and more of C is subjected to oxidative losses due to continued cultivation, while on the other hand it leads to large-scale addition of C to the soil through crop residues, resulting either a net build up or depletion of SOC stock (Kong et al. 2005). This SOC stock comprises labile or actively cycling pool and stable, passive or recalcitrant pools with varying residence time. Labile carbon pool is the fraction of SOC with most rapid turnover rates. Its oxidation drives the flux of CO_2 from soils to atmosphere. Such pool is important, as it fuels the soil food web and therefore greatly influences nutrient cycling in soil for maintaining its quality and its productivity (Chan et al. 2001; Mandal et al. 2005, 2007). Some of the most important labile pools of SOC currently used as indicators of soil quality are microbial biomass carbon (C_{mic}), mineralizable carbon (C_{min}), particulate organic carbon (C_p), oxidizable organic carbon (C_{oc}) fractions etc. Highly recalcitrant or passive pool is very slowly altered by microbial activities (Weil et al. 2003) and hence hardly serves as a good indicator for the purpose (Majumder et al. 2007).

Addition of organic manures, either alone or in combination with inorganic fertilizers, significantly increased the SOC stock. The C sequestration potential (CSP), defined as the rate of increase in the SOC stock vis-à-vis the antecedent baseline stock in the 0–0.2 m depth, ranged from 0.18 Mg C ha^{-1} $year^{-1}$ (unfertilized control) to 0.57 Mg C ha^{-1} $year^{-1}$ (50% RDF + 4 Mg ha^{-1} groundnut shells). In this study, the positive and linear correlation between changes in SOC stock and the total cumulative C inputs to the soils (external organic compounds plus crop residue) over the years ($Y = 0.29X-7.0$; $R^2 = 0.98$***, $p = 0.001$) was a strategically important information. It implies that even with 22 years of continuous input of biomass-C ranging from 0.6 to 3.4 Mg C ha^{-1} $year^{-1}$, the soil C sink capacity was not filled. Therefore, Vertisols have a high SOC sink capacity. Yet, the soil C sink capacity is finite (Six et al. 2002), and a different rate of C loading causes a new steady state of SOC over time. A periodic assessment of SOC stock, even at decadal intervals, may provide guidelines for sustainable management of soils (Srinivasarao et al. 2012a).

Similarly, in Vertisols of Central India, retention of crop residues of sorghum and application of farmyard manure (FYM) equivalent to 25 kg N ha^{-1} along with 25 kg N ha^{-1} supplied through chemical fertilizers for 22 years considerably increased the SOC stock (Srinivasarao et al. 2012a). Conjunctive use of crop residues and *Leucaena* clippings increased the profile SOC stock (68.5 Mg ha^{-1}), with

SOC build up being 39.8%, and the amount of SOC sequestration was 14.4 Mg C ha^{-1} (Table 1.1). These parameters were positively correlated with cumulative C input and also reflected in the sustainable yield index (SYI). Higher grain yield (1.19 Mg ha^{-1}) by application of 25 kg N (CR) + 25 kg N (*Leucaena*) was obtained. For every Mg (ton) increase in SOC stock in the root zone, there was 0.09 Mg ha^{-1} increase in grain yield of sorghum. They also reported that stabilization of the SOC stock (zero change under cropping) requires a minimum input of 1.1 Mg C ha^{-1} $year^{-1}$. Application of 50 kg N ha^{-1} through synthetic fertilizer also maintained the SOC stock at the antecedent SOC level. Therefore, a combined use of organic manure (crop residues and FYM) or green leaf manure along with chemical fertilizer is essential for enhancing SOC sequestration in sorghum cultivation in Vertisols during the post monsoon season in Central India.

The results obtained from the long-term permanent manurial trials in Tamil Nadu showed a build-up in OC status of soil with application of N, P and K in combination with organic manure. In these experiments, an initial decline in OC content for 7 years and a build-up in the last 9 years were observed. Under the intensive cropping system of cultivation, the soil organic carbon build-up was observed in all the treatments, including the unmanured control, and was maximum with the combined application of inorganics and organics (100% NPK + Farmyard manure (FYM)), which was attributed to enhanced root biomass over a period of 30 years (Santhy and Devarajan 2005).

Venkanna et al. (2014) conducted experiments to study the changes in organic and inorganic carbon stocks in soils under different land-use systems in semiarid tropical Warangal district (Fig. 1.1), Andhra Pradesh. It was observed that Vertisols and associated soils contained greater total C stocks, followed by Inceptisols and Alfisols (Fig. 1.2). Among the different land-use systems, total C stock was highest in soils under forest, followed by fodder, paddy, maize, cotton, red gram, intercrop, chilli and permanent fallow; while the lowest content was under the castor system. Soil nitrogen also followed a similar trend as SOC stock. A significant correlation ($P < 0.05$) was obtained between SOC stock and soil nitrogen with Mandal-wise annual rainfall. A surface map of soil C stock and soil N was prepared for Warangal district using Kriging interpolation techniques, and total C stock was estimated to be 0.088 Pg, out of which SOC stock was 77% and SIC stock was 23% for the district. In a relationship developed between Walkley-Black Carbon and SOC estimated through the dry combustion method using a CN analyser, it was found that Walkley–Black carbon could recover up to 90% of SOC for semiarid tropical soils. The relationship between C inputs and C stock was almost linear up to a carbon input of 4 Mg ha^{-1} $year^{-1}$ (Fig. 1.3).

Studies conducted by International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) revealed that, in Maharashtra, conversion of forest land into agricultural land resulted in a decline of SOC, rapidly in the first year and slowly thereafter attaining equilibrium within 30–50 years. The conversion of forest land into crop land has been reported to decline significantly the SOC content to reach a Quasi-Equilibrium Value (QEV) of 1–2% within 5–15 years (Balaguravaiah et al. 2011). In

Table 1.1 SOC sequestration rate with different integrated nutrient management practices under important rainfed production systems

Production system#/ location*/ duration^/no. of years+ of permanent manurial experiments	Treatment details	Best management practices	SYI	C input Mg C ha^{-1} $year^{-1}$	C sequestration Mg C ha^{-1}	C sequestration rate Mg C ha^{-1} $year^{-1}$	Critical C input for zero management Mg C ha^{-1} $year^{-1}$
Groundnut # (Anantapur)* (1985–2004)^ (20 years)+	T_1 = control (no fertilizer), T_2 = 100% recommended dose of fertilizer (RDF) (20:40:40 N, P_2O_5, K_2O), T_3 = 50% RDF+ 4 Mg groundnut shells (GNS) ha^{-1}, T_4 = 50% RDF+ 4 Mg FYM ha^{-1}, T_5 = 100% organic (5 Mg FYM ha^{-1})	T_3 = 50% RDF+ 4 Mg groundnut shells (GNS) ha^{-1}	0.48	3.45	11.43	0.57	1.12
Finger millet (Bangalore) (1978–2004) (27 years)	T_1 = control, T_2 = 10 Mg FYM ha^{-1},T_3 = 10 Mg FYM ha^{-1}+ 50% NPK, T_4 = 10 Mg FYM ha^{-1} + 100% NPK, T_5 = recommended NPK (50: 50:25 kg NPK ha^{-1} – finger millet)	T4 = 10 Mg FYM ha^{-1} + 100% NPK	0.59	3.10	15.4	0.82	1.13
(Finger millet–groundnut) (Bangalore) (1991–2004) (13 years)	T_1 = control, T_2 = 10 Mg FYM ha^{-1},T_3 = 10 Mg FYM ha^{-1}+ 50% NPK, T_4 = 10 Mg FYM ha^{-1} + 100% NPK, T_5 = recommended NPK (25:50:25 kg NPK ha^{-1} – groundnut; 50: 50:25 kg NPK ha^{-1} – finger millet)	T_4 = 10 Mg FYM ha^{-1} + 100% NPK	Groundnut: 0.21; finger millet: 0.76	3.03	9.3	1.64	1.62

Rabi sorghum (Solapur) (1985–2006) (22 years)	T_1 = control, T_2 = 25 kg N ha^{-1} (urea), T_3 = 50 kg N ha^{-1} (urea), T_4 = 25 kg N ha^{-1} through sorghum residue (CR), T_5 = 25 kg N ha^{-1} through FYM, T_6 = 25 kg N ha^{-1}(CR) + 25 kg N ha^{-1}(urea), T_7 = 25 kg N ha^{-1} (FYM) + 25 kg N ha^{-1}(urea), T_8 = 25 kg N ha^{-1} (CR) + 25 kg N ha^{-1}(*Leucaena* clippings), T_9 = 25 kg N ha^{-1} (*Leucaena*), T_{10} = 25 kg N ha^{-1} (*Leucaena*) + 25 kg N ha^{-1}(urea)	T_8 = 25 kg N ha^{-1} (CR) + 25 kg N ha^{-1}(*Leucaena* clippings)	0.48	3.40	14.4	0.89	1.10

Srinivasarao et al. (2012a, b, c, d, e, f, 2014)

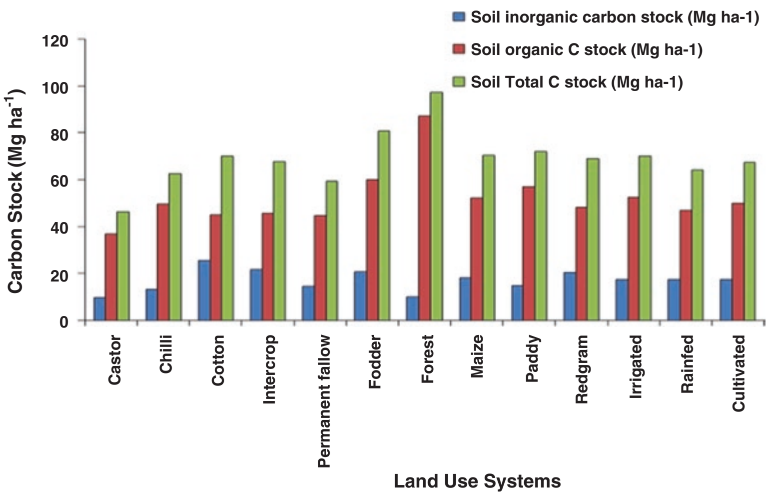

Fig. 1.1 Carbon stocks (Mg ha^{-1}) under different land use systems in Warangal district (Venkanna et al. 2014)

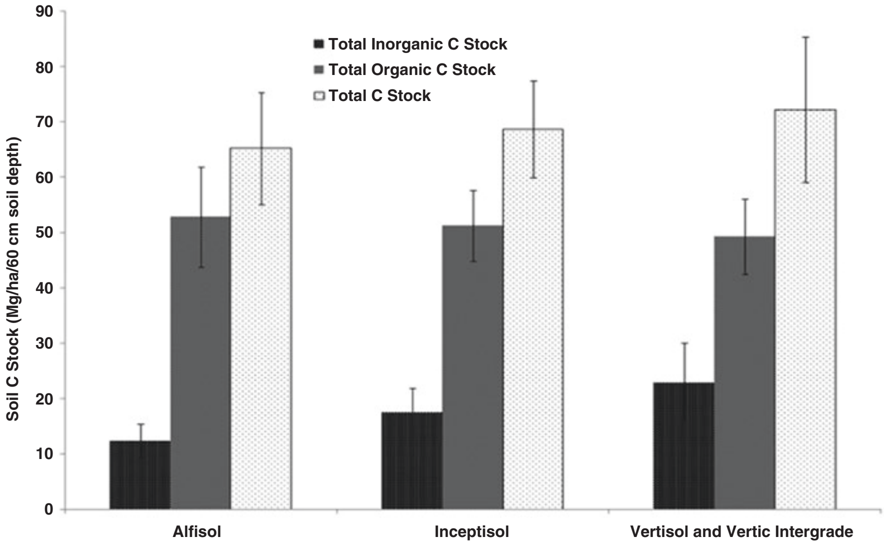

Fig. 1.2 Carbon stocks (Mg ha^{-1}) in different soils at 0–60 cm depth in Warangal district (Venkanna et al. 2014)

this study, of the four benchmark sites under different systems (horticultural, agricultural and forest), the forest system (FS) contained a higher amount of SOC, which ranged from 0.7% to 0.9%. The corresponding figures for horticultural systems and agricultural systems (AS) were 0.8% and 0.5%, respectively. The QEV was found to be highest (0.76–0.80%) in the 70-year-old forest ecosystem. Out of the three

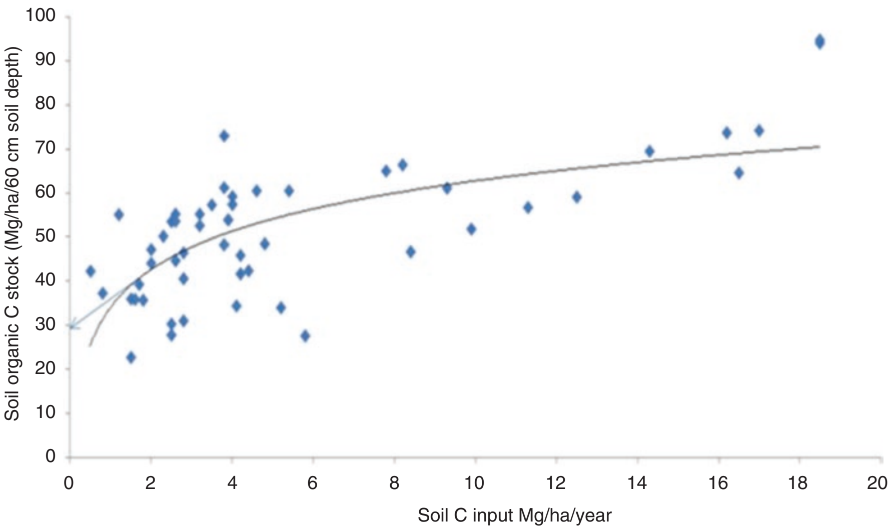

Fig. 1.3 Relationship of carbon inputs and carbon stocks in soils (Venkanna et al. 2014)

systems, the QEV of the SOC decreases in AS to a greater extent. Among the different cropping systems, horticulture-based cropping systems (orange-based cropping) had a higher amount of water-soluble carbon and water-soluble carbohydrates than arable field crop; however, the least amount of these parameters was found under the cotton-based cropping system.

Among ten soil series, soil respiration was higher in the surface soils, indicating greater biological activity in the upper layers of soil profile (Ramesh et al. 2007). The soil respiration decreased with increasing soil depths. In comparison to the three management systems, high management (HM) in agricultural and horticultural systems recorded higher soil respiration values over low and farmers' management. Boripani series under the forest ecosystem recorded highest soil microbial biomass C (SMBC) (384.4 μg C g^{-1} soil) over all other series under the study. Analysis of MBC and N showed a similar trend as that in soil respiration studies, where greater microbial biomass was recorded in the surface layers over the sub-surface ones. A gradual decreasing pattern was observed with increasing soil depths. The surface soils recorded significantly higher values of organic carbon than the sub-surface depths. The C:N index was found to be maximum for horticulture (0.50) and forest (0.45) systems in case of black soils and forest system (0.76) and permanent fallow (0.69) in red soils. Among the annual crops, cereal-based cropping systems were found to have a high value of index as compared to cotton and soybean-based cropping system, although more or less similar index was observed in the entire three dominant crop-based systems.

Bhattacharyya et al. (2007) reported that the SOC values in the surface (0–30 cm) follow the trend of forest system > permanent fallow (grassland), horticultural system > agricultural system > wasteland. The SOC in surface horizon under agricultural systems shows higher values for cereal-based system (0.79%), followed by soybean systems (0.70%) and cotton-based systems (0.68%). Interestingly, the soil inorganic carbon values were highest in cotton-based systems (1.53%), followed by soybean-based systems (0.66%) and cereal-based systems (0.29%). Koppad and Tikhile (2014) studied the SOC distribution pattern in different land use classes in Uttara Kannada district of Karnataka and reported that SOC content in dense forest at 1.0 m depth was 1.29%, followed by horticulture plantation (1.22%), and less SOC was found in agriculture land (0.75%). The dense forest with mixed species sequesters more carbon than plantations of mono species. Padalkar et al. (2013) reported from Malvan district of Maharashtra that mudflats having dense vegetation of mangroves contain higher percentage of organic carbon than mudflats with low vegetation. Sharma (2012) reported that application of 25 kg N ha^{-1} (FYM) +25 kg N ha^{-1} (urea) recorded 40% higher organic carbon content in Vertisols of Solapur after 13 years. In cotton-based system at Akola, organic carbon content was significantly higher in conventional tillage + one interculture (4.67 g kg^{-1}) system, followed by the practice of reduced tillage + one interculture (4.21 g kg^{-1}), which were 20% and 8% greater, respectively. In finger millet at Bangalore, highest carbon stock was recorded with minimum tillage (MT) + 100% organic N (9.01 Mg ha^{-1}), which was on par with reduced tillage (RT) + 100% organic N (8.24 Mg ha^{-1}), followed by RT + 50% organic N + 50% inorganic N (7.37 Mg ha^{-1}). When compared with conventional tillage (CT) (5.81 Mg ha^{-1}), significantly higher carbon stock was observed with MT (7.39 Mg ha^{-1}) (21%) and RT (7.17 Mg ha^{-1}) (19%). Application of 100% organic N recorded significantly higher carbon stock (7.72 Mg ha^{-1}), followed by 50% organic N + 50% inorganic N (6.73 Mg ha^{-1}) (Sharma 2014).

1.4 Cropping Systems Effect on Soil Organic Carbon Pool

1.4.1 Rice-Based Cropping Systems

Significant improvement in organic carbon content (0.52%) was found in sun hemp–rice–rice cropping system, which was comparable with green gram–rice–rice system (0.67%) among other rice-based cropping systems tested after 2 years of cropping in sandy loam soils of Anantapur in the scarce rainfall zone (Bhargavi et al. 2007). The improvement in SOC in sun hemp–rice–rice and green gram–rice–rice cropping systems is due to incorporation of sun hemp and green gram haulms in addition to roots, stubbles and leaf fall during crop growth period Mg.

Long-term fertilizer experiments are considered as tools for providing viable information on the impact of continuous application of fertilizers and manures with varying combinations on soil fertility and sustainability (Reddy et al. 2006). There was an improvement in soil organic carbon accumulation with the practice of either integrated use of recommended dose of fertilizer (RDF) and FYM or use of FYM alone at Jagitial (Balaguravaiah et al. 2011). Organic carbon content increased from 7.9 g kg^{-1} to 10.5 g kg^{-1} over 8 years (Fig. 1.4). Soil organic carbon build-up was observed in all the treatments.

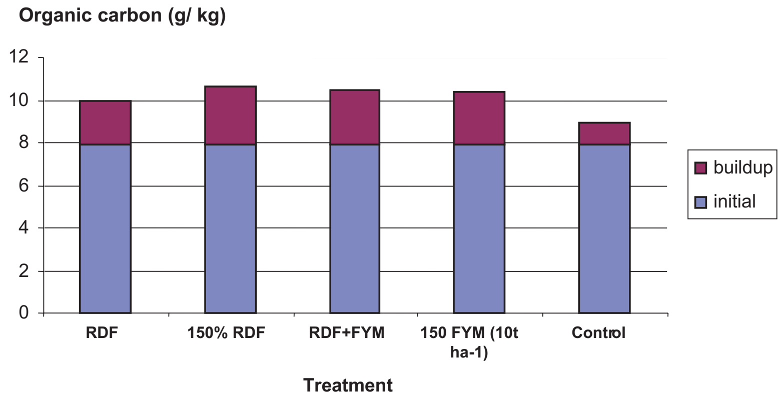

Fig. 1.4 Accumulation of SOC under different soil management practices in rice–rice system (Balaguravaiah et al. 2011)

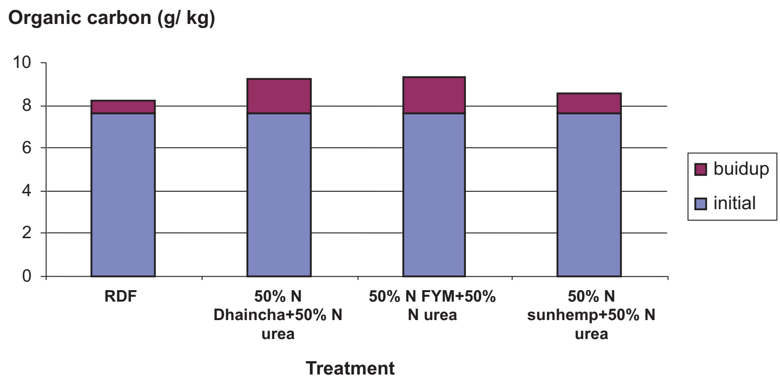

Fig. 1.5 Accumulation of SOC in rice–pulse system (Balaguravaiah et al. 2011)

Application of 25% or 50% of N through *Gliricidia* or FYM improved the organic carbon content in soil after 37 seasons of continuous cropping during *kharif* and *rabi* season (Balaguravaiah et al. 2011). A depletion in organic carbon was observed in treatments where organics were not applied, that is, control, 50% RDF and 100% RDF (Fig. 1.5). About 50% increase in organic carbon was observed in 50% RDF + 50% N through *Gliricidia*. Further, application of 25% or 50% of N through *Gliricidia* along with 50% NPK resulted in similar yield as that of 100% RDF and saved about 25% N for *rabi* rice (Reddy et al. 2006). Variations in organic carbon after 18 years of rice–rice system at Andhra Pradesh Rice Research Institute (APRRI), Maruteru (Fig. 1.6), showed that carbon accumulation was highest in 50% RDF +50% N through green manure (GM) (9.2 g kg^{-1}) followed by 50% RDF + 50% N through FYM (6.8 g kg^{-1}). The lowest carbon content of 5 g $kg^{-1}$was found in control (Balaguravaiah et al. 2011).

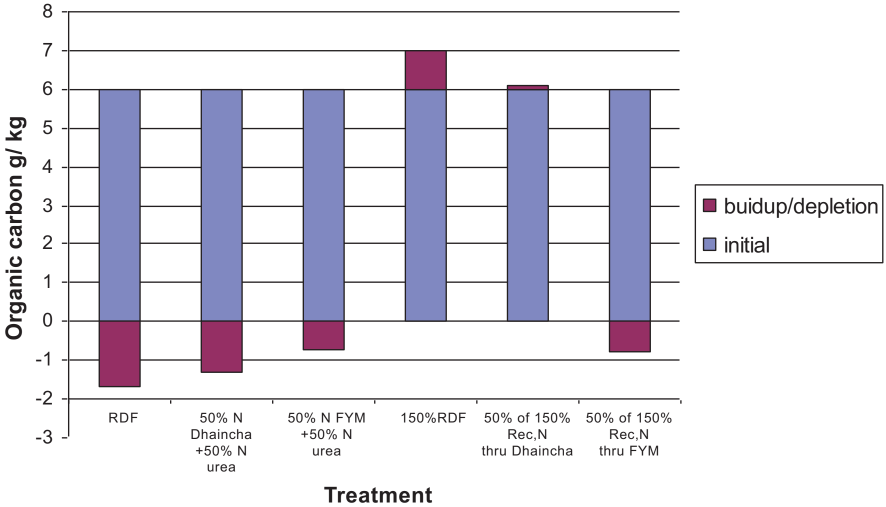

Fig. 1.6 Accumulation of SOC in rice–maize system (Balaguravaiah et al. 2011)

1.4.2 Rice–Pulse System

Build-up of soil organic carbon in the rice–pulse system at Agricultural Research Institute, Garikapadu, on red sandy loam soils was observed in treatments where dhaincha or sun hemp or FYM contributed to 50% of recommended N dose of fertilizer (RDF) than 100% of RDF (Fig. 1.5) through inorganic source of fertilizer alone (Balaguravaiah et al. 2011). Organic carbon accumulation in soil increased from 7.6 to 9.3 g kg^{-1} in different nutrient management options.

1.4.3 Rice–Maize System

However, organic carbon accumulation was found to be negative over initial status in rice–maize system at Agricultural Research Institute, Garikapadu, on red sandy loam soils of Nagarjuna Sagar Project (NSP) left command area in spite of addition of FYM or incorporation of dhaincha for 3 years (Balaguravaiah et al. 2011). Probably, this can be attributed to the exhaustive nature of both the crops (Fig. 1.6). The results suggest that a large quantity of organics should be recycled or to be added to sustain SOC as well as yields in this particular cropping system, which is becoming popular in coastal area (especially in Krishna western delta) in recent past/years due to its high remuneration than the rice–pulse system, which exist earlier in these areas.

1.4.4 Rainfed Groundnut Cropping System

The results of long-term Integrated Nutrient Management (INM) experiment (1985–2010) revealed that the accumulation of organic carbon was higher than inorganic carbon in all the soil profiles under different management practices. There was an improvement in SOC status in 50% RDF + 4 Mg FYM ha^{-1}, and groundnut shells applied plots only with reference to initial status (Balaguravaiah et al. 2005a). Total carbon was highest in the treatment where a combination of organic and inorganic manures was applied. Total carbon ranged from 69.25 Mg ha^{-1} (control, i.e. no manures and fertilizers) to 95.21 Mg ha^{-1} (50% RDF + 4 Mg FYM ha^{-1}). These results showed that regular additions of nutrients through fertilizers along with organic manures are necessary for carbon sequestration, particularly in soils with nutrient deficiencies. The increase in organic carbon levels after 21 years of long-term groundnut cropping, fertilization and manuring showed a positive balance of organic carbon in all the treatments (Srinivasarao et al. 2009). The build-up of organic carbon ranged from 0.05% in control (i.e. no manures and fertilizers) to 0.34% in 50% RDF + 4 Mg FYM ha^{-1}. Application of 4 Mg groundnut shells ha^{-1} along with 50% RDF was found to improve organic carbon content equally in the top 20 cm of the profile.

The Soil Quality Index (SQI) and Sustainability Yield Index (SYI) were also calculated for the above treatments, and SQI was highest (1.473) in the treatment 50% RDF + FYM @4 Mg ha^{-1}, followed by 100% RDF treatment (Balaguravaiah et al. 2005b). However, the SYI was almost at par in both the treatments.

1.4.5 Sugarcane-Based System

In sugarcane sole cropping system at Anakapalle (high-rainfall north coastal zone), organic carbon build-up was observed in all treatments except control where slight depletion was observed after 3 years (Balaguravaiah et al. 2011). The build-up of carbon was highest in 100% recommended dose of N (RDN) through inorganic, followed by 100% RDN through FYM and 100% RDN through sugarcane trash compost.

1.4.6 Mesta-Based Cropping System

In a field experiment at Amudalavalasa (high-rainfall north coastal zone of Andhra Pradesh), mesta was grown under rainfed conditions in red loam soil for 3 years with application of different organics. Slight depletion in SOC was observed where neem cake was applied at 1.25 Mg ha^{-1} (Balaguravaiah et al. 2011). In all other treatments, namely FYM at 5 Mg ha^{-1}, vermicompost at 2.5 Mg ha^{-1} and poultry manure at 2.5 Mg ha^{-1}, the SOC increased from 1.3 to 3.7 g kg^{-1}.

1.5 Carbon Management Through Different Land Use Systems

Carbon management through afforestation and reforestation in degraded natural forests is a useful option and agroforestry is useful, as it sequesters carbon in vegetation and possibly in soils. Also, more intensive use of land for agricultural production reduces slash-and-burn/shifting cultivation and to that extent agroforestry increases the income of the farmers. In India, average sequestration potential of C in agroforestry has been estimated to be 25 Mg C per ha over 96 million ha, but there is a considerable variation in different regions depending on the biomass production. Evidence is now emerging that agroforestry systems are promising management practices to increase above ground and soil C stocks to mitigate greenhouse gas emissions. The carbon sequestration potential of tropical agroforestry systems in recent studies is estimated between 12 and 228 Mg ha^{-1}, with a median value of 95 Mg ha^{-1} (Ram Newaj and Dhyani 2008). Higher status of soil organic carbon (SOC) was recorded under different alternate land use systems than in agricultural land and fallow land (Reddy 2002). Among different land use systems, higher status of SOC (Mg ha^{-1}) was recorded under agri-silviculture (19.93) followed by silvi-pasture (17.47), agri-sylvi-horti system (17.02), *Leucaena leucocephala* (15.68), *Acacia albida* (15.23), *Eucalyptus camaldulensis* (13.22), *Tectona grandis* (12.54), *Dendrocalamus strictus* (11.65), *Azadirachta indica* (11.43) and agricultural land (9.4). Carbon mitigation potential was also high (4.23) in the agri-silviculture system as compared to that in fallow land (Table 1.2).

Soil organic stocks of Nalgonda district under different cropping systems were estimated, and it was found that there was a wide variation in carbon stocks between different cropping and land use systems (Reddy 2006). Among different cropping systems, higher carbon density (mean) was observed in irrigated systems such as sugarcane (5.5), followed by cotton (5.05) and rice (4.9). Among rainfed crops,

Table 1.2 Soil organic carbon per unit area and carbon mitigation potential of different land use systems (Reddy 2002)

Sl. no.	Land use systems	SOC (Mg ha^{-1})	C mitigation potential
1	Fallow land	4.7	1.0
2	Agricultural land	9.4	2.0
3	Agri-silviculture	19.93	4.23
4	Silvi-pasture	17.47	3.71
5	Agri-silvi-horti system	17.02	3.42
6	*Eucalyptus camaldulensis*	13.22	2.80
7	*Leucaena leucocephala*	15.68	3.23
8	*Dendrocalamus strictus*	11.65	2.47
9	*Acacia albida*	15.23	3.23
10	*Azadirachta indica*	11.43	2.42
11	*Tectona grandis*	12.54	2.66

carbon density was more in castor + red gram intercropping system (4.09) than in sole castor crop (3.4 kg m^{-2}). However, carbon density was more influenced by soil type and clay content (Table 1.3). The SOC of Nalgonda district ranged from 2.0 to 13 kg m^{-2}, and the majority of the area comes under carbon density range between 3.5 and 5.0 kg m^{-2}.

Many agronomic, forestry and conservation practices including best management practices lead to a net gain in carbon fixation in soil. Soils gaining SOC are also generally gaining in other attributes that enhance plant productivity and environmental quality. In general, there is favourable interplay between carbon sequestration and various recommended land management practices related to soil fertility, tillage, grazing and forestry. Once sequestered, carbon remains in the soil as long as restorative land use and other best management practices are followed. It is suggested that long-term application of inorganic fertilizers along with organic manures plays a vital role in not only obtaining higher crop yields but also sustaining soil fertility and sequestering high amounts of organic carbon in the long run even under arid, semiarid and sub-humid climates. The dynamics of carbon sequestration process must be evaluated in the context of local soil and crop attributes.

Table 1.3 SOC density (kg m^{-2}) in different crop/land use systems (Reddy 2006)

Soil classification	Crop/land use system	SOC (kg m^{-2})
Typic Rhodustalf	Castor–red gram	4.155
Vetric Ustropept cal	Castor–red gram	3.865
Typic Ustorthent	Castor–red gram	2.990
Paralithic Ustropept cal	Castor–red gram	6.472
Typic Haplustalf	Castor	3.512
Typic Haplustalf	Rice	3.062
Aquic Ustropept	Rice	4.841
Typic Rhodustalf	Rice	1.924
Lithic Ustorthent	Rice	3.645
Typic Ustropept	Rice	4.024
Typic Rhodustalf	Rice	4.284
Typic Haplusterts	Rice	3.132
Typic Haplustalf	Rice	6.578
Leptic Haplusterts cal	Rice	6.595
Typic Haplustalf cal	Rice	13.323
Typic Paleustalf cal	Rice	2.912
Rhodic Paleustalf	Cotton–red gram	3.379
Lithic Ustropept	Sorghum	3.707
Rhodic Paleustalf	Red gram	4.823
Typic Haplustalf	Red gram	4.915
Typic Paleustalf cal	Cotton	5.671
Leptic Haplusterts cal	Sugarcane	7.996
Typic Haplustalf cal	Sugarcane	2.358

1.6 Conclusion

Management practices such as conservation tillage, application of residue and manures, appropriate cropping systems including legumes, green leaf manuring through leaves of N-fixing trees such as *Leucaena*, conjunctive use of organic and inorganic sources of nutrients, balanced fertilization, etc., play an important role in improving organic C in soil. Besides management practices, soil types, parent material, clay content and other soil properties and climate are very important factors that determine carbon sequestration, carbon stock, CO_2 emissions and overall net carbon balance in soil. The Deccan Plateau has huge diversity in terms of climatic and edaphic conditions besides land use systems and soil management practices. Therefore, carbon inputs and outputs and net carbon balances of carbon pools also vary widely. Long-term application of inorganic fertilizers along with organic manures in integrated manner plays a vital role in not only obtaining higher crop yields but also sustaining soil fertility and sequestering high amounts of organic carbon in the long run under low-, medium- and high-rainfall regions. Cropping systems such as rice–maize, if continued for long may deplete soil organic carbon. Recommended management practices including conservation tillage, erosion control and residue recycling are suggested. In the rice–rice cropping system, prior raising of sun hemp or green gram was the best option for sequestering organic carbon and to bring sustainability. Since significant reduction is observed in seasonal CH_4 emission, in scientific irrigation practices over continuous flooding, SRI cultivation and aerobic rice are better options in tank-fed and borewell-irrigated areas. The highest SOC is observed in the agri-silviculture system, followed by the silvi-pasture and agri-silvi-horti systems. Regular additions of nutrients through fertilizers along with organic manures are necessary for carbon sequestration, particularly in soils with nutrient deficiencies. With the introduction of carbon trading, agroforestry systems may become more attractive. In crop husbandry as well as agroforestry, research addressing both biophysical and socio-economic issues and identifying, developing and bringing out best management practices with reference to carbon sequestration and sustainable production needs to be intensified. Large areas of degraded lands are available for re-vegetation and reforestation. These lands must be given high priority for carbon sequestration. To mitigate climate change, there should be policy reforms to encourage environmental sustainability (including the establishment of environmental guidelines), improve infrastructure and planning related to carbon sequestration research, long-term monitoring and large financial commitment. Procedures are needed to be developed for soil carbon accounting system, and policies need to be established, which provide incentives for net soil carbon sequestration at the global scale. With the introduction of carbon trading, agroforestry systems may become more attractive. In agroforestry, research addressing both biophysical and socio-economic issues of carbon sequestration is needed. However, the main challenge remains how to make the farmers adopt the agroforestry to meet their demand of fodder, fuel and food grain and enter into carbon market.

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2 Inclusion of Legumes in Rice–Wheat Cropping System for Enhancing Carbon Sequestration

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Abstract

Sustainability of the rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system (RWCS) is fundamental for the food security of Asian countries. Continuous practice of RWCS has emerged soil and environmental issues, which are now increasingly being evident. Lack of crop diversification, intensive tillage practices, residue burning, overexploitation of groundwater and imbalanced use of fertilizers have been found as major reasons for deteriorating soil health and sustainability of RWCS. Results of long-term experiments demonstrated that depletion of soil organic carbon (SOC) in RWCS primarily threatens the sustainability of the system. In parallel, increase in the SOC of tropical soils is equally important for conserving the natural resources and up-scaling resource-use efficiency. Grain legumes add a significant amount of C to soil through root biomass, leaf fall and release of root exudates. Moreover, the potential of legume cover crop on soil health is also known. Therefore, inclusion of grain legumes in RWCS is a promising approach for crop diversification and maintaining positive C balance. Further, stabilization of non-labile C (recalcitrant C-pool) from legume residue is important for SOC persistence in the long term. Particular to the Indo-Gangetic Plain region, growing of mung bean (*Vigna radiata*) in summer fallow of RWCS and inclusion of chickpea (*Cicer arietinum*) in RWCS have

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been found to be effective to improve the SOC, particularly when legume residue is returned to soil. Rice–wheat–mung bean/urdbean (*Vigna mungo*), rice–wheat–cowpea (*Vigna unguiculata*), rice–chickpea/lentil (*Lens culinaris*)/field pea (*Pisum sativum*) and pigeon pea (*Cajanus cajan*)–wheat are alternative rotations, which could be popularized in RW-growing areas for improving soil health and to enhance C-sequestration. In-depth understanding of C-sequestration processes is essential to design alternative pulse-inclusive rotation/s and mitigating the known consequences of continuous RWCS.

Keywords
Carbon sequestration · Cropping system · Legumes · Pulse crop residues

2.1 Introduction

Rice–wheat cropping system (RWCS) is the most extensively grown (~13.5 m ha) cropping system of South Asia (Chauhan et al. 2012). Certainly, the dramatic success of so-called "Green Revolution" enabled with improved crop management and high-yielding cultivars to a large extent improved the productivity and profitability of RWCS. Thus, the importance of RWCS is paramount for food and livelihood security of a large number of farmers in the Asian countries. Basically, the conventional RWCS is mostly input intensive and exhaustive in nature. Several experimental reports indicated that long-term practice of conventional RWCS has led to the several second-generation problems such as deterioration of soil fertility and multi-nutrient deficiencies, the decline in soil organic C (SOC), deterioration of soil physical properties, and much more. Subsequently, substantial slowdown in the productivity of RWCS is increasingly being evident. In Upper-Gangetic and Trans-Gangetic Plains of India, the consequences of continuous practice of conventional RWCS are prominent and alarming (Chauhan et al. 2012; Nandan et al. 2018b). Therefore, concerted efforts should be directed towards mitigating the issues associated with the long-term cultivation of RWCS.

Extensive research evidence specified that improvement in SOC is fundamental for higher productivity and sustainability of RWCS. Although rice soils serve as a potential sink for terrestrial C-sequestration and reduced soil oxidation favours C-stabilization, the flooded rice ecology is also the major source of two potential greenhouse gases (GHGs) – methane (CH_4) and nitrous oxide (N_2O) (Zhang et al. 2016). Conventional flooded rice is the source of ~19% total agricultural CH_4 emission worldwide (USEPA 2006; Hazra and Chandra 2016). Maintenance and build-up of SOC are challenging in RWCS of tropical environments because of faster temperature-mediated oxidation of SOC (Mandal et al. 2007); almost similar feeding zone and plant nutrient demand of the component crops in the RWCS also lead to mono-cropping (Hazra et al. 2014; Venkatesh et al. 2017). Again lack of crop diversification in RWCS causes several soils and environment issues, and intensifies pest problems (Chauhan and Abugho 2013; Congreves et al. 2015). However, pulses or grain legumes were the integral part of crop rotation in rice-based systems during the 1960s in Indian states such as Uttar Pradesh, Bihar and West Bengal. But, later, a large number of pulse-growing farmers of the Indo-Gangetic Plain (IGP) inclined towards wheat cultivation because of the fast development of irrigation facilities and availability of input-responsive, high-yielding wheat cultivars.

Pulses or grain legumes are well known for their role in soil health restoration, resource conservation and sustainable crop production (Ghosh et al. 2007). With inherent characteristics such as deep root system, higher leaf fall, biological N-fixation and release of root exudates, legume crops are acknowledged as potential candidate crops for improving soil C stock and soil overall quality (Ghosh et al. 2012). Hence, pulses are increasingly being advocated for diversifying cereal–cereal rotation, with the objectives of arresting degradation of natural resources, improving soil quality and ensuring long-term sustainability (Kumar et al. 2012, 2016). Presently, conservation agriculture (CA) is becoming popular in RWCS in the South Asia where pulses or grain legumes are recommended as a 'missing ingredient' for the restoration of soil health and resource conservation under CA (Snapp et al. 2002; Nandan et al. 2018a). It is important to mention that the sustainability of RWCS in northwestern India is threatened by overexhaustion of groundwater, development of secondary salinization and deterioration of soil physical condition that eventually paved the way to include a less water and input-demanding crops such as short-duration pigeon pea in the rainy season in place of the rice crop (Kumar et al. 2016; Singh et al. 2018). Despite the advantages, pulses or grain legumes are often overlooked in irrigated cereal-based input-intensive production systems. However, a higher emphasis is currently given to upscale the pulse crops area in South Asian countries to meet the growing domestic demand of pulses. Several governmental initiatives have already in place to enhance the pulses area and production. Therefore, the inclusion of pulses in new niches including irrigated RWCS will certainly contribute to higher pulse production and conserve depleting natural resources.

2.2 Present Overview of RWCS

Spreading over large parts of India (10.3 m ha), Pakistan (2.3 m ha), Nepal (0.6 m ha), Bangladesh (0.5 m ha) and Bhutan, RWCS is the most important cropping system of South Asia (Timsina and Connor 2001; Chauhan et al. 2012). In China, the system is being practised in an area of ~13.0 m ha. More than 85% of the RWCS being practiced in South Asia is concentrated in the IGP region. In view of the production and area coverage, the RWCS ranks first in 30 major cropping systems of India. Decline in soil quality particularly SOC (Venkatesh et al. 2013), emerging multi-nutrient deficiency (Venkatesh et al. 2017), overexploitation of ground water (Humphreys et al. 2010; Hazra and Chandra 2016) and progressive development of secondary salinization are increasingly being realized for the present declining trend of productivity in RWCS. As already mentioned, a number of problems have cropped up in the region due to intensive tillage operations including puddling (wet tillage) for rice cultivation. The prevalence of low level of SOC is the most serious constraint in achieving the potential productivity. In the IGP regions, the soil of RW-growing areas is predominantly alluvial type and was very fertile during the 1980s. However, continuous practice of RWCS without any crop diversification and following the flawed conventional practices has crumbled the soil fertility as well as soil quality. As estimated from the current rate of fertilizer application and nutrient removal by the component crops in RW rotation, the apparent nutrient balance is mostly negative. As a result, there is emergence of secondary and micronutrient deficiencies in the soil under the system.

In order to create an anaerobic flooded ecology for rice crop establishment, puddling (wet tillage) is practiced since a long time (Tripathi et al. 2005). The puddling operation is carried out with the objective of creation of an impervious layer for improving water retention and suppressing the weeds. However, long-term practice of puddling had a negative impact on soil aggregation, beneficial microorganisms and overall soil environments (Soane et al. 2012; Pandey et al. 2012). The belowground (root) growth of successive wheat crop is constrained by puddling in rice field, since it affects nutrient acquisition and overall crop performance (Hassan and Gregory 1999; Ishaq et al. 2001).

It is important to mention that two states of the IGP region, namely Punjab and Haryana, contribute to almost 80% of wheat and 50% of rice production of India and acknowledged as the most productive rice–wheat-growing area and as such known as the food bowl of India (Chauhan et al. 2012). The consequences of long-term practice of RWCS is high up in Trans-Gangetic and Upper-Gangetic Plains including Punjab and Haryana states. According to Chauhan et al. (2012), the situation may further deteriorate if the conventional practice continues in RW-growing areas. To reverse the degradation and ensuring sustainability of RWCS, attempts are made to develop strategic exp. and soil management framework. Declining water table in RW-growing areas is a major concern at present. In fact, in Upper- and Trans-Gangetic Plains, the water table below 9 m increased from 3% in 1973 to about 90% in 2004 and almost 100% in 2010 because of heavy pumping of groundwater through submersibles to meet the higher demand of water in rice crop (Kumar et al. 2010). In this perspective, agricultural production in Punjab, Haryana and Western Uttar Pradesh would not be sustainable unless major steps are taken to improve management of groundwater (Hira 2009). Intensive use of N fertilizers coupled with anaerobic rice production ecology facilitates higher emission of greenhouse gases in RWCS. Furthermore, the increasing NO_3^- concentration in groundwater in RW-growing areas causing serious health issues. In view of the above fact, it is high time to think about the alternative strategies to conserve the declining resources and achieve the desired crop productivity without much disturbing the ecology.

2.3 Importance of SOC in RWCS

The rice–wheat cropping system is predominantly grown in tropical environments, where the native SOC stock is low. Such low SOC is frequently documented as a potential yield-limiting factor for RWCS. Given the important role it plays in ensuring optimal physical, chemical and biological properties of soil, SOC is a critical soil attribute that directly influences the soil productivity (Blair and Crocker 2000). Also, soil nutrient availability, water retention capacity and soil-buffering ability are directly attributed to the quality and quantity of SOC (Paudel et al. 2014). According to the Bot and Benites (2005), soil C level determined the abundance of nutrient and equilibrium of various nutrient elements in soil. Increasing SOC in tropical RW-growing areas is a major challenge due to fast mineralization of SOC, intensive tillage practice that facilitates the detachment of aggregates and redistribution of C-rich sediments over the landscape and thereby accentuates C loss from soil to the atmosphere (Jenny and Raychaudhuri 1960). Further, substantial parts of soluble C fraction called dissolved organic carbon (DOC) are leached out from the soil profile (Moore et al. 1998).

Several studies have been carried out in RWCS, and the results mostly suggested that a higher level of SOC is essential to improve the productivity of component crops. From the long-term experiments in RWCS in Asia, Ladha et al. (2003) reported that depletion of SOC is one of the primary reasons for decline in grain yield. From a 19-year-old RWCS, the impact of different C parameters on crop performance was also examined, and the strong relationship between rice equivalent yield and microbial biomass C ($r^2 = 0.95$), mineralizable C ($r^2 = 0.68$), very labile C ($r^2 = 0.92$) and oxidizable organic C ($r^2 = 0.92$) was reported. In large parts of RW-growing areas in India, farmers use only N fertilizer as a plant nutrient source. The imbalance or faulty fertilization practices also have accelerated the loss of SOC. In a sandy–loam soil, prominent yield increment of rice and wheat crops was apparent with increase in SOC.

Agriculture contributes to ~20% of total anthropogenic GHG emission (Aydinalp and Cresser 2008). For example, rice-based cropping systems including the RW system largely contribute to total GHG emission (Kumar and Ladha 2011). In view of this, sequestering C in soil reduces GHG load in the atmosphere (Chan et al. 2008). In general, the fertilizer N use efficiency (NUE) is very low in RWCS (21–31% in rice and 32–52% in wheat) (Katyal et al. 1985). One of the reasons for low NUE is the low SOC, particularly in coarse-textured permeable soils. The farmers of Upper-Gangetic and Trans-Gangetic Plains used to apply a high rate of fertilizer N, and a part of the added N converts to NO_3, leaches down and pollutes the groundwater. At present, the NO_3 pollution is emerging as a real threat in different rice-growing areas of northwest India. Increasing SOC may be effective in reducing the environmental hazards through NO_3 pollution and will also upscale the NUE. At present, concerted efforts are being made to improve the soil quality and sustainability of RWCS by means of CA (Jat et al. 2014). In an integrated approach of conservation tillage, crop residue retention was found to be effective to improve the SOC, and the increase in SOC also helps to achieve a higher productivity of both the component crops.

2.4 Role of Pulses in Enhancing SOC

The potential of pulses or grain legumes to enhance SOC has been acknowledged in a number of literature studies. In fact, the plant architecture coupled with its distinct inherent characteristics favour C-sequestration. The legume could be a potential driver of crop diversification and agricultural sustainability with its short duration in nature, ability to withstand resource scarcity, deep root system and ability to sequester C.

2.4.1 Cover Crop and System Intensification

In the tropical environments, fallowing (cultivated fallowing) has a negative impact on SOC. The magnitude of impact largely depends on the length and time of the fallow period. According to Srinivasarao et al. (2012), the rate of increase in SOC due to a change in cropping intensity is a function of climatic conditions, total biomass production and ground cover duration. Cover crops or catch crops are normally grown to trap the fallows (Poeplau and Don 2015). Therefore, it is a promising option to sequester C in soils with inclusion of leguminous cover crops (Fig. 2.1). Development of short duration cultivars of mung bean and urdbean allows pulse crops to utilize the fallow period (Dabney et al. 2001). The increase in SOC by cover crops is associated with more production of crop belowground biomass, improved soil microflora and increase in nutrient input. The cover crop benefits are more conspicuous when the crop residues are returned. Added to this, cover cropping improves biodiversity in the agro-ecosystem (Lal 2004). Legume inclusion in predominating cropping systems coupled with residue addition prevents rapid loss of soil moisture, improves SOC and bio-physical properties of soil (Kumar et al. 2018). Important factors controlling the SOC levels include climate, parent material, soil fertility, biological activity, cropping patterns and land use. In cereal–cereal rotation, particularly in RWCS, legumes can be grown as a green manure or, as a catch crop during summer, or as a substitute crop.

2.4.2 Root Carbon

Mostly, grain legumes have deep and robust root system. Substantial amount of C leftover in soil exists as root biomass following harvest of pulse crops, which contributes to SOC. The root of pigeon pea crop extends more than 1.5 m and is recognized as a potential crop for deep soil C-sequestration. The sequestration of C in deep soil is less prone to the oxidative process and thus has longer persistence in soil. Nowadays, there is renewed interest has been generated in the area of deep soil C through deep-rooted legumes. Besides this, a significant part of photosynthetic C of leguminous

Fig. 2.1 Cover cropping of mung bean (*Vigna radiata*) in summer (April–June)

plant is accumulated in soil as root exudates such as amino acids, phenolic acids and organic acids, etc., which also serves as the source of organic C (Kumar et al. 2006). Endowed with higher lignin-type compound, the root of legumes contributes to non-labile C (recalcitrant C pool) in soil with long residence time (Hazra et al. 2018a, b). Hence, a significant amount of root lysis and root exudates in pulse crops could be the important C-input. Soil microorganisms are of great importance to agro-ecosystem functioning and sustainability through their contributions to nutrient cycling and soil structure maintenance. Besides the SOC enhancement, pulses like mung bean and chickpea have the ability to enhance the soil microorganisms inhabiting its rhizosphere, thereby improving soil biological properties and soil health.

2.4.3 Leaf Litter Fall

Leaf litter fall is a unique character of most of the grain legumes. Leaf litter from legumes adds organic matter and essential plant nutrients to the succeeding crop. As estimated by Sharma et al. (1980), a significant fall of 30.0 and 16.7 q ha^{-1} leaves (dry weight) in pigeon pea crop sown during the rainy and post-rainy seasons, respectively. Crops such as chickpea (*Cicer arietinum)* and lentil also have high leaf fall during senescence. This way addition of leaf C to the soil can significantly contribute to the soil C stock (Fig. 2.2).

2.4.4 Characteristics of Pulse Residue and SOC

Soil organic carbon status reflects the balance between C inputs and C losses over time. We can represent this as,

$$dCs / dt = hA - (kCs + Cr)$$

where *d*Cs/*dt* = changes over time in mass of organic C stored in the soil profile; A = carbon addition (crop residue including roots); *h* = humification coefficient

Fig. 2.2 Leaf litter fall in pigeon pea (*Cajanus cajan*)

(amount of residual C that stabilizes as SOC); Cs = soil organic carbon pool; k = decomposition rate and Cr = amount of carbon lost through erosion. The quality and quantity of pulse residue may vary substantially from that of cereals. Growing a pulse in place of a cereal crop could potentially influence both A and h, thereby influencing the magnitude of SOC changes. Many C-sequestration studies have stressed upon the assessment of total soil N because of its importance in C-sequestration in agro-ecosystems (Bronson et al. 2004).

2.5 Inclusion of Legumes in RWCS and C-Sequestration

Crop diversification remains an important step towards the goal of increasing the profitability and sustainability of agriculture (Hatfield and Karlen 1994). Legumes are often the primary choice (Hazra et al. 2014) for such diversification. Pulses crop can serve a key role in crop diversification/intensification in different production system including RWCS. Inclusion of grain legumes (pulse crops) in the cropping system has been known since time immemorial (Ghosh et al. 2007). In this system, pulse crops like mung bean, urdbean, pigeon pea, chickpea and lentil can be included. The inclusion of legume in RWCS has multiple advantages including N addition through biological N fixation, profile nutrient cycling through deep root system, reduction in soil compaction, increase in SOC and control of weeds through allelopathic effect of root exudates (Wani et al. 1995; Singh et al. 2005).

Development of short-duration mung bean cultivars enables farmers to utilize summer fallow in between wheat harvest and before transplanting of rice. Inclusion of summer mung bean in RWCS not only improves the total system productivity but also enhances the productivity of cereal component crops (rice and wheat) particularly when practiced for a long term (Hazra et al. 2014, 2018a, b). From a long-term experiment at the Indo-Gangetic Plain (Kanpur), Ghosh et al. (2012) quantified that less-labile C ($Cfrac_3$) is the dominating C fraction in rice soils and inclusion of mung bean improved the SOC by 6% and soil microbial biomass C by 85%. They also specified that the positive changes in soil organic C was mainly associated with a higher quantity of biomass production (particularly belowground biomass), reducing the fallow period between crops. Results of the same long-term experiments also revealed that replacing wheat with chickpea either completely or in alternate year (rice–wheat–rice–chickpea; 2-year rotation) in the conventional rice–wheat system had a positive impact on SOC restoration and enhancing C management index (CMI) (Ghosh et al. 2017). A similar positive effect of summer mung bean in the RW system on SOC was also reported in Mollisols and Inceptisols of IGP (Ghosh and Sharma 1996). Likewise, Venkatesh et al. (2013) reported that long-term inclusion of grain legumes such as mung bean and chickpea in conventional maize–wheat system of subtropical IGP can improve soil health, particularly SOC. They also specified that pulse crop can improve both the labile and non-labile C fractions. Singh and Sandhu (1980) and Newaj and Yadav (1994) also reported that SOC content increased over the initial level with inclusion of grain legumes in the cereal-based cropping systems. The effect of grain legumes was found to be more prominent where nutrient-rich pulse residue was returned to soil. Nowadays, indicators such as CMI, lability index and C fractions are increasingly being used by the researchers to evaluate soil C parameters, and these parameters are acknowledged as more sensitive indicators than TOC (Whitbread et al. 1998). Substantial improvement in CMI values has been reported with inclusion of legume components in the cropping system (Diekow et al. 2005; Blair et al. 2006). Basically, the composition of legume residue is distinctly different from that of cereal residue. In view of this, a hypothesis was postulated by Ghosh et al. (2016) to compare the C input through cereal and legume residues on TOC and its fractions in tropical IGP environments. Results revealed that enrichment in different C fractions and TOC was almost similar to the incorporation of either rice or lentil crop residue. They also proposed that incorporation of minimum one crop residue and optimal recommended fertilization in post-rainy season lentil crop is essential to maintain the SOC in rice–lentil rotation in tropical IGP condition. The in-depth understanding is still lacking in this subject. A comparative assessment of RW and different cereal–legume rotations for C-sequestration and C-stabilization is imperative to design a sustainable and alternative legume-inclusive crop rotation/s.

2.6 Pulses to Ecosystem Services

Pulses or grain legumes directly or indirectly contributes enormously to ecosystem services. The energy-use efficiency is declining consistently in conventional RWCS. For sustainability in energy management, the efforts would be made for the efficient use of commercial energies and harnessing renewable energy sources as supplementary and substituting commercial energy sources. Being a low-input (fertilizer, pesticides and water) demanding crop, pulses help in reducing the energy demand for cropping (Canfield et al. 2010). An estimated 2.6–3.7 kg CO_2 is released to the atmosphere for each kg N fertilizer production that leads to an overall emission of 300 Tg of CO_2 into the atmosphere (Jensen et al. 2012). The N_2O is one of the most potent GHGs, released mainly (~60%) from agricultural field. Nitrogenous fertilizer is recognized as the potential source of N_2O and from every 100 kg of N fertilizer about 1.0 kg of N is emitted as N_2O (Jensen et al. 2012). In this perspective, pulses with reduced use of fertilizer N and other inputs certainly have minimal adverse effect on the ecosystem. According to Drinkwater et al. (1998), legumes have less adverse impacts on environmental and agro-ecosystems because of improved SOC concentration and optimizing the C and N cycles. Deep-rooted pulses (e.g. pigeon pea) can improve porosity and alleviate subsoil compaction (Hulugalle and Lal 1986). Further, the BNF contribution improves soil biology and reduces N_2O emissions (Peoples et al. 2009). An improved biodiversity can also be achieved by inclusion of pulses in cropping systems.

2.7 Researchable Issues

- The potential of pulse crops for deep soil C-sequestration is poorly understood. In-depth investigation is thus warranted to quantify the stabilization of below-ground root biomass of pulses crops. Importantly, improving the slow C pool or humus content in lower soil depth is a sustainable strategy to enhance the SOC pool, as the deep C pool is usually protected against crop and soil management practices. Our hypothesis is that growing pulses, which have a deep root system, facilitate deep placement of their residue (better quality in terms of C:N ratio, lignin, cellulose than cereal) beneath the plough layer deposit of humus or non-labile C and remain stable for a longer period.
- Increasing the content of resistant C pool or humus is an important strategy to enhance the SOC pool. A comparative assessment of cereal and legume residues in increasing the resistant C pool would be helpful to develop strategic crop residue management.
- Comparative estimation of GHG emission in cereal–cereal and cereal–pulse systems may provide useful information for strategic management of GHG emission following cropping system approach.
- Changes in microbial diversity with inclusion of pulses in RWCS are also a researchable issue that has direct influence on C-sequestration. Investigating the shifts in soil microbial activity, abundance and community driven by different agricultural practices would be conducive in maintaining and enhancing the fertility and productivity of soils and protecting soil ecosystems against disturbances. Bio-sequestration of C, both soil and biota, is a truly win–win situation.
- Potential of pulses genotypes for SOC restoration is another researchable issue. In fact, a large number of genotypes of different pulse crops such as pigeon pea, chickpea, urdbean, mung bean and field pea across the country have been popularized in terms of yield, disease and pest resistance and heat tolerance. Variations in water use efficiency and nutrient acquisition of some genotypes are also tested; however, scope exists to test these genotypes as to their carbon sequestration potential so that SOC enrichment in the cereal-based system is achieved by inclusion of pulses without incurring additional cost.
- Presently, the area under CA in RWCS is increasing in South Asian countries, and pulses hold an important component for crop diversification. All the possible inclusion of pulses in RWCS under CA practices needs to be studied to advocate appropriate pulse-inclusive crop rotation for resource conservation and climate change mitigation.

2.8 Conclusion

Pulses or grain legumes offer opportunities to diversify or intensify RWCS and to mitigate the negative consequences of continuous RWCS. Growing concerns to increase the SOC and minimizing the ecological issues call for sustainable crop management practices in RWCS. Existing literature advocates inclusion of pulses in

RWCS for an extensive period to improve soil organic C and its different pools. However, research information on the subject is not adequate and requires in-depth study, particularly on sub-soil C-sequestration, C-stabilization and rhizodeposition of C from legumes. Further, evaluation of the potential of different legume crops in RWCS in view of SOC is imperative to design strategic pulse inclusive rotations.

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3 Effect of Land Use and Management Practices on Quantifying Changes of Phytolith-Occluded Carbon in Arable Soils

S. Kundu, S. Rajendiran, M. Vassanda Coumar, and Ajay

Abstract

Sequestration of carbon in the terrestrial ecosystem is one of the strategies to mitigate climate change and global warming. However, the resident time of stored carbon in soil may vary according to its chemical nature and physical protection. There are easily oxidizable and stable C fractions, and their storage and dynamics in terrestrial systems are influenced by land use and management strategies. Therefore, it is inevitable to study the impact of land use and management practices on different carbon fractions to maintain the required balance of these C fractions to enhance C sequestration. In this context, phytolith-occluded carbon (PhytOC) is an important very stable soil organic carbon fraction biomineralized in plant silica. The PhytOC substantially contributes to the terrestrial sequestration of carbon, and it resides in soil for millennial time scale. This chapter mainly focuses on its variation in different plant species and in different land use systems, influence of various management practices on PhytOC and potential measures to enhance PhytOC in terrestrial ecosystems.

Keywords

Agro-ecosystems · Carbon sequestration · Land use changes · Phytolith-occluded carbon · Plant phytoliths

3.1 Introduction

With the increase in human population, the demand on agriculture, forest and other land systems is rapidly increasing at the global level, which often results in degradation of the soil resource. Soil organic carbon and its various pools (both active and

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passive pools) is a major determinant of sustainability of land use system. Land use and land cover changes have been shown to have significant impacts on soil physical structure, which often result in changes in soil organic carbon (C) storage and turnover (Jastrow 1996; Six et al. 2002). The net carbon loss from soils adds to the atmospheric CO_2 concentration, leading to higher global temperatures (IPCC 2001), which, in turn, accelerates the decomposition of SOM (Jones et al. 2005), whereas net soil CO_2 sequestration helps to mitigate the greenhouse effect and improves soil quality. Phytolith-occluded carbon (PhytOC) is of plant origin and is formed through silica biomineralization in plants (mainly within leaves), which leads to the formation of very small (~silt sized) opaline features called 'phytoliths'. During such process of silica biomineralization, occlusion of carbon takes place within phytoliths, called phytolith-occluded carbon (PhytOC). PhytOC, an important fraction of soil organic carbon, is very stable in the soil environment and substantially contributes to the terrestrial sequestration of carbon for a long period (millennia) (Wilding et al. 1967). This PhytOC fraction reduces emission for long term (millennia), as against many other soil organic carbon fractions, which may decompose over a much shorter time. The PhytOC was widely studied in archaeological, palaeobotanical, palaeoenvironmental and biogeochemical point of view. Morphotypes of silicophytoliths were used in the identification of taxonomical group of plant species (Twiss et al. 1969; Ellis 1979). In the recent years, several experiments under different cropping systems and soil types demonstrated that phytolith has a potential to sequester carbon in the soil as PhytOC for a long term (Parr and Sullivan 2005, 2011; Parr et al. 2009, 2010).

Some of the major agricultural crops, grasses and forest trees are known to be prolific producers of phytolith and PhytOC. The rate of phytolith production and the carbon occluded in phytoliths varies among the plant community and under various management practices. Hence, a great potential exists to enhance PhytOC production and accumulation in the soils of various land use systems (Li et al. 2013; Parr and Sullivan 2011; Rajendiran et al. 2012). However, from soil carbon sequestration point of view, there is very little information available about the potential of PhytOC in soil carbon sequestration. An in-depth knowledge of the PhytOC and its potential in long-term carbon sequestration is necessary. An attempt is, therefore, made in this chapter to elaborate the impact of land use management on carbon fractions, particularly PhytOC, the process of formation of phytolith and PhytOC; quantification and assessment of terrestrial carbon sequestration potential; and the options for enhancing terrestrial carbon sequestration through PhytOC.

3.2 Soil Organic Carbon Fractions/Pools

Soil organic carbon content has been recognized as one of the important indicators of soil health/quality. It interacts with other soil components – affecting water retention, infiltration, aeration, aggregate formation, bulk density, pH, buffering capacity, cation exchange properties, nutrient mineralization, sorption of agrichemicals and activity of soil organism. Changes in the levels of organic matter, caused by land use, can be better understood by alterations in the different compartments. Generally,

Table 3.1 Possible repositories for additional carbon storage in terrestrial ecosystems or their products, and approximate residence times for each pool. Mean residence time is the average time spent by a carbon atom in a given reservoir

Repository	Fraction	Examples	Mean residence time
Biomass	Woody	Tree boles	Decades to centuries
	Non-woody	Crop biomass, tree leaves	Months to years
Soil organic matter	Litter	Surface litter, crop residues	Months to years
	Active	Partially decomposed litter, carbon in macroaggregates	Years to decades
	Stable	Stabilized by clay, chemically recalcitrant carbon, charcoal carbon	Centuries to millennia
Products	Wood	Structural, furniture	Decades to centuries
	Paper, cloth	Paper products, clothing	Months to decades
	Grains	Food and feed grain	Weeks to years
	Waste	Landfill contents	Months to decades

IPCC (2000)

SOC has been divided into three pools: an active pool consisting of labile C (simple sugars, organic acids and microbial metabolites) with a mean residence time in days, an intermediate or slow pool consisting of plant residues and physically stabilized carbon and a resistant carbon pool consisting of lignin and other chemically stabilized ones with a mean residence time of more than 1000 years (Buyanovsky et al. 1994). The possible repositories for additional carbon storage in terrestrial ecosystems and their products with their mean residence time are given in Table 3.1.

Researchers across the world used different concepts and ideas on soil organic carbon pools or fraction by adapting different criteria and norms. Initially, Jenkinson and Rayner (1977) identified five pools in their organic matter cycling model ranging from a decomposable pool, with a radiocarbon age of less than 1 year, through a biomass pool at 25.9 years, to a chemically stabilized pool with a radiocarbon age of 2565 years. Then SOM fractionation has been carried out on the basis of extraction of humic substances (Schnitzer 1982), dissolved organic C (Cook and Allan 1992), particle size (Christensen 1986), natural abundance (Balesdent et al. 1990; Lefroy et al. 1993), microbial biomass C (Sparling 1992) and ease of oxidation of C (Loginow et al. 1987). Based on the degree of oxidation, carbon fractions are grouped into two different pools as labile (oxidizable by $KMnO_4$) and non-labile (not oxidizable by $KMnO_4$) carbon pools (Blair et al. 1995). Chan et al. (2001) further reported that the total organic carbon (TOC) can be apportioned into different pools by modifying the Walkley and Black method using 5, 10 and 20 ml of concentrated H_2SO_4, which resulted in three acid-aqueous solution ratios of 0.5:1, 1:1 and 2:1. The amount of C, thus determined, allowed the apportioning of TOC into very labile C (organic

C oxidizable by 12.0 N H_2SO_4), labile C (the difference in C oxidizable by 18.0 N and that by 12.0 N H_2SO_4), less labile C (the difference in C oxidizable by 24.0 N and that by 18.0 N H_2SO_4) and non-labile C (difference in C between TOC and SOC). These concepts are frequently tailored or modified depending on their necessity and also to quantify the changes in soil organic carbon under different land use management systems. The TOC content was mostly used to quantify the stocks and changes in organic matter. In many cases, the changes resulting from land use are not duly reflected in TOC values (Roscoe and Burman 2003), mainly due to the high C concentrations in stable and little in mineral association (Lal 2006). However, a minor variation in such big C pool in terrestrial ecosystems may have a significant effect on the C flux (Harrison et al. 1993). Due to environmental complexities, it is sometimes difficult to quantify soil C changes (McKenzie et al. 2000; Skjemstad et al. 2000; Clark 2002). However, researchers across the world predicted the soil carbon dynamics under different land use and management systems.

3.3 Impact of Land Use and Management Practices on Soil Organic Carbon

The C balance of terrestrial ecosystems can be changed markedly by the impact of human activities, including deforestation, biomass burning and land use change (Bhattacharyya et al. 2000). Soils in tropical regions are low in SOC, particularly those under the influence of arid, semiarid and sub-humid climates (Katyal et al. 2001). Carbon stocks in major soil types and land use systems in the semiarid tropical region of southern India were studied, and it was reported that the soil organic carbon (SOC) stock was highest in Alfisols (52.84 mg ha^{-1}) followed by inceptisols (51.26 mg ha^{-1}) and Vertisols and its associated soils (49.33 mg ha^{-1}). Among the different land use systems, total C stock was highest in forest soils, followed by fodder system, paddy, maize, cotton, red gram, intercrop, chilli and permanent fallow and lowest in the castor system (Venkanna et al. 2014). Also, in different forest systems, there is a significant change in soil organic carbon. For example, soil carbon pool varied in the order of wet temperate forest (165.24 mg ha^{-1}) > deciduous forest (138.64 mg ha^{-1}) > tropical thorny forest (135.42 mg ha^{-1}) > tropical riparian fringing forest (104.94 mg ha^{-1}). Further, among the fractions, tropical thorny and riparian forest had more labile carbon fractions, whereas wet temperate forest had more non-labile carbon fractions (Sreekanth et al. 2013). Similarly, changes in carbon stock and its fractions were also observed in grassland and pastureland use systems. Maintaining or improving organic C levels in tropical soils is more difficult because of its rapid oxidation under prevailing high temperatures (Lal 1997). The amount and duration of carbon gain within an ecosystem depend on the temporal dynamics of its different pools: Transient pools may increase rapidly but quickly settle down, whereas carbon that is incorporated into more stable pools can be slow, but in the long term it increases. Consequently, the initial impact of land use or management change occurs disproportionately in pools with shorter residence times (Huggins et al. 1998), whereas increases in stable soil pools occur slowly over a much longer time period (Fig. 3.1). Early

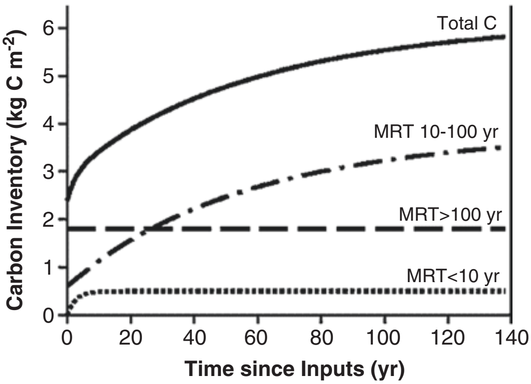

Fig. 3.1 Predicted response of different pools of soil organic matter for an agricultural soil converted to forest in northeastern USA (Gaudinski et al. 2000)

response reflects changes in the relatively small pools with mean residence time (MRT) <10 years (leaf and root residues). Pools with intermediate MRT (10–100 years, including humified organics in litter layers) dominate the overall response because this pool contains most organic matter in the soil. Persistent carbon pools (MRT >100 years) do not change appreciably over a 100-year period.

While comparing across the land use system, grasslands store approximately 34% of the global terrestrial stock of carbon, forests store approximately 39% and agro-ecosystems approximately 17% (World Resources Institute 2000). Conversion of the grassland or forest land system to the agricultural system had negative impact on soil carbon pools. Therefore, proper management of SOC is important for sustaining soil productivity and protection from land degradation. Among the tillage practices, conservation agricultural practices and long-term recycling of crop residue support the natural systems by storage of more crop residues in soil (Bhat et al. 1991; Saha and Ghosh 2013). Long-term fertilizer experiments in India also revealed that integrated or balanced nutrient management resulted in build-up of organic carbon content of soils (Nambiar and Ghosh 1984; Katkar et al. 2012). Also, cereals-based cropping system had low carbon storage when compared to the legume-based cropping system. It is obvious from the results that land use and management systems may influence soil organic carbon storage and dynamics.

3.4 PhytOC: A Stable Organic Carbon Fraction

PhytOC is an organic carbon fraction that is stored in plant phytoliths (opal silica) and is formed through the process of biomineralization in the tissues of plant leaves and stems. The hard silica encasement physically protects the encased organic carbon (occluded carbon). The phytolith content of grasses varied from 1% to 5%, but it may be up to 15% on a dry weight basis. Since 1970, PhytOC was mostly used for carbon dating of sediments (Wilding 1967). PhytOC is very stable in the soil environment and is considered to be a very important fraction of soil organic carbon and plays an important role in soil C cycle (Parr and Sullivan 2005). In certain soils and

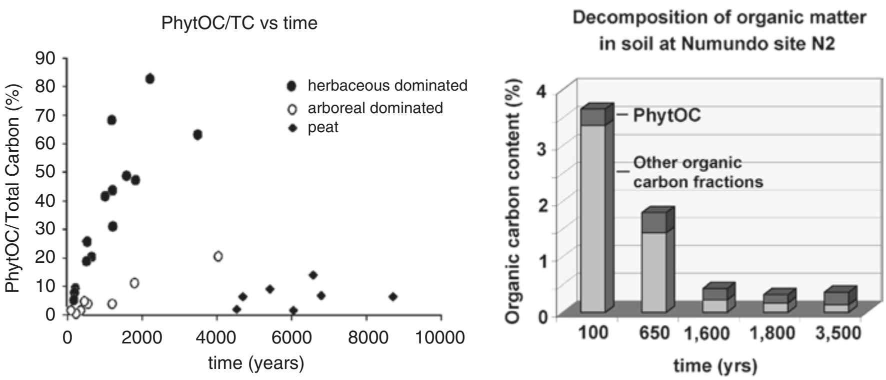

Fig. 3.2 Phytolith carbon sequestered as a proportion of total carbon in buried soil layers and stability against environmental degradation versus age for the Numundo (West New Britain) upland buried soils and a peat wetland soil (Byron Bay, Australia) (Parr and Sullivan 2011)

in sediments even after 2000 years of litter leaf decomposition, the PhytOC represents up to 82% of total C, indicating its resistance to decomposition as compared to other organic carbon fractions (Fig. 3.2) (Parr and Sullivan 2005). Mostly, the topsoil layer contains phytolith less than 3% of the total silica, and in some soil it has been reported as high as 30%. The phytolith-occluded organic carbon constitutes normally 5% of phytolith content and in certain cases as high as 20%.

Studies conducted under varying climatic conditions, namely (i) tropical (West New Britain), (ii) temperate (Midwest of the USA) and (iii) subtropical (Eastern Australia) showed that the soil carbon sequestration rate due to PhytOC under natural vegetation was between 0.4 and 0.9 gC m^{-2} $year^{-1}$. This indicates that PhytOC plays an important role in long-term soil carbon sequestration processes, and it represents nearly 15–37% of the long-term global soil carbon sequestration rate under natural vegetation systems. If the average PhytOC rate from these three studies is multiplied by the global area of land under vegetation, it indicates that the annual global rate of e carbon sequestration in soil from silica bio-mineralization in native vegetation is ~300 million tonnes of e-CO. The results also demonstrate that the PhytOC yields of crops can be much higher than those for native vegetation. The rate of secure carbon storage by PhytOC produced by a sugarcane variety was up to 40 times greater than the rate under natural vegetation and 100 times greater than that of some plant species (Parr et al. 2009).

3.5 Variability in Plant Phytoliths and PhytOC Content

The rates of phytolith production and the carbon occluded in phytoliths vary among the plant community and also within the community. For accumulation of good amount of opal silica in the plant tissues, plant should efficiently uptake more silica from the soil. Whilst many plant species are considered to be effective silica accumulators in the form of monosilicic acid, other plant species can exclude effectively monosilicic acid uptake (Marschner 1995). Higher plants were divided into three groups according to their silicon content (SiO_2, expressed as a percentage of shoot dry weight): (i) members of Cyperaceae and wetland species of Gramineae (e.g. rice) with 10–15%; (ii) dryland species of Gramineae (e.g. wheat and sugarcane) and a few dicotyledons with 1–3%; and (iii) most dicotyledons, especially legumes with less than 0.5% (Marschner 1995). Although silica occurs in many plants, some tree species and herbaceous plants such as Poaceae and Cyperaceae are generally considered the most prolific producers of phytoliths (Ter Welle 1976; Krishnan et al. 2000). In herbaceous types of plants, most of the cell wall deposits silica that contains occluded carbon. The leaves of grasses are particularly good at occluding carbon through silica bio-mineralization processes. As a result, long-term phytolith accumulation rates under grasslands are commonly five to ten times greater than forest land (Drees et al. 1989).

Phytolith content and its variability among different cultivars of the agricultural crops (millets, wheat, maize, sugarcane and rice) and even in some grasses like bamboo have been reported by several authors. In rice, Si accumulation up to the level of 10% of shoot dry weight was observed (Epstein 1999). The SiO_2 concentration, accumulation and distribution in different plant organs of rice have been reported, and it was observed that 65.5% of total phytolith was only in leaf (Sun et al. 2008). In case of wheat and sugarcane, phytolith content varies from 2.68% to 7.85% (Parr and Sullivan 2011) and from 1.6% to 2.2% (Parr et al. 2009), respectively. Similarly, the PhytOC content in the phytolith also varied widely. For example, the carbon content (PhytOC) in phytoliths extracted from oats varied from 5.0% to 5.8% (Siever and Scott 1963) and sugarcane from 3.1% to 15.4% (Parr et al. 2009). The phytolith-occluded carbon content of the wheat cultivars ranged from 0.06% to 0.60% of dry leaf and stem biomass (Parr and Sullivan 2011). PhytOC content of plant is directly related to the quantity of phytolith. The efficiency of carbon encapsulation also varied among the individual varieties (Li et al. 2013). The average PhytOC content of different plant species is listed in Table 3.2. In our study,

Table 3.2 General information and PhytOC content of the dominant arable crops

Farm crops	Area (million hectare)	Plant Si-rich organs	PhytOC (%)	
			Mean	SE
Crops (total)	1532.6	–	0.13	0.05
Cereals (total)	697.7	Stem, sheath and leaf	0.19	0.07
Rice	164.1	Stem, sheath and leaf	0.25	0.07
Wheat	220.4	Stem, sheath and leaf	0.16	0.08
Maize	170.4	Stem, sheath and leaf	0.16	0.05
Soybeans	103	Stem and leaf	0.02	0.01
Roots and tubers	54.3	Stem and leaf	0.02	0.01
Oil-bearing crops	62	Stem and leaf	0.08	0.08
Seed cotton	35.2	Stem and leaf	0.02	0.01
Sugarcane	25.4	Sheath and leaf	0.25	0.07

Song et al. (2013)

Table 3.3 Rate of accumulation of dry matter, phytolith and phytolith-occluded carbon in different plant parts of rice at maturity

Rice cultivars	Straw		Root		Husk	
	Phytolith content (%)	C content of phytolith (%)	Phytolith content (%)	C content of phytolith (%)	Phytolith content (%)	C content of phytolith (%)
MR-219	12.47	3.37	8.30	2.13	14.06	5.67
P-1121	23.62	1.87	10.70	1.87	21.643	3.20
WGL-32100	21.32	2.23	11.40	1.90	24.37	2.40
MTU-1081	22.75	2.20	7.05	1.70	22.05	2.80
JGL-3844	19.24	2.00	9.17	1.51	18.31	3.33
SUREKHA	20.98	2.27	8.26	2.03	19.65	2.63
PRATIKSHYA	26.39	2.53	6.54	2.27	21.49	3.80
KAVYA	23.33	2.53	8.45	1.97	21.18	2.37
VARALU	23.13	1.93	5.50	1.63	15.45	3.20
KRANTI	15.72	1.40	7.20	1.13	16.01	4.20
MTU-1010	18.48	2.30	7.26	1.43	13.13	6.30
OR-1912-24	16.33	2.53	8.51	2.13	14.27	4.80
JAGTIAL SANALU	20.76	2.27	10.40	1.77	20.34	2.13
JGL-3828	16.59	2.43	7.44	1.77	13.96	5.90
BPT-5204	14.47	2.90	8.43	2.20	14.52	5.50
CD ($P = 0.05$)	1.62	0.24	0.37	0.20	0.31	0.72

Prajapati et al. (2014)

we also observed the phytolith and PhytOC content variability in rice cultivars, and rice crop has potential to sequester more C through PhytOC and may contribute to global C cycle (Table 3.3).

3.6 PhytOC Sequestration Rate of Different Plants

The data from several experiments indicate that considerable variations in PhytOC yield between plant species and within species were noticed. For example, the soil carbon sequestration rate for high PhytOC-yielding sugarcane variety (~0.364 tonnes e-CO_2 ha^{-1} year^{-1}) is more than twice that of the lowest PhytOC-yielding sugarcane variety, and thereby the carbon sequestration potential is increased to the tune of ~0.24 tonnes e-CO_2 ha^{-1} year^{-1}. The PhytOC yield of a sugarcane crop was 18.1 g C m^{-1} year^{-1}, an accumulation rate that is substantial over the long term (millennia) and yet comparable to the rates of carbon sequestration that are achievable (but only for a few decades) by land use changes (Parr et al. 2009). Recent research also indicates that plant phytoliths have great potential to sequester CO_2 from the atmosphere (Table 3.3). For example, the phytolith C bio-sequestration fluxes from millet, rice, wheat and sugarcane range up to 0.04, 0.13, 0.25 and 0.36 mg-e-CO_2 ha^{-1} year^{-1}, respectively (Parr et al. 2009, 2010; Parr and Sullivan 2011; Zuo and Lü

Table 3.4 Comparison of PhytOC contents in plant tissues, estimated PhytOC fluxes per ha t CO_2 equivalents and global total PhytOC sequestration rate in different plants

Plant species	PhytOC contents of dry material (mg g^{-1})	PhytOC sequestration fluxes (mg e-CO_2 ha^{-1}-$year^{-1}$)	Global PhytOC sequestration rates (mg e-CO_2 $year^{-1}$)	References
Rice	0.4–2.8	0.03–0.13	1.94×10^7	Li et al. (2013)
Bamboo	2.4–5.2	0.01–0.71	1.56×10^7	Parr et al. (2010)
Sugarcane	3.1–15.4	0.12–0.36	0.72×10^7	Parr et al. (2009)
Wheat	0.6–6.0	0.01–0.25	5.3×10^7	Parr and Sullivan (2011)
Millet	0.4–2.7	0.01–0.04	0.27×10^7	Zuo and Lü (2011)

2011). Moreover, the flux of C occluded within the phytoliths of bamboo species ranges up to 0.71 mg-e-CO_2 ha^{-1} $year^{-1}$ and with current global bamboo forests covering an area of around 22 million ha could potentially be securely sequestering~1.56×10^7 mg of atmospheric CO_2 per year. Parr et al. (2010) have suggested that if all potentially arable land (4.1 billion ha) is exploited to grow bamboo or other similar grass crops, the global potential of phytolith C bio-sequestration is approximately 1.5×10^9 mg CO_2 per year. This would result in effectively reducing global CO_2 emissions by a rate equivalent to 11% of the current increased CO_2 in atmosphere (Parr et al. 2010).

These phytolith carbon bio-sequestration rates indicate a substantial potential (~50 million tonnes of e-CO_2 $year^{-1}$) for increasing the rate of carbon bio-sequestration in wheat crops (Table 3.4). Hence, this process offers an opportunity to use the plant species that yield high amounts of PhytOC to enhance terrestrial carbon sequestration. There are studies that demonstrated that simply growing high PhytOC-yielding cultivars over low PhytOC-yielding cultivars results in additional sequestration of carbon in soil by ~ 5 Mt e-CO_2 $year^{-1}$ and 53 Mt e-CO_2 $year^{-1}$ for sugarcane (20 million ha) and wheat (214 million ha), respectively (Parr et al. 2009; Parr and Sullivan 2005).

Most of the economically important agricultural plant species such as barley, maize, rice, sorghum, sugarcane and wheat were known to be prolific producers of phytoliths (Lanning et al. 1980; Piperno and Pearsall 1993; Parr and Sullivan 2005; Prajapati et al. 2014; Rajendiran et al. 2012; Li et al. 2013). There are several cultivars available in each of the crops mentioned above and their phytoliths and PhytOC contents also vary. After the crop harvest, PhytOC in the straws/stovers find its way to soil. It was demonstrated that about 50% of total biomass produced from these crops finally reaches the soil through residue incorporation, wastes after feeding the animals, animal excreta, farmyard manure in the form of compost and burned ashes.

3.7 PhytOC Sequestration Potential of Some Important Agricultural Land Use Systems

An attempt was made to roughly estimate the PhytOC contribution of some of the widely cultivated agricultural crops across the world and also in India. Based on the information available in the literature, area of cultivation, phytolith content in straw and amount of PhytOC that reaches the soil were estimated (Tables 3.5 and 3.6). It shows that total phytolith production is approximately 5.08 million tonnes y^{-1} by considering the minimum phytolith content of the crops. Further, it is also inferred that by adopting high PhytOC-yielding cultivars instead of low PhytOC-yielding cultivars, additional carbon produced is about 18.97 million tonnes $year^{-1}$, which substantially contributes to the terrestrial carbon stocks in the Earth. However, utilization of the existing potential for carbon sequestration mainly depends on the efficacy and efficiency of the production system and management of PhytOC in soils. These data clearly demonstrate that there is an opportunity to enhance short- and long-term carbon sequestration by cultivation of high PhytOC-yielding plant species.

In India, the major cereal crops grown are rice, wheat, maize and sorghum, and in many parts of the country, these crops are even raised in two or three seasons in a year. The cultivated area of rice, wheat, maize, sorghum and sugarcane in India is 44, 28, 8.4, 9.2 and 4.2 million ha, respectively. Considering the minimum phytolith content for these crops, total phytolith and PhytOC yields are approximately 0.874 million tonnes $year^{-1}$ (considering average carbon content of phytoliths as 5%). At the same time, if we consider maximum phytolith content for these crops, the values are 1.921 million tonnes $year^{-1}$. It shows that growing high PhytOC-yielding cultivars provides additional 1 million tonne of carbon per year in these croplands (Table 3.6). The potential can be further improved through conventional breeding and biotechnological approaches to increase the PhytOC yield without compromising grain yield and other favourable characters.

3.8 PhytOC Accumulation in Soil

On a global scale, organic carbon stored in soil quantitatively dominates the carbon cycle, out-storing that possible by the current vegetation cover by at least twofold (Schlesinger 1990) and has the potential to assist in the mitigation of greenhouse gases with appropriate management (Chan et al. 2008; Walcott et al. 2009). Soil PhytOC accumulation is an important persistent C sink mechanism for croplands and other grass-dominated ecosystems. Moreover, Jansson et al. (2010) suggests that the production of PhytOC in croplands could be greatly enhanced through crop breeding. The carbon occluded in phytoliths has been demonstrated to be an important long-term terrestrial carbon fraction in soil representing up to 82% of total soil carbon in buried topsoil after 2000 years of in situ decomposition. Moreover, it has been demonstrated that relative to the soil organic carbon fraction that decomposes over shorter time scale, PhytOC is highly resistant against decomposition and persists in the soil environment for a long period.

Table 3.5 Estimation of total PhytOC production potential of some of the widely cultivated agricultural crops of the world

Crop	Area (M ha)	Straw/stover yield (t ha^{-1})	Total straw (M t $year^{-1}$)	Phytolith content of straw (%)		Phytolith production (M t $year^{-1}$)		PhytOC[a] production (M t $year^{-1}$)	
				Min	Max	Min	Max	Min	Max
Rice	153	4.0	612	5.0	15.0	30.60	91.80	1.53	4.59
Wheat	218	3.5	763	3.5	6.0	26.70	45.78	1.33	2.29
Maize	145	6.0	870	2.0	7.0	17.40	60.90	0.87	3.05
Sorghum	44	5.0	220	9.0	12.0	19.80	26.40	0.99	1.32
Sugarcane	16	25.0	400	1.3	2.6	52.00	10.40	0.26	5.20
Barley	56	3.0	168	1.2	3.0	20.10	50.40	0.10	2.52

Rajendiran et al. (2012)
[a]PhytCO is calculated by considering the average carbon content of phytoliths as 5%

Table 3.6 Estimation of total PhytOC production potential of major agricultural cropping system in India

Crop	Area (M ha)	Straw/stover yield (t ha^{-1})	Total straw (M t)	Phytolith content of straw (%)		Phytolith production (M t)		PhytOC[a] production (M t $year^{-1}$)	
				Min	Max	Min	Max	Min	Max
Rice	44.0	3.0	132.0	5.0	15.0	6.60	19.80	0.330	0.990
Wheat	28.0	4.0	112.0	3.5	6.0	3.92	67.20	0.196	0.336
Maize	8.4	5.0	42.0	2.0	7.0	0.84	29.40	0.042	0.147
Sorghum	9.2	6.0	55.2	9.0	12.0	4.97	66.24	0.248	0.331
Sugarcane	4.3	20.0	86.0	1.3	2.6	1.12	22.36	0.056	0.112
Barley	0.8	4.0	3.2	1.2	3.0	0.04	0.10	0.002	0.005

Rajendiran et al. (2012)
[a]PhytCO is calculated by considering the average carbon content of phytoliths as 5%

Phytoliths may experience a range of fates after their formation within plants. For example, soil erosion by wind or water may transport phytoliths; they may be burnt in a grass fire, or they may pass through the digestive systems of animals. Regardless of such fates, the potential of durability and persistence of phytoliths against such processes has been well documented (Baker et al. 1961; Wilding and Drees 1974; Hart and Humphreys 1997; Bowdery 2007). After harvest of crop plants, the phytoliths present in them finally reach the soil. The rate of phytolith production in soil is also affected by factors other than plant species including soil properties, climate and geomorphology. Concentration of phytoliths in the soil varies from several orders of magnitude from one region to the next (Drees et al. 1989). For example, variations in opal yield in plants ranged from 10 kg ha^{-1} $year^{-1}$ in New Mexico (Norgren 1973) to 300 kg ha^{-1} $year^{-1}$ in Oregon (Pease and Anderson 1969). Although the concentration of phytoliths in soils generally constitutes up to 3% on a total soil basis (Drees et al. 1989), some soil horizons are almost completely composed of phytoliths (Riquier 1960).

Estimated annual PhytOC accumulation rates (0.72–0.88 g m^{-2} $year^{-1}$) in the tropical and subtropical sites were remarkably similar (Parr and Sullivan 2005). Annual PhytOC accumulation rates in the case of two temperate soils were 15 g m^{-2} $year^{-1}$ and an average carbon content of phytoliths for similar soil was 0.36 g m^{-2} $year^{-1}$ (Wilding 1967). These PhytOC accumulation rates are between 15% and 37% of the estimated global mean long-term soil carbon accumulation rate of 2.4 g C m^{-2} $year^{-1}$ over the last 10,000 years (Schlesinger 1990), indicating that PhytOC accumulation is an important process in the long-term sequestration of terrestrial carbon.

3.9 Effect of Land Use Change and Management Practices on PhytOC

After harvest of the crop, crop residues such as roots, fallen leaves and stubbles will remain in the soil. Proper crop residue management can add some amount of PhytOC to the soil. Apart from this, providing favourable soil environment for accumulation and complexation of PhytOC with soil components also reduce the losses of this carbon fraction and facilitate for the long-term storage of PhytOC in soil. PhytOC production potential of crop species, amount and mechanism of PhytOC that reaches the soil from these crop plants has been studied under different agroecological conditions to maximize the terrestrial carbon sequestration potential of PhytOC (Wilding 1967; Parr and Sullivan 2005, 2011; Parr et al. 2010).

Phytoliths allow carbon to be protected in a similar way that clay platelets protect organic matter. Phytoliths offer potential to boost carbon sequestration in agricultural soils, wetlands and degraded saline and acid sulphate-affected areas (Parr and Sullivan 2005). Long-term phytolith accumulation rates under grasslands are commonly five to ten times greater than under forests. At present, sugarcane is grown on ~20 million ha worldwide. A decision to grow the currently available sugarcane varieties that are high PhytOC-yielding rather than the low PhytOC-yielding varieties would result in the soil carbon sequestration of an additional ~5 million tonnes e-CO_2 every year from this one crop alone. Similarly, other grass crops (e.g. wheat, rice, sorghum and corn) and pastures are grown on much larger areas of land than sugarcane and these crops promise to have a much greater potential than sugarcane to enhance soil carbon sequestration through increased PhytOC yields (Parr et al. 2009). Plant breeding or selection for enhanced PhytOC yields in such crops would likely increase these secure soil carbon sequestration rates further. The type of plant grown affects the quantity of organic matter that can be returned to the soil. Selecting plants with greater root mass and/or slower decomposing roots will aid SOC sequestration. Deep-rooted perennial plants are generally required to improve SOC in deeper soil layers (below the surface ~10 cm). Further deep placement of organic material is likely to have longer sequestration than shallow placement due to reduced microbial activity. Carbon-to-nitrogen ratios (C:N) of particular plants can affect the length of storage of carbon in the soil. Organic matter with a high C:N (e.g. wheat) breaks down more slowly than residue with low C:N (e.g. legumes) and is more likely to contribute to increased soil carbon where inputs are sustained (Hoyle and Murphy 2006).

The simulation models (Fig. 3.3) explain the long- and medium- term effect of land use change and management practices on SOC accumulation mainly through PhytOC and assume that the natural rate of organic carbon sequestration is 2.4 g C m^{-2} $year^{-1}$ (Schlesinger 1990), the PhytOC decomposition rate is 25% per millennia and the crop is grown continuously. The change of tillage increased organic carbon sequestration rate to 57 g C m^{-2} $year^{-1}$ and reached equilibrium after 25 years (West and Post 2002) and soil is mature in this case. In both the cases, the carbon sequestration rate of 18.1 g C m^{-2} $year^{-1}$ was measured in the high PhytOC-yielding sugarcane crop (Parr and Sullivan 2005).

Conversion of cultivated agricultural land to either forest or grasslands may yield 33.5 g C m^{-2} $year^{-1}$ (Post and Kwon 2000) and a change of tillage practices from conventional to no tillage may accumulate 50.7 g C m^{-2} $year^{-1}$ (West and Post 2002). Compared to the above-mentioned practices, PhytOC accumulation rates are comparatively smaller. But the period of carbon sequestration of such land use

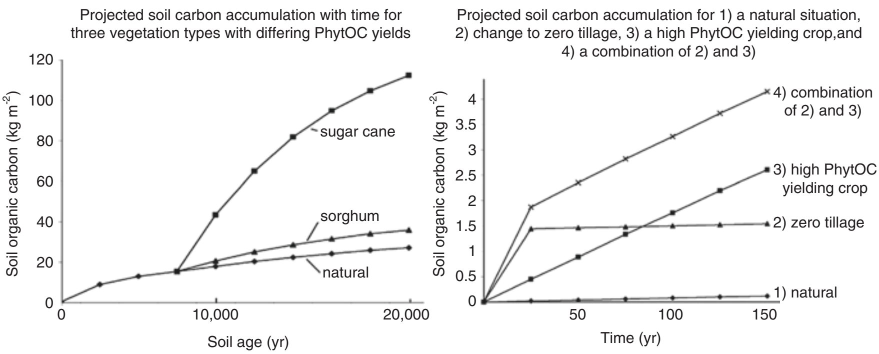

Fig. 3.3 Projected effect of long- and medium-term land use change and management practices on SOC accumulation mainly through PhytOC (Parr and Sullivan 2011)

changes lasts only for short duration and carbon sequestration ceases whenever new soil carbon equilibrium is established. But the carbon sequestered within phytolith will continue for millennia. Afforestation and reforestation of land and change of tillage practices from conventional to no tillage have been recently suggested to provide benefits in terms of increased carbon sequestration (West and Post 2002; Fang et al. 2001). However, the short-term carbon sequestration benefits provided by afforestation or reforestation and changes in tillage practices may need to be balanced against a substantially lowered long- and medium-term carbon sequestration by PhytOC accumulation under forest and agricultural lands.

3.10 Potential Measures to Increase the PhytOC Sequestration

Phytolith C sinks may be further enhanced by adopting cropland management practices such as optimization of cropping system and fertilization (Table 3.7). Parr and Sullivan (2011) and Li et al. (2013) revealed that the enhancement of rice and wheat area percentage might significantly increase the total phytolith C sink in croplands because of their higher phytolith content than other crops. Silicon fertilizer application, rock powder amendment and organic mulching will increase soil bioavailable silicon input, plant silicon uptake and phytolith content for cereals and sugarcane (Song et al. 2012; Li et al. 2013). Traditional fertilization (N, P and K fertilizer application) may also increase total phytolith C sink in croplands by enhancing crop output. Although the potential measures proposed for promoting cropland phytolith C sink are commendable, the exact efficiency and costs of the proposed measures need further assessment before implementation to sequester globally significant amounts of atmospheric CO_2.

Table 3.7 Potential measures to enhance global cropland phytolith carbon sink

Types	Measures	Mechanisms
Optimization of cropping system	Enhancement of cereal percentage in croplands	Enhancing crop output and phytolith content
	Enhancement of multi-cropping index	Enhancing crop output
Fertilization	Silicon fertilizer application	Enhancing crop phytolith content
	Rock powder amendment	Enhancing crop phytolith content
	Organic mulching	Enhancing crop output and phytolith content
	Traditional fertilization	Enhancing crop output

Song et al. (2013)

3.11 Conclusion

To sum up, phytolith-occluded carbon is an environmentally stable and can be sustained for several hundreds or thousands of years in most regions of the world and has a potential to contribute the terrestrial carbon sequestration. Phytolith production in plants varies spatially and temporally and also varies under different land use and soil management conditions. Hence, the phytOC produced in the plant species under specific environmental situation and the amount that reached the soil from plant should be quantified. Also the soil process and properties that affects the stability and the losses of phytOC to be studied and such losses are quantified. The full potential of this carbon fraction for increasing soil carbon sequestration in different land use systems has yet to be studied. This kind of information and studies would provide much greater opportunities to securely bio-sequester carbon in the plants and subsequently in the soil for a long period. The opportunity exists to enhance both medium- and long-term carbon sequestrations by cultivation of high PhytOC-yielding plant species of the major agriculture, forest and grassland systems. This opportunity will be maximized if the other factors affecting phytolith yield of plants and those that enhance the phytolith stability in the soil environment are optimized. The cropland phytolith C sinks may be further enhanced by adopting cropland management practices such as optimization of cropping system and fertilization. In the future, studies should mainly be focused on breeding and biotechnological tools for the trait of enhanced PhytOC yield in crop plants would result in plant cultivars with much greater PhytOC yields than are currently available. The suitable land use and soil management practices that restore more PhytOC in a particular cropping system are to be developed. The potential of PhytOC production and accumulation in many grasses, forest trees and wild cultivars is to be excavated. Selection of specific cultivars of crops and other grasses for high PhytOC yields and the increasing percentage cropland for these species and sustainable land use management options would increase the rate of terrestrial bio-sequestration of carbon substantially.

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Soil Management for Regulating C Pools: Perspective in Tropical and Subtropical Soils

4

Debashis Mandal

Abstract

Worldwide tropical region covers an area of about 8 billion ha. Tropics are increasingly threatened by intensive and inappropriate land use. According to some global data, land use change has resulted in losses of 25–50% of SOC in topsoil. The objective of this chapter is to highlight and synthesize the soil management options, which help to sequester carbon in tropical and subtropical regions. Some improved soil management practices for capturing and storing carbon with favourable impact on capturing carbon include growing cover crops, sowing crops with conservation tillage, maintaining balance level of soil fertility, and converting marginal and degraded lands to restorative land uses. A meta-analysis of 137 studies largely from tropical countries showed that the cover crop has the capability of annual change rate of 0.32 ± 0.08 mg ha^{-1} $year^{-1}$ in the topsoil. Long-term conservation tillage experiments revealed that the improvement in soil organic C was proportionately higher in poorer soils than in soils with inherently higher organic C content. Integrated nutrient management involving addition of organic manures/composts along with inorganic fertilizers results in improved soil aggregation and greater carbon sequestration, especially in macroaggregates. Agricultural intensification also enhanced C-sequestration as increase in one tonne productivity of rice and wheat, resulting in a C-sequestration of 0.85 mg ha^{-1}. Likewise, conversion of degraded croplands to grassland can result in an annual increase of 3% or more SOC concentration. Through this conversion, C-sequestration rate of 0.3–0.8 mg ha^{-1} $year^{-1}$ was achieved in tropical West Africa. Some researchers even reported a higher sequestration rate between 1.2 and 1.7 mg ha^{-1} $year^{-1}$ in the case of land conversion from degraded cultivated land to grassland. Maximizing the productivity of existing agricultural land and applying best management practices to that land would slow the loss of soil C. Soil C management needs to be considered within

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a broader framework of sustainable development. Widespread adoption of RMPs by resource-poor farmers of the tropics is urgently warranted.

Keywords
Carbon sequestration · Conservation tillage · Cover crops · Land restoration · Soil management

4.1 Introduction

Soil plays a very important role in the global biogeochemical cycle of carbon (C). The accumulation of soil organic carbon (SOC) within the soil is a balance between the return or addition of plant animal residues and their subsequent losses due to decay by microorganisms and other processes. Soil and land use changes can trigger a process of soil carbon accumulation over time. Eventually, the system may reach to a new carbon stock equilibrium or saturation point, and no new carbon will be absorbed. However, soil systems attain a quasi-equilibrium phase after accumulation as well as loss of SOC over time, which largely depends on the land use system. Therefore, after each change in the land use system, a period of constant management is required to reach a new quasi-equilibrium stage. This way, the SOC is stabilized to another quasi-equilibrium value characteristic of that changed situation in terms of new land use pattern, vegetation cover and management practices. Climatic conditions, such as temperature and rainfall, exert a major influence on the amount of organic matter in soil. Typically, accumulation of organic matter in soil is greater when there is more precipitation and cooler temperature. Similarly, decomposition of organic matter is greater in warmer and drier climates. Other factors that affect the rate of organic matter decomposition include soil aeration, pH level and the microbial population in soils. Agricultural management practices can also influence the amount of soil organic matter (SOM). Increased tillage of the soil decreases organic matter. Tillage increases aeration, which leads to drier soils and greater rates of decomposition. Increased summer fallow in crop rotation also decreases SOM because fewer plant tissue residues are being added to the soils.

Recently, the role of SOC in regulating various pools of C has been increasingly acknowledged by many researchers including soil scientists, geologists, foresters, climatologists and geomorphologists. Under natural conditions, soil systems maintain a balance, as the loss of materials from soil is approximately recovered through regenerative process (Verheijen et al. 2009; Mandal et al. 2006; Mandal and Sharda 2011).

Tropical regions located between 23°27′ north and south of equator cover approximately 40% of the world's land area, 5.4 billion ha of the total land area of 13 billion ha. Subtropical regions are located between 23° 27′ and 30° N and S of the equator. Tropics and subtropics together cover an area of about 8 billion ha. Tropics, especially India, are increasingly threatened by intensive and inappropriate land use. Inappropriate land use and unsustainable land management practices deplete soil quality and further aggravate the degradative soil processes.

Sub-Saharan Africa, south and central Asia, China and South America are the global hotspots in the tropical region because of their high priority for soil restoration and C management. Long-term experimental studies have confirmed that soil organic carbon is highly sensitive to land use changes from native ecosystems such as forest or grassland to agricultural systems, resulting in loss of organic carbon (Jenkinson and Rayner 1977; Paul et al. 1997). Changes in land use and vegetation also cause carbon depletion by influencing soil respiration and carbon fluxes in soil (Post and Kwon 2000). Management of soil to increase SOC levels can, therefore, increase the productivity and sustainability of agricultural systems (Cole et al. 1997). Enhancing SOC concentration from a low level of 0.1–0.2% in tropical soils to its critical limit of 1.1% is a tremendously challenging task (Lal 1981, 2004).

The global carbon cycle shows that the world's soils contain 1500–2000 giga tonnes (Gt) of carbon depending on the soil depth. In contrast, vegetation, mainly perennial, contains 600–700 Gt C. Prior to the industrial development in the nineteenth and twentieth centuries, deforestation and land cultivation were the main sources of green house gas emission. However, in recent time, it is reported that about one-fourth of anthropogenic carbon dioxide emissions are due to land use change, especially deforestation, and the rest is due to fossil burning in the past 20 years (Barnett et al. 2005).

It is estimated that arable lands have lost about 40% of their carbon content in less than 50 years. The drastic effect of tillage is explained by the so-called de-protection of soil organic matter physically protected inside soil aggregates (Balesdent et al. 2000). This results in an increase in mineralization of organic matter and the flux of CO_2 into the atmosphere (Reicosky and Lindstrom 1995). Entropic factors such as land use, land cover and agricultural practices govern actual C stock in soils. This is well illustrated by the C content of French soils (Arrouays et al. 2001), which ranges from more than 100 mg ha^{-1} for some natural soils to 30 mg ha^{-1} in arable or vineyard soils. These low values are explained by the significant loss of C that occurs during the first year of soil cultivation of grassland or forest soils, mainly due to tillage.

The objective of this chapter is to highlight and synthesize the soil management options, which help to sequester carbon in tropical and subtropical regions. Land management practices that increase carbon input tend to increase the attainable C-sequestration, while the actual C-sequestration is determined by the soil management techniques that reduce carbon storage, such as erosion, tillage, residue removal and drainage. Although the potential soil carbon sequestration capacity is equivalent to the cumulative historical C-loss, only up to 60% of this capacity is attainable through sustainable land management practices (The World Bank 2012; for ref. carbon sequestration in agricultural soils). Changes in climate and atmospheric CO_2 can alter the rates of soil erosion by wind or water (Fig. 4.1). Soil erosion can be directly affected by change in quantity and quality of erosive forces, for instance, by the amount and intensity of precipitation (erosion by water), and wind speed and direction (erosion by wind) on an event basis. Change in climate and CO_2 concentration can indirectly affect erosion through effects on the degree and timing of crop cover, and the production and decay of residue. Change in soil water content, affected by changes in the ratio of precipitation to evapo-transpiration, can also

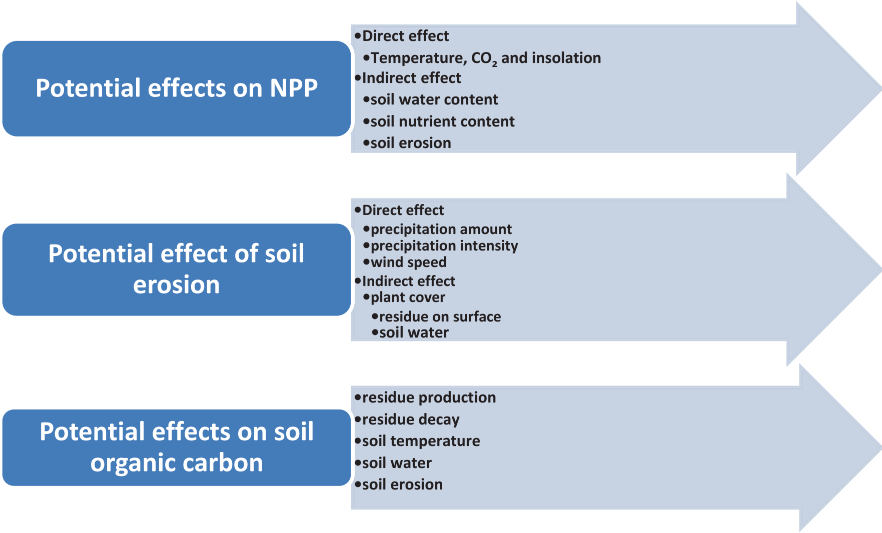

Fig. 4.1 Potential interactive effects of changes in climate and CO_2 on net primary production (NPP), soil erosion and soil organic carbon

influence erosion. Generally, water erosion increases (Wischmeier and Smith 1978) and wind erosion decreases as the soil becomes wetter. Water erosion and wind erosion both tend to be dominated by extreme events, which might occur only rarely.

4.2 Influence of Vegetation Type on Carbon Storage

The current rate of carbon loss due to land use change and inappropriate soil management is between 0.7 and 2.1 pg C year^{-1}. Land use change includes the modification of land cover types, for example, intensification of agricultural management or other changes in the farming system. Land use and land cover changes (LULCC) are the result of the interplay between socio-economic, institutional and environmental factors. According to some global data, LULCC has resulted in losses of 25–50% of SOC in top soil (Post and Kwon 2000; Lal 2004). Conversion of natural grassland and forest cropland can result in even higher losses of up to 40% of the original C stocks (Mann 1986; Ogle et al. 2005). It is reported that soil carbon in tropical forests declined by 7.7% between 1990 and 2007 (from 164.0 to 151.3 pg C) largely because of SOC loss caused by deforestation (Pan et al. 2011). Likewise, although the subtropical part of the Indian Himalayan mountain region is predominantly under forest cover, with soils having high organic carbon content, in the past few decades, significant changes in climate and land use have caused SOC depletion, leading to a declining trend in productivity. The influence of climate and land use on SOC in the subtropical Indian Himalayan region was studied by several researchers (Martin et al. 2010; Mandal et al. 2010). It is interesting to note that in

Table 4.1 Change of carbon stock due to land use change in different regions of the world

Regions	Average change in carbon stock from land conversion (mg C ha^{-1})	Average trade-off index (mg C ha^{-1} per mg crop yield ha^{-1} $year^{-1}$)
Tropics	−120.3	−76.9
Subtropics	−68.3	−27.0
Temperate	−62.9	−26.9

the Indian subtropical Himalayas, the C stock is greatly influenced by vegetation type and cultivation. A higher rate of humification led to more SOC accumulation in Quercus and Rhododendron forest than under conifers. Forest soil contained higher SOC than those observed in cultivated lands. However, at lower soil depth (1.5 m), SOC stocks were more in cultivated soils than in forest soils. The higher subsoil SOC in cultivated soil might be due to faster movement of dissolved organic carbon into deeper horizons in cultivated soils than in forest soils. The amount of SOC lost due to land conversion in this area was nearly 20% of the original SOC. Agroforestry, for example, offers a sustainable alternative to deforestation (Schroeder 1994) with a potential of several tonnes ha^{-1} $year^{-1}$ of C-sequestration in both soils and trees. Different scenarios are possibly based on increasing C inputs, decreasing C losses or some combination of both. In order to increase C inputs, it is necessary to increase biomass, while to decrease loss, it is necessary to reduce or eliminate tillage practices and also to arrest soil erosion. The average carbon loss resulting from the conversion of natural ecosystems to croplands is highest in the tropics (Table 4.1). This loss is largely because tropical forests store much more biomass carbon than any other biome (Ruesch and Gibbs 2008). Nearly two times as much carbon is lost for each converted hectare in the tropics than in temperate regions (Table 4.1). Consequently, the mean trade-off index is 2.85 times higher in tropical soils than in temperate soils (West et al. 2010).

4.3 C-Sequestration Through Land Reclamation and Management

The capacity of land sink for capturing C progressively declined from 28.1% to 24.2% over a period between 1970 and 2006 (Canadell et al. 2007). Some improved soil management practices for capturing and storing carbon with favourable impact on soil structure include growing cover crops, sowing crops with conservation tillage, maintaining balance level of soil fertility and converting marginal and degraded lands to restorative land uses (Fig. 4.2). Improving soil's resistance to forces causing detachment and transport involves enhancing soil structure. Any land reclamation practice, which improves the soil structure and enhances the soil quality, leads to C-sequestration. Once the C is captured and retained in the soil, the life of enhanced SOC can be maintained only through restorative land use practice and recommended management

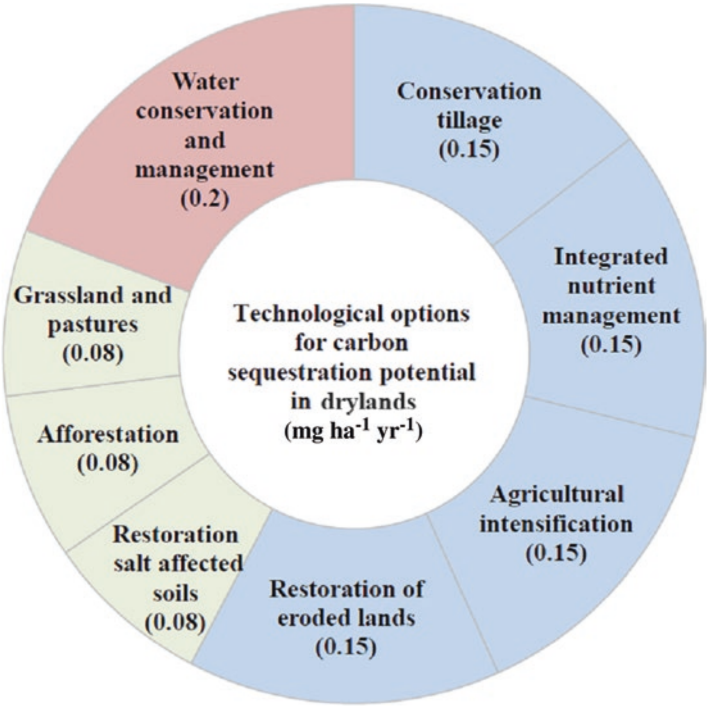

Fig. 4.2 Carbon sequestration potentials (mg ha^{-1} $year^{-1}$) of various land management options in tropical soils

practices (RMPs). Soil's capacity for C-sequestration depends on mineralogy, clay content, temperature, moisture regimes and aggregate-forming ability (Lal 2004).

4.3.1 Cover Crops

Introduction of cover crops in existing cropping system is a promising option to sequester carbon in tropical agricultural soils. A meta-analysis of 137 studies largely from tropical countries showed that the cover crop has the capability of annual change rate of 0.32 ± 0.08 mg C ha^{-1} $year^{-1}$ in the top soil (Poeplau and Don 2015). An extrapolated estimate based on this finding revealed that cover crop has a potential global SOC sequestration of 0.12 ± 0.03 pg C $year^{-1}$, which would compensate for 8% of the direct annual greenhouse gas emissions from agriculture. Besides an increased carbon input, cover crops have the additional advantages to increase biodiversity as well as to reduce soil erosion and drought stress for the following crop when used as mulch cover in water-limited systems. Through formation of a quick and protective ground cover, cover crops improve SOC content, enhance soil biodiversity, improve soil structure and minimize risks of soil erosion (Lal 2004). An increase in SOC content with incorporation of legume cover crops was observed in

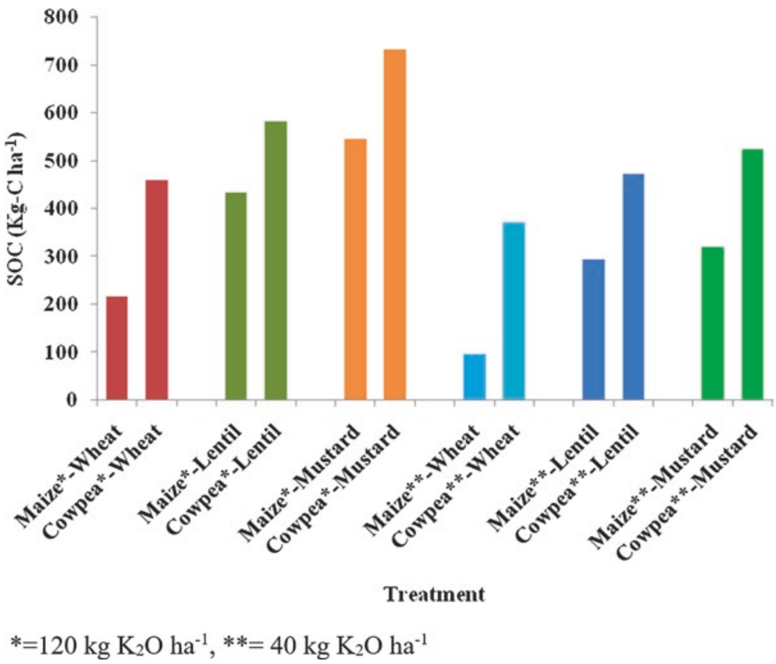

Fig. 4.3 Build-up of soil organic carbon (SOC) as affected by cover crop and potassium application (ICAR-IISWC 2004–2005) (∗120 kg K_2O ha^{-1}; ∗∗40 kg K_2O ha^{-1})

continuous corn. Indeed, experiments conducted at subtropical Himalayan region revealed that cover crop-based rotation such as cowpea–wheat, cowpea–lentil and cowpea–mustard added more SOC than cereal-based rotation such as maize–wheat, maize–lentil and maize–mustard. Among cover crop-based rotation, the annual rate of increase in SOC was highest (734 kg C ha^{-1}) in cowpea–mustard, with 120 kg K_2O ha^{-1}, whereas lowest (97 kg C ha^{-1}) in maize–wheat rotation with 40 kg K_2O ha^{-1} (Fig. 4.3).

Both erosion and biological oxidation remove carbon from soils. Conventional ploughing exposes soil to solar radiation, mixes residues into soils and adds air to macropores, all leading to an increase in metabolic rate of microbial populations. The greatest losses of soil carbon and organic matter occur under intensive and continuous cereals (0.105 to −0.460 mg C ha^{-1} $year^{-1}$) and fell when mixed rotations and cover crops are cultivated (0.033 to −0.065 mg C ha^{-1} $year^{-1}$) (Pretty et al. 2002).

4.3.2 Conservation Tillage

The benefits of conservation tillage in decreasing runoff and soil erosion are widely recognized. When it is used in conjunction with crop residue mulch and cover crops, conservation tillage improves soil structure and enhances SOC pool. Data given in

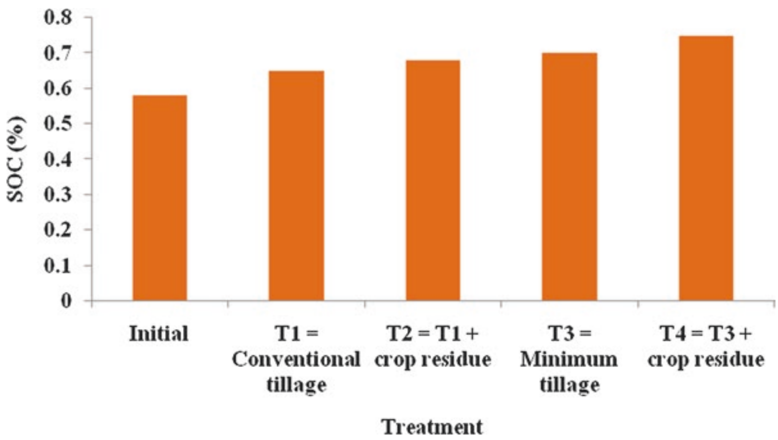

Fig. 4.4 Effect of tillage and crop residue on soil organic carbon (SOC) (ICAR-IISWC 2006–2007)

Fig. 4.4 show that the use of no-till system for consecutive 8 years increased the SOC content and residence time of carbon in soil probably due to encapsulation of SOC within stable aggregates and alteration in soil quality. The benefits of conservation tillage in C-sequestration are due to both increases in SOC content and decreases in CO_2 emissions caused by ploughing and to reduction in fuel consumption.

The impact of conservation tillage on soil organic C-sequestration may be greater in degraded soils than in fertile soils (Franzluebbers 2005). This is possibly because the ratio of soil organic C with conservation tillage to conventional tillage followed an exponential trend [ratio = 1.06+ 3.00e$^{(-0.15CT)}$; $r^2 = 0.33$, $n = 96$]. This trend also revealed that the ratio was logarithmically greater in soils with inherently lower organic C than in soils with inherently higher organic C content. Therefore, on a relative basis, the increase in soil organic C was proportionately higher in poorer soils.

4.3.3 Soil Fertility Management

Nutrient management is essential to increase crop yield. There is a strong relationship between crop yields and the amount of SOC accumulation in the root zone. It is estimated that for each tonne of C-sequestration, nearly 83 kg N, 20 kg P and 15 kg K is needed (Lal 2004). Several studies in tropical regions of India have documented a positive relationship between SOC concentration in the root zone and yield of a number of crops including wheat, rice and maize. For example, in alluvial soils of north India, wheat grain yield without fertilizer application increased from 1.4 mg ha^{-1} at an SOC concentration of 0.2% to 3.5 mg ha^{-1} in soils with an SOC concentration of 0.9%. The effect of SOC concentration with the application of chemical fertilizers on wheat productivity was smaller, indicating an interaction between SOC and fertilizer use. Judicious nutrient management is crucial to soil organic C (SOC) sequestration in tropical soils (Mandal et al. 2007). Adequate supply of nutrients in soil can enhance biomass production and SOC content (Van Kessel and Hartley 2000). Use of organic manures and compost enhances the SOC pool more than application of the same amount of nutrients as inorganic fertilizers (Gregorich et al. 2001). Long-term manure application increases the SOC pool (Gilley and Risse 2000), which not only sequesters CO_2 but also enhances productivity of soil (Swarup et al. 2000; Manna et al. 2005). It is, however, argued that SOC sequestration is a major challenge in soils of the tropics and subtropics, where climate is harsh and resource-poor farmers cannot afford the input of organic manure and crop residues. The rate of C-mineralization is high in the tropics because of high temperature and low humification efficiency (Ladha et al. 2003). Integrated nutrient management involving addition of organic manures/composts along with inorganic fertilizers results in improved soil aggregation and greater carbon sequestration, especially in macroaggregates (Benbi and Senapati 2010; Sodhi et al. 2009). With the application of nitrogen and phosphatic fertilizer together, the SOC increased at a rate of nearly 250 kg ha^{-1} over 18 years in North China (Ludwig et al. 2010, 2012). Incorporation of organic manures includes decomposition of organic matter, where roots, hyphae and polysaccharides bind clay particles to microaggregates bind to form C-rich macroaggregates. This type of C is physically protected within macroaggregates. The free primary particles are cemented together into microaggregates by persistent binding agents characterized by humification of organic matter and stimulated accumulation of C aggregates.

4.3.4 Agricultural Intensification

Adopting recommended farming practices is an important and effective strategy for soil conservation. Recommended farming practices involve agricultural intensification on prime agricultural land through use of improved varieties and adoption of appropriate cropping systems that enhance cropping intensity and elimination of summer fallow. In fact, the SOC pool in 0–15 cm depth increased linearly with increase in cropping intensity. Improvements in crop yield by adoption of recommended technology enhance SOC pool and improve soil quality.

Intensive agriculture with improved nutrient and water management results in enhanced C-sequestration due to higher crop productivity and greater return of crop residues, root biomass and root exudates to soil. Findings of a 25-year study from Punjab revealed that intensive agriculture resulted in improved SOC status by 38% (Benbi and Brar 2009). Enhanced C-sequestration was related to increased productivity of rice and wheat; 1-tonne of increase in crop productivity resulted in a C-sequestration rate of 0.85 mg ha^{-1}.

4.3.5 Land Restoration

Many different strategies have been shown, under controlled conditions, to successfully rehabilitate degraded land, restore land capabilities and enhance the productivity of land. Conversion of marginal agricultural land to restorative land use such as conversion of degraded farmland into agroforestry systems, conversion of degraded croplands and pasture to forest and conversion of degraded croplands into grassland reduces soil erosion and increases SOC pool. The rate of sequestration may differ among soil types, management and ecological factors.

4.4 Grassland Management

Soils typically account for 70–90% of the total carbon sequestrated in a grassland ecosystem. According to Hurst et al. (2005), livelihood of about one billion people in tropical countries are directly dependent on livestock rearing and hence on grasslands. However, a large extent (74–76%) of tropical pasture and range lands are in the degraded state (Dregne and Chou 1992). Therefore, improved conservation practices and better management is necessary to improve C-sequestration. Some examples of improved practices are controlled grazing, rotational grazing, sivli-pastoral practices with legume species and fire management. Restoration of pasture lands by grass legumes (*Medicago truncatula* and *Astrebla lappacea*) in semiarid vertisol soils of Australia increased SOC concentration from 1.3% to 1.6% in 4 years. Transformation of degraded croplands to grassland can result in an annual increase of 3% or more SOC concentration (Conant et al. 2001). Through this conversion, C-sequestration rate of 0.3–0.8 mg ha^{-1} $year^{-1}$ was achieved in West Africa (Batjes 2001). Some researchers even reported a higher sequestration rate between 1.2 and 1.7 mg ha^{-1} $year^{-1}$ in case of land conversion from degraded cultivated land to grassland (FAO 2004; Vagen et al. 2005).

Based on a comprehensive study in a typical mid-hills watershed of the Himalayas, the rate of erosion from an open degraded area was estimated to be 35 mg ha^{-1} $year^{-1}$ (ICIMOD 1998). The grass cover on the forest land with sparse trees was found to hold surface soil litter, thus controlling loss at lower levels, that is, less than 5 mg ha^{-1} $year^{-1}$. From cultivated onward sloping terraces, the loss varied from 3 to 25 mg ha^{-1} $year^{-1}$ (ICIMOD 1998). Some evidence exists to show that soil degradation due to land use changes in the Himalayas affects C pools significantly. Selective watershed studies indicated that the decline in pasture land from the 1980s to the end of the twentieth century varies from 12% in the Indian mountains to 99% in China (Chhetry 1998; Jianchu et al. 2000). Land use changes caused by deforestation and land conversion have a strong relation to soil degradation and C-emission to atmosphere. In other words, the C-sequestration process is a function of land use and land management practices, which have a direct linkage with socio-economic factors as well. Table 4.2 presents the net emission in the Himalayan region due to land use changes reported by several investigators (Devkota 1992; Upadhyay et al. 2005). Assuming a maximum potential of carbon sequestration of 100 mg per hectare, about 13,276 million mg carbon can be sequestered through grassland management only in the Himalayan region (Table 4.2). Likewise, in tropical savanna and other grasslands (2.25×10^9 ha), about 250 pg of carbon can be stored in soils. Across the globe, cropland has been expanded by 27% during the post-Green Revolution phase (between 1961 and 2005). In the tropical region, mostly this expansion has occurred in forest and pasture lands (Gibbs et al. 2010). Assuming a 45 mg ha^{-1} $year^{-1}$ of change in soil

Table 4.2 Pastureland and net emission due to land use changes in the Himalayan region

Country	Area (m ha)	Pasture land (m ha)	Net C emission owing to change in erosion rate due to land conversion
India	52.82	18.01	36 million mg C $year^{-1}$ (based on Upadhyay et al. 2005)
Pakistan	44.44	4.45	
China	168.91	90.20	
Others	87.86	20.1	
Global Himalayan mountain	354.03	132.76	

erosion rate due to this type of land conversion (Upadhyay et al. 2005), nearly 5974 million mg of additional accelerated soil loss, which in turn cause a displacement of 179 million mg of carbon and 36 mg of C emission per year.

Following the conversion of cropland to forest and grassland across the Loess Plateau of China through their ambitious *Grain for Green* project, the average C-sequestration rate increased by 0.3 mg ha^{-1} $year^{-1}$ in 16 years. Although the initial goal of the project was to control soil erosion, it has remained greatly influential in increasing both the rate and overall quantity of C-sequestration in the soil. It is also very interesting to note that the land converted to grassland had higher C-sequestration rate than even forest and shrub land (Deng et al. 2014).

4.5 Conclusion

Worldwide, overgrazing, deforestation and other exploitative land systems caused land degradation and attendant SOC depletion in many land-based ecosystems. Historically, soils have lost 40–90 pg carbon (C) globally through cultivation and disturbance at a rate of about 1.6 ± 0.8 pg C y^{-1}, mainly in the tropics. Since soils contain more than twice the C found in the atmosphere, loss of C from soils can have a significant effect on atmospheric CO_2 concentration, and thereby on climate. Halting land use conversion would be an effective mechanism to reduce soil C losses, but with a growing population and changing dietary preferences in the developing world, more land is likely to be required for agriculture. Maximizing the productivity of existing agricultural land and applying best management practices to that land would slow the loss of soil C. There are, however, many barriers to implementing best management practices, the most significant of which in developing countries are driven by poverty. Management practices that also improve food security and profitability are most likely to be adopted. Soil C management needs to be considered within a broader framework of sustainable development. Policies to encourage fair trade, reduced subsidies for agriculture in developed countries and less interest on loans and foreign debt would encourage sustainable development, which in turn would encourage the adoption of successful soil C management in developing countries. Likewise, a widespread adoption of RMPs by resource-poor farmers of the tropics is urgently warranted. If soil management is to be used to help addressing the problem of global warming, priority needs to be given to implementing such policies.

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5 Soil Management Practices of Major Crops in the United States and Their Potential for Carbon Sequestration

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Abstract

Although the United States has no areas considered strictly tropical, there are subtropical and warm humid regions in the south where agricultural production is high. Practices in these regions, and the results of research on their effects towards carbon sequestration in soils, are certainly transferable to tropical regions. Soil management (e.g., tillage and amendment) and crop management (e.g., cropping system and cover crops) practices in the United States (with emphasis on the southern region) as well as new technologies and advances are covered in this chapter. Regulatory pathways for increasing carbon stores in managed agricultural lands in the United States are unlikely; therefore, willingness on the part of farmers to adopt practices aligned with C sequestration goals must be engendered. Reduced tillage and cover crop inclusion are being adopted more commonly in the United States. Reuse of organic waste materials for the benefit of agricultural production is also increasing. Breeding for greater or more stable root mass, and new methods for monitoring the flux of C from the soil to the atmosphere both represent exciting frontiers of discovery in this area.

Keywords

Carbon longevity · Cover crops · Soil organic carbon · Tillage · United States

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5.1 Introduction

There is an urgent global call for better management of the earth's carbon resources through soil management. In answering this call, appreciation for the complex interrelatedness of the carbon cycle and the soil ecosystem is necessary to make deliberate and effective, rather than hastily prescribed, actions. The United States is a relatively large nation with wide-ranging climatic, topographic, and geologic conditions (Table 5.1). Therefore, the concept of scale, in both the spatial and temporal dimensions, must be reconciled by scientists and agricultural practitioners alike to effectively harness the potential of a massive and heterogeneous soil matrix for

Table 5.1 Soil carbon types, composition, and relative stabilities in the soil environment

Soil carbon type	Decomposability	Mean residence time	C:N ratio	Composition	Chemical compounds
Residues/light fraction	Readily decomposible	<0.5 years	10–25	Decaying plant and other biological tissues, surface residues	Simple sugars, amino acids, starches
	Moderately resistant	<5 years	20–200	Structural tissue components	Polysaccharides, cellulose, hemicellulose
Soil organic matter	Decomposible (active pool)	<2 years	15–30	Active living biomass (e.g., microbes, roots, insects), particulate organic matter (POM)	Proteins, amino acids, organic acids, cellulose, lignin
	Resistant (slow pool)	15–100 years	10–25	Nonliving biomass in partial decay	Lignified tissues, fats, waxes, resins, polyphenols, cell wall fragments
	Highly stabile (passive pool)	500–10,000 years	7–10	Humus, humin, humic acid, fulvic acid, charcoals	Generally large, amorphous, and complex compounds (soil humic substances), randomly ordered aromatic structures, and highly structured crystalline graphenes (soil charcoals/bio char)

Adapted from Stevenson (1994), Brady and Weil (2002), Baldock (2007) and Dungait et al. (2012)

sequestering carbon. Throughout the southern United States, high mean annual temperatures prevail. Though true tropical conditions do not exist within the contiguous 48 states, there are substantial production systems operating in subtropical and adjacent climates. Therefore, the consequences of a national or global agenda that favors the uniform promotion of selected soil management practices over others for the purpose of building or sequestering soil carbon are potentially powerful and unpredictable, and should be considered carefully.

The 4 per mille program proposed by the French Minister of Agriculture to offset carbon emissions by increasing soil organic carbon (SOC) stocks by 0.4% each year has been signed into agreement by 192 nations and ratified by 114 (Minasny et al. 2017). The United States, to date, is not one of these nations. Unfortunately, there is also no cohesive agenda specifically addressing the sequestration of carbon within the United States. However, there are policies and efforts at the national, regional, and local scales to provide for the conservation of soil as a natural resource, and to protect and restore the long-term productivity of the soil to provide food security and ecosystem services. These policies and efforts include recommended practices aligned with increasing SOC.

Regulations that govern the addition of organic materials such as biosolids, sludges, and manures are primarily in place to reduce potential releases of the nutrients phosphorus and nitrogen that contribute to water pollution. In contrast, regulatory requirements for other soil carbon management practices such as tillage, residue management, and/or crop diversification practices in the United States are rare. This is due to a strongly held national tradition supporting the primary rights of the landowner, though these rights may vary from state to state. Approximately 40% of the US land area is given to agricultural production (NASS 2012). Exploitation of the soil matrix in the United States for the purpose of sequestering carbon, therefore, necessitates enlistment of the willing land owner. Adoption of general conservation practices in agriculture, even without the focus on soil carbon sequestration, varies widely by cropping system and by region (Wade et al. 2015). This effort to increase adoption of practices that promote the storage and sequestration of carbon will include the public tools of research, investment, education/outreach, and in the absence of comprehensive regulation, the cultivation of social capital as drivers.

The focus of this chapter is to assess the potential of major cropping systems to sequester carbon in soils in the United States. These include corn, cotton, soybean, and wheat-based systems. Management of crops and soils to enhance C-sequestration is explored, as are emerging technologies and practices and their effects on C fluxes in these cropping systems.

5.2 Management Practices

5.2.1 Soil Management Practices

5.2.1.1 Conservation Tillage and Carbon Sequestration

During the latter part of the nineteenth and the first half of the twentieth centuries, growers in the United States intensively practiced deep tillage using moldboard plow and disk. This resulted in the low accumulation of crop residues on the soil

Table 5.2 Estimation of global greenhouse gas emission (GHG) by different sectors (IPCC 2014)

Sectors	GHGs contribution (%)
Agriculture, forestry and other land use	24
Electricity and heat production	25
Industry	21
Other energy	10
Transportation	14

surface, accelerating soil degradation through water and wind erosion, and promoting severe loss of soil organic carbon (SOC). The book "Plowman's Folly" (Faulkner 1942) is credited with initiating the no-tillage (NT) movement in the United States. It explained that the moldboard plow is the least satisfactory field operation for land preparation in terms of loss of fertile top soil. As a result, people developed an interest in conservation tillage systems that would protect and maintain soil health.

The terrestrial ecosystem holds 2500 gigatons (Gt) of soil carbon to a depth of 1.0 m that consists of 1550 Gt of organic carbon and 950 Gt of inorganic carbon. The amount of carbon in the soil ecosystem is 3.3 times that of the atmospheric pool and 4.5 times that of the biotic pool of the earth (Lal 2004a). However, the 2014 Intergovernmental Panel on Climate Change (IPCC) assessment report estimated that agriculture was responsible for 24% of the greenhouse gas (GHG) emission. The contributions of different sectors in GHG emission are listed in Table 5.2.

The soil carbon loss through farm practices such as tillage, and removal of crop residues, in the United States was estimated at 4 Gt per year (Lal et al. 2004). Therefore, conservation tillage systems including no-tillage (NT), reduced tillage (RT), and mulch tillage (noninversion tillage to partially incorporate crop residues) are considered the efficient options for carbon sequestration in croplands.

Conventional tillage (CT) often results in loss of SOC and increased emission of CO_2 from soil to atmosphere (Potter et al. 1998). Several studies from the United States have reported a decrease in SOC under CT systems. For example, in a study conducted in Texas, Potter et al. (1998) showed that NT had accumulated 264 kg C ha^{-1} $year^{-1}$ more than CT under cotton in an Orelia sandy clay loam soil at Corpus Christi. However, under corn, the CT system accumulated 93 (low fertilizer rate) and 157 kg C ha^{-1} $year^{-1}$ (high fertilizer rate), illustrating the importance of crop biomass incorporation for SOC buildup in heavy clays west of the Mississippi river along the Gulf of Mexico in the Southern United States. Buildup and maintenance of SOC are related to climatic conditions, and the levels of SOC are relatively higher in the northern United States than in the southern. This is largely due to cooler mean annual temperatures that result in a decreased rate of degradation of soil organic matter (SOM) (Franzluebbers et al. 1995; Paustian et al. 1997; Wright and Hons 2005). A study conducted in Texas on a long-term tillage system (Franzluebbers et al. 1995) reported that the loss in SOC was 49% in CT compared to no-tillage (NT) in a silty clay loam soil. Similarly, Ussiri and Lal (2009) reported about 0.46 g (CO_2-C m^{-2} day^{-1}) higher CO_2 fluxes in CT system than NT due to the increased

Table 5.3 Area under conservation agriculture (CA) by continent (Kassam et al. 2014)

Continent	Area (million ha)	Percentage of total	CA as a percentage of arable cropland
South America	55.4	45	57.3
North America	40.0	32	15.4
Australia and New Zealand	17.1	14	69.0
Russia and Ukraine	5.1	4	3.3
Asia	5.0	4	0.9
Europe	1.4	1	0.5
Africa	1.0	1	0.3
World	125	100	8.8

loss of SOC in the CT caused by accelerated decomposition of SOM by tillage. Moreover, it was reported that tillage can accelerate the SOM decomposition rate by incorporating crop residues, breaking the macroaggregates, and aerating the soil, all of which lead to better contact between crop residues and soil (Prior et al. 1997). Several factors controlling the decomposition process include temperature, water, and oxygen content, substrate quality and substrate availability and these factors can be affected by soil management practices such as tillage and residue management.

Carbon sequestration in the soil can be achieved by changing the amount of crop residue retention and removal. The conservation tillage system is one of the most efficient soil management practices for modifying the relationship between crop residue retention and removal. Globally, the area under NT systems (125 million ha) has grown many times since its initiation (Table 5.3).

The U.S. enjoys the largest area under NT at approximately 39 million ha (USDA 2012). In a study conducted on a silty clay loam soil, Govindasamy et al. (2017) reported that the SOC was higher (1.1%) in the NT system compared to CT (0.5%). Similarly, Potter et al. (1998) reported that SOC content in the Orelia sandy clay loam soil was higher in NT system, followed by the systems of minimum tillage, chisel plow, and moldboard plow. Again, the NT system stored more SOC in the 0–2.5 cm depth than the CT system in continuous grain sorghum and soybean, and sorghum–soybean rotation (Havlin et al. 1990). Reducing soil disturbance and increasing surface residue cover in the NT system inhibit the loss of SOC from the soil. According to Hooker et al. (2005), increases in the total organic C in NT compared to CT is attributed to retention of quality crop residues. Furthermore, Six et al. (2000) reported that increase in total SOC in NT than CT was due to a greater amount of C-rich macroaggregates and reduced rate of macroaggregate turnover in soil. Overall, the positive effect of the NT system on SOC storage depends on soil type, crop residue qualities, climatic conditions, nutrient status, and timing of agricultural practices. Further, to achieve the maximum benefit of a long-term conservation tillage system, the growers have to follow a cropping system that includes cover crops (where possible) and application of organic manures to add quality residues.

5.2.1.2 Organic Soil Amendments

Soil C can be increased through direct additions of organic materials. Incorporation of organic soil amendments for the benefit of agriculture is practiced extensively throughout the United States. Many amendments may be considered raw or primarily labile, as in the case of green manures, most crop residues, animal wastes, and many low energy organic waste products (Lee et al. 2007). Other materials may be pre-stabilized or contain C in relatively refractory forms. These include biochar and charcoals, biosolids, and composts (Woolf et al. 2010). A great deal of attention has been placed on the use of organic amendments to build SOM, soil quality, soil tilth, or soil health, with only tangential appreciation for the storage or sequestration of carbon as it pertains to global C cycling. The excitement over the last decade for biochar's potential for long-term sequestration is the most notable exception to this attitude (Lehmann 2007; Smith 2016).

Primarily, labile materials used as organic soil amendments will contribute over the short term to SOC "storage" while also slowly contributing a small mass to sequestered SOC. Transformation of plant residues follows the general pattern of Fig. 5.1. Alteration of the original chemical compounds occurs through microbial attack and decomposition, after which condensation and polymerization occur at mineral surfaces (Stevenson 1994). The rate and proportions of amendments reaching sequestered status as humic materials depends upon the chemical composition of the material (e.g., lignin and cellulose), C: N ratio, soil properties, and environmental factors such as temperature and water (Kleber 2010). There is an enormously high level of variability in the composition of these materials that will lead to a similarly high level of variability in the eventual stabilization to humic substances. Therefore, labile organic amendments as a general class cannot be relied on to provide sequestration of C.

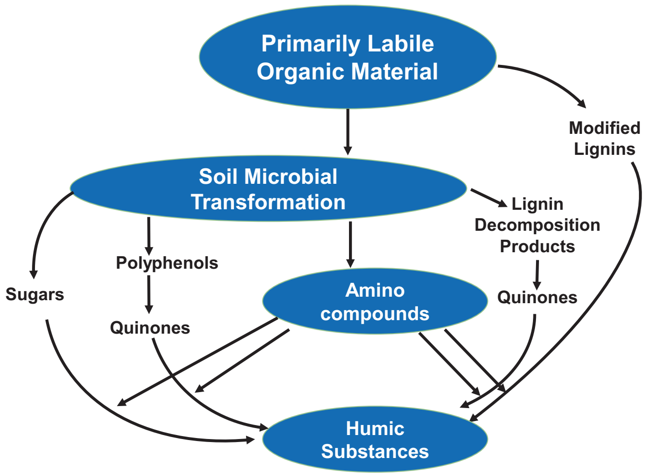

Fig. 5.1 Pathways to stabilization of plant residues and other primarily labile organic soil amendments to the humic phase in soil. (Modified from Stevenson 1994)

Biochar represents the most refractory of the pre-stabilized organic amendments. It is formed from the pyrolysis of vegetative material, including wood, manure, or crop residue (Deluca et al. 2015; Lehmann 2007). The composition and properties of the final product are a function of the feedstock and the production process (time, temperature, gas mix). A large range of potential outcomes affects the agronomic value, crop response, and soil properties following application of biochar. The use of biochars in agriculture production in the United States is not as extensive as the use of less stable organic amendments, but may be growing. Meanwhile, there is a public debate amongst researchers and policy makers concerning the claim that biochar production and incorporation into the soil is truly carbon negative (Glaser et al. 2009). Despite this debate, the use of biochar as soil amendment remains a viable pathway towards increasing C sequestration due largely to its remarkable longevity. Overall efficiencies in C sequestration will continue to improve as new biochar production technologies and reductions in the use of fossil fuels come on line.

5.2.2 Crop Management Practices

5.2.2.1 Cropping Systems (Corn, Cotton, and Soybean Based)

Cropping systems that add more carbon-rich residue and improve soil fertility help promote carbon storage and potential sequestration. Perennial crops also increase belowground C and reduce soil disturbance (Conant et al. 2001). Cultivation of multiple crops, therefore, has more potential to store and sequester C than monoculture systems.

In the United States, corn (*Zea mays* L.), cotton (*Gossypium hirusutum* L.), and soybean [*Glycine max* (L.) Merr.] are the major crops and the corn–soybean rotation is adopted by a majority of the growers in the Midwestern United States. Each crop, grown in rotation or followed by cover crops, serves to increase properties associated with soil health, including SOC. Several studies have been conducted to estimate the increase in SOC under different cropping systems. In Ohio, corn–wheat (*Triticum aestivum* L.)–alfalfa (*Medicago sativa* L.) rotation with no-till increased the SOC rate by 0.76 Mg ha^{-1} $year^{-1}$ in upper 30 cm of soil over continuous corn cropping (Jarecki et al. 2005) (Table 5.4). Moreover, the use of cover crop in the offseason has been found to increase the SOC rate compared to the fallow period. In Pennsylvania, Dell et al. (2017) conducted a bioenergy cropping system study using corn (3 year)–soybean (1 year)–alfalfa (4 year) rotation, and compared with perennial crops such as switch grass (*Panicum virgatum* L.) and reed canary grass (*Phalaris arundinacea* L.). The SOC rates of 0.4, 1.1, and 0.8 Mg C ha^{-1} $year^{-1}$ have been observed after 8 years in the bioenergy rotation, reed canary grass, and switch grass, respectively (Table 5.4). A higher sequestration potential has been observed in fields with perennials crops and dairy forage rotations than many annual cropping systems. The predicted sequestration over 40 years in dairy forage rotations (8–14 Mg C ha^{-1}) was much greater than corn–soybean rotations (−4.0–0.6 Mg C ha^{-1}) due to multiple years of perennial alfalfa (Dell et al. 2017).

In the case of cotton, there are only a few case studies conducted that have analyzed the effect of crop rotation on SOC in the United States. A study conducted in

Table 5.4 Effect of cropping systems on soil organic carbon (SOC)

Region/state	Cropping systems	Soil layer (cm)	Study duration (years)	SOC (Mg C ha^{-1} $year^{-1}$)[a]	Source
Ohio	(a) Corn NT (previously in hays for 12 years)	30	14	0.38	Jarecki et al. (2005)
	(b) Corn–wheat–alfalfa (with cattle manuring)		20	0.76	
Pennsylvania	(a) Corn (3 years) – Soybean (1 year) – Alfalfa (4 years)	10	8	0.40	Dell et al. (2017)
	(b) Switchgrass (8 years)			1.10	
	(c) Reed canary grass (8 years)			0.80	
Alabama	(a) Cotton (10 years)	20	10	0.11	Mitchell and Entry (1998)
	(b) Cotton + winter legume (10 years)			0.26	
	(c) Cotton (legume)–corn (winter small grain)–soybean			0.32	

[a]SOC values have been converted to Mg C ha^{-1} $year^{-1}$ for consistency based on information provided in the source file

Alabama for 10 years revealed an increase in cotton productivity and SOC sequestration when rotated with corn and winter legumes that led to higher biomass retention than cotton monoculture (Mitchell and Entry 1998) (Table 5.4). A significant increase and linkage between SOC and cotton seed yield indicated that higher biomass inputs from cover crops and corn in rotation with cotton improved carbon sequestration and cotton yield (Mitchell and Entry 1998).

Residue management is a key factor in sequestering SOC. In a study conducted at Michigan, annual residue retention in the soil was estimated as 10, 6.0, 3.0, 5.5, and 8.0 Mg ha^{-1} for corn, sugar beet, navy bean, oat, and alfalfa, respectively (Zielke and Christenson 1986). The cropping systems that included corn as one of the crops resulted in up to 10% more carbon sequestration because of the larger amount of residue returned to the soil (Lucas et al. 1977; Zielke and Christenson 1986). Similar results of variation in SOC were observed with greater residue inputs from corn–corn–corn–sugar beet rotation as compared to the navy bean–sugar beet rotation (Dick et al. 1998). Therefore, various components of cropping systems and different crop management practices such as crop rotations (Burney et al. 2010), residue retention (Wilhelm et al. 2004), use of varieties with more root mass to deposit C deeper in soil (Kell 2012), and cover crops during fallow periods (Burney et al. 2010; Poeplau and Don 2015) facilitate the process of SOC sequestration.

In the case of cotton, there are only a few case studies conducted that have analyzed the effect of crop rotation on SOC in the United States. An experiment conducted for 10 years revealed an increase in cotton productivity and SOC sequestration when rotated with corn and winter legumes that led to higher biomass retention than cotton monoculture (Mitchell and Entry 1998). A significant increase and linkage between SOC and cotton seed yield indicated that higher biomass inputs from cover crops and corn in rotation with cotton improved carbon sequestration and cotton yield (Mitchell and Entry 1998). A long-term study with 98 years of 2- and 3-year rotations of cotton with corn and soybean resulted in SOC concentration of 10 g C kg^{-1}, whereas SOC under cotton monoculture with a legume cover crop was 7.5 g C kg^{-1} and 3.9 g C kg^{-1}in continuous cotton without any cover crop (Reeves 1997).

5.2.2.2 Cover Crops

Cover cropping offers a potential strategy to reduce the losses of SOC and improve soil structure and properties. It also holds the potential to add C through increased surface residue and belowground biomass, increase soil aggregation, and cover the soil surface, all of which serve to increase soil health, soil quality, and/or soil tilth. Moreover, cover crops can fix the atmospheric CO_2, which decreases the CO_2 contribution to the greenhouse effect (Reicosky and Forcella 1998). In a meta-analysis compiling the data from 139 plots across the 37 locations, Poeplau and Don (2015) estimated that introduction of cover crops can lead to substantial SOC sequestration, which would compensate 8% of the direct annual greenhouse gas emission from agriculture. Again, despite the claim, much of the SOC increase would qualify more as stored than as sequestered.

Accumulation of SOC through the inclusion of cover crops may vary depending on the cover crop species, soil type, soil moisture, initial SOC stocks, crop management practices, and environmental factors (Chu et al. 2017; Lal 2004a). Kuo et al. (1997) reported that cereal rye (*Secale cereale* L.) and annual rye grass (*Lolium multiflorum* Lam.) were better suited for building SOC (with a gain of 0.10–0.17 g SOC kg^{-1} soil $year^{-1}$) compared to Austrian winter pea (*Pisum sativum* subsp. *arvense*), hairy vetch (*Vicia villosa* Roth), and canola (*Brassica napus* L.) in Washington, United States. Wiesmeier et al. (2016) showed that an 11–16% decrease in SOC is expected with the 3.3 °C increase in the mean temperature. Parton et al. (1987) observed a lower decay rate of SOC in lower temperature and higher precipitation in the Great Plains in the United States. High precipitation can also increase SOC accumulation compared to low precipitation regions, as the increased water promotes greater biomass accumulation by the cover crops (Trost et al. 2013).

The inclusion of cover crops can replace the bare fallow period with an additional period of C assimilation and improve the net ecosystem C balance of a cropland (Haque et al. 2015). In a study conducted for 4 years in Tifton, GA on a loamy sand soil, Hubbard et al. (2013) reported the increase in SOC by 0.3–4.7 mg g^{-1} of soil in a cropping system, where sun hemp (*Crotolaria juncea* L.) and crimson clover (*Trifolium incarnatum* L.) were rotated with sweet corn (*Zea mays* L.). Similarly, Mullen et al. (1998) noted that cover cropping in corn using hairy vetch and wheat (*Triticum aestivum* L.) increased the SOC by 47 and 2%, respectively, at the 0–5 cm depth compared to no cover crop in a long-term (11 years) no-till system in Milan, TN. In a no-till corn–soybean [*Glycine max* (L.) Merr.] production system in Ames, IA. Kaspar et al. (2006) reported that SOC increased by 0.03, 0.12, and 0.16 g kg^{-1} $year^{-1}$ in oat, rye, and oat-rye mixture cover crop treatments, respectively. Ruis and Blanco-Canqui (2017) estimated that cover crop inclusion has the potential to offset 100% and 56% of SOC stock lost under low and high residue removal rates, respectively.

Since much of the SOC originates from plant biomass, cover crop systems accumulating more biomass could lead to higher SOC. Therefore, the benefits of the cover crops could be limited by late planting and early termination. For example, Mirsky et al. (2011) reported that cover crop biomass was decreased by 2000 kg ha^{-1} when fall planting was delayed by 51 days in Pennsylvania, United States, and observed a substantial decrease in the biomass accumulation with earlier spring termination. A large amount of C input from cover crops is also added through the roots, which can contribute more effectively to the relatively stable C pool than aboveground C inputs (Kätterer et al. 2011). Overall, the effect of cover crops on SOC are generally not detected immediately, but can be observed over a sustained period (Ruis and Blanco-Canqui 2017). The ecosystems with higher biodiversity have the ability to absorb and sequester more C than the ecosystems with lower biodiversity (Lal 2004b).

5.3 New Research Opportunities

5.3.1 Breeding for Improved Biomass and Root Growth

The role of plant breeding in achieving a biological means to mitigate rising atmospheric CO_2 concentrations has received increased attention in the last few years. The global recognition of a finite fossil fuel reservoir has brought attention to the potential of bioenergy crops as an alternative source of energy fuel without contributing as rapidly to atmospheric C. As an incentive, the process of biofuel production adds the plant biomass to the soil organic carbon pool. Recognizing this potential, many governments and private entities have extended their funding to support research projects for increased biomass production with the help of conventional breeding, genetic engineering, and genome editing (Liu et al. 2016; Zhu et al. 2016). Apart from this, when plants produce greater aboveground and belowground biomass, they trap more atmospheric C and recycle it back to the soil carbon pool.

Genetic improvement of plants, through conventional and modern plant breeding, has traditionally focused on the selection of high biomass production only in the economic parts. Attention has been placed on the grain portions, fruits, vegetative growth in forage crops, flower and foliage in ornamental crops, and belowground mass in root crops. Historically, the nutritional and stress tolerance have secured considerable importance to the breeders. Modulating plant genetic makeup for the benefit of the environment, however, was not thought of until very recently. Bioenergy crops have started to bridge the gap between hunt for high plant growth and betterment of the environment. Though high biomass is a prerequisite to breeding bioenergy crops, it is also the primary target in forage crops. In the forest and agricultural sectors in particular, selection by human activities favors faster-growing species. Faster growth is aligned with the sequestration of more carbon from atmospheric CO_2. It is potentially possible to design plants that can photosynthesize at faster rate in a wide range of light conditions from dawn through dusk. The C-4 pathway is already benefiting more from enriched atmospheric carbon and breeders are trying to design C-4 types of many globally important crops. From a research perspective, high biomass production is always a function of cell size and number, rate of cell division, organization of photosynthetic system, and ultimately the genotypic makeup of the organism. Thus, a wide array of research strategies is converging on a common goal to fix more atmospheric carbon and trap it back to the soil.

Variation in the efficiencies of light-dependent reactions has been an unintended target in conventional breeding programs. As a result, the modern cultivars of agricultural crops have evolved with better photosynthetic capacity and higher biomass production. Genetic engineering has recently come up with some solutions for improving the efficiency of light reactions of photosynthesis leading to high biomass production (Lefebvre et al. 2005). They replaced the tobacco Rubisco enzyme with a faster Rubisco from cyanobacterium, *Synechococcus* elongates, which led the plants to higher rates of CO_2 fixation. The catalytic activity of the photosynthetic enzyme Rubisco is linked to CO_2 assimilation rates in crop plants. As such it is now a major focus area for editing to increase biomass.

Hybridity and ploidy have proven potential as strategies toward breeding for high biomass. Hybrid vigor achieved through superior cross-combination has been the foremost tool to gain advantage in numerous economic traits, such as growth rate in economic parts, biomass, seed size (Baranwal et al. 2012). In an experiment Fort et al. (2016) proved that hybrids displayed increased early stage growth rate in *Arabidopsis*. Miller et al. (2012) showed that all hybrids displayed higher biomass production compared to their respective parents. Modern sugarcane crops and all horticultural crops are examples of the superiority of polyploids over their normal types; whereas all major agricultural crops in the United States are hybrids.

MicroRNAs or miRNAs are naturally occurring small and non-coding RNA approximately 20–22 nucleotides long, which influence plant development and signaling (Borges and Martienssen 2015). Few families of miRNA (like miR156, MiR858 and miR397) when overexpressed or partially suppressed in different plants have been discovered to impact plant growth performances in many crops (Rubinelli et al. 2013; Jia et al. 2015; Sharma et al. 2016;). Discoveries relating the expression of miRNA to the regulation of lignin content of plant roots may have specific benefits toward the sequestration of carbon in soils (Smith et al. 2013; Lu et al. 2013).

The vigorous root systems of desirable species strongly impact the restoration of carbon in the soil (Lemus and Lal 2005). Grasses and other perennial crops maintain substantial belowground biomass that recharges the soil carbon pool. In contrast, annual plant species, which die every year, have a shallower root system. Still, they add significant quantities of organic matter into the soil and serve to recharge soil carbon reservoir. Experimental results show the essential role of plant genetics in influencing and improving plant root architecture, and thus the overall root-dependent plant growth (Kato et al. 2006). Plant root growth varies in response to variation in soil microbes (Jobbagy and Jackson 2000), cultivars (Tuberosa et al. 2010; Bayuelo-Jime'nez et al. 2011), known mutants of the same parent (Benfey et al. 2010; Coudert et al. 2010). Though there is considerable scope to breed cultivars for high root growth (Schenk and Jackson 2002; Hu et al. 2003), present cultivars of important agricultural crops don't extend their root depth much beyond 1 meter. Geneticists and plant breeders have been able to discover some genes that improve root architecture and are associated with plant yield (Steele et al. 2006; Hund et al. 2007). The significant role of high belowground biomass in recycling atmospheric carbon and contributing toward soil carbon pool has been demonstrated conclusively (Galdos et al. 2010; Collins et al. 2010).

5.3.2 Relationship Between Soil and Atmospheric C

Soil temperature and soil moisture are the two major environmental variables that determine the magnitudes of soil carbon fluxes in both natural and managed ecosystems (Schlesinger and Andrews 2000). Since the biological processes of respiration are temperature-dependent, soil temperature is normally the main modulator of soil respiration over a wide range of soil moisture conditions. However, since soil microorganisms require water to function, soil moisture becomes the controlling factor as soils dry out (Poll et al. 2013). Precipitation and irrigation cause wet–dry cycles in the soil, which in turn produce pulses in soil microbial activity and carbon and nitrogen turnover in the soil (Borken and Matzner 2009; Unger et al. 2010). Immediately after precipitation and irrigation, rapid changes in soil conditions can result in soil CO_2 pulses that can be several orders higher than the previous emission rates. In a study conducted by Sharma et al. (2014) in the Southern US Great Plains, soil respiration measurements were made using automated soil flux chambers from a field planted to irrigated cotton (*Gossypium hirsutum* L). Prior to irrigation, the soil CO_2 flux ranged from 0.5 to 1.5 μmoles m^{-2} s^{-1} (Fig. 5.2). Within a few hours after irrigation, the soil CO_2 flux shot up to 4.8 μmoles m^{-2} s^{-1}, which is approximately 200% higher than the flux levels observed prior to irrigation. These high-intensity fluxes from agricultural lands have been less studied, and their contribution to carbon dynamics when expanded spatially to account for the agricultural activity occurring in many fields across the landscape is largely unknown.

A study performed in a long-term experiment (33-year) site in College Station, Texas, United States, evaluated the effect of tillage on the magnitude of soil respiration. The study found that conventionally tilled winter wheat (*Triticum aestivum* L) fields had higher soil CO_2 flux compared to no-tillage plots (Zapata et al. 2016). Average soil CO_2 flux for winter wheat was 2.03 μmol m^{-2} s^{-1} in no-till and 2.43 μmol m^{-2} s^{-1} in conventional till, which could be attributed to more active plant growth and root development observed in cultivated soils (Fig. 5.3). The magnitude of soil CO_2 flux was not related to the amount of soil organic carbon as no-till had

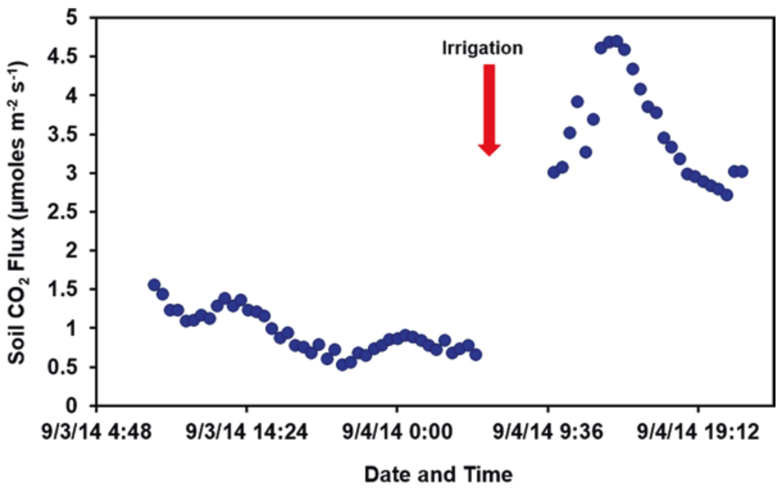

Fig. 5.2 Soil CO_2 flux measured before and after irrigation from a cotton field in the Southern Great Plains in September, 2014. The soil CO_2 flux was measured using a LI-8100 long-term chamber system. (Sharma et al. 2014)

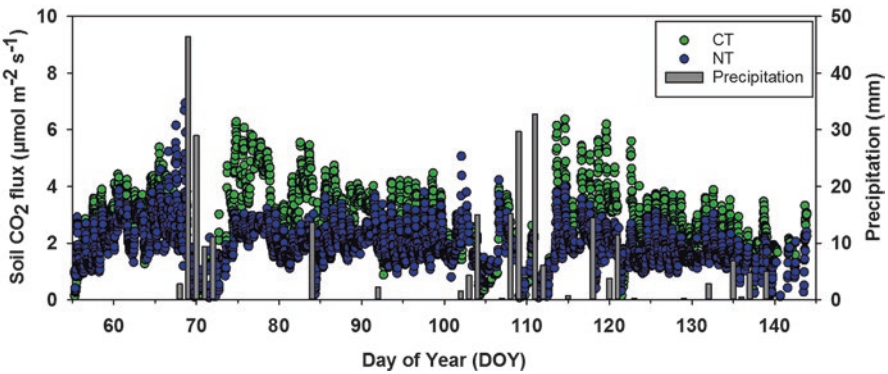

Fig. 5.3 Half-hourly soil CO_2 flux and precipitation measurements from winter wheat plots under long-term conventional-till (CT) and no-till (NT) treatments in College Station, Texas, United States. (Zapata et al. 2016)

the highest organic carbon content (10.11 g kg^{-1}) but released less amount of CO_2 compared to conventional till (7.91 g kg^{-1}). Cumulative half-hourly soil carbon emissions during the measurement period (Feb–May 2014; $n = 3901$) was the highest in conventional tillage field (204.6 g C m^{-2}). Cumulative soil CO_2 emission during the same measurement period from no-tillage plot was 171.15 g C m^{-2} (16% less than conventional). Results showed that the lack of soil disturbance in no-tillage plots did not substantially reduce soil respiration from that field. This could be due to favorable soil moisture conditions in the no-till plots as soil temperatures were similar in conventional and no-till plots (Zapata et al. 2017).

Reducing respiratory loss of soil carbon from agro-ecosystems is a major step in achieving environmental sustainability**.** Conservative tillage management practices along with strategic irrigation strategies could play an important role in achieving this goal in agricultural systems.

5.4 Conclusion

Sequestration of C in the soil on managed agricultural lands in the United States under major row cropping systems has a substantial, though largely untapped, potential for success. Progress in this approach for reducing global atmospheric CO_2 stocks will require enlistment of land-owners and agricultural practitioners into an army of the willing. Major areas of focus for current practice and ongoing research include tillage and residue management, the direct incorporation of labile and long-lasting organic soil amendments, developing cropping systems that enhance stable C capture, cover cropping, breeding crops for improved aboveground and belowground biomass, and the reduction of soil carbon loss through microbial respiration. It is important to recognize that the soil system is complex and more study is needed to better define the interactions between primary biological, physical, and chemical processes at work. It is equally important to recognize that not all C inputs into the agricultural soil system will qualify as "sequestered," and that much of what practitioners are currently capable of managing will produce far more SOC that is simply "stored" for the short term.

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Soil Carbon Dynamics in Different Land-Use and Management Systems in Tropical Coastal Regions of India

6

Pratap Bhattacharyya, P. K. Dash, S. R. Padhy, K. S. Roy, S. Neogi, and A. K. Nayak

Abstract

Carbon dynamics in both East and West coasts of India under different land-use systems are discussed in this chapter. We primarily focused on East coast regions and rice-based cropping systems. However, horticulture, forestry, agroforestry, and horti-silvi-pastoral and mangrove ecosystem are covered with the light of different carbon pool stocks and sequestration rate and their dynamics. Rice-based production systems, particularly rice-rice, rice-fish, and rice-pulse are analyzed on the aspect of carbon pool dynamics both under organic and inorganic nutrient management practices in Eastern India. Forest and mangrove ecosystem showed a distinct carbon sequestration potential which acts as carbon sink. West coast behaved differently than that of East coast in respect of carbon stocks and carbon dynamics in forest and mangrove systems. Scientific manipulation of coastal land-use could provide a potential solution to climate change mitigation and GHG emission. Conversion from plow to no till, incorporation of cover crop and forage crops in rotation, judicious use of crop residues, mulching, and climate-resilient practices are some of these kinds. We know that soil erosion by water and air in the widespread degradation process in coastal region in India and adaptation of economic and conservation-effective measures could reduce erosion and greenhouse gas emission and retain soil organic carbon pools in those vulnerable regions.

Keywords

Carbon dynamics · Coastal regions · Land-use systems · Management practices · Mangrove ecosystem

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6.1 Introduction

Soil carbon (C) dynamics is important for sustainable management of agricultural systems, and it affects significantly the global C cycling (Chen et al. 2004). Concerns about global warming and increasing levels of carbon dioxide (CO_2) in the atmosphere trigger public awareness and scientific attention toward the global C cycle vis-à-vis soil organic C dynamics. A considerable part of the atmospheric C pool comes from terrestrial ecosystem of which soil is a major component (Lal 2004). The soil organic matter (SOM) is considered as the key factor which controls the dynamic nature of soil C (Lal et al. 1997). The accumulation and turnover of SOM is a major factor in soil fertility and ecosystem functioning and determines whether soils act as sinks or sources of C in the global C cycle (Post and Kwon 2000). Anthropogenic activities have significantly altered global C pools and fluxes by altering land cover and land use (Bolstad and Vose 2005). The nature and type of land-use systems directly impact the dynamics of the terrestrial C pools. Land-use changes or shifts in cultivation can also regulate soil organic C (SOC) dynamics (Howard et al. 1998). The rate at which C is lost or gained from the soil also depends upon the agricultural management system (Buyanovsky and Wagner 1998; Li et al. 2007). For example, suitable land-use systems or management practices could help in sequestering C in the soil and also reduce greenhouse gas (GHGs) emissions.

India is having a geographical area of 329 million hectares (M ha) accounts for 2.5% of the total land area of the world. It hosted about 16% of the world population. Major land uses of India include 161.8 M ha of arable land, of which 57.0 M ha is irrigated, 68.5 M ha of forest and woodland, 11.05 M ha of permanent pasture, and 7.95 M ha of permanent crops (Lal 2004). These large land bases obviously have higher potential to sequester C and enhance productivity while improving environment quality.

Coastal region refers to the zone of interaction between sea and land. Marine as well as terrestrial resources are considered in this zone including both non-renewable and renewable resources. Anthropogenic activities and interaction of those with natural processes are the drives for ecological functions in coastal region. However, primarily, we have documented as Eastern and Western coastal zone of India as two broad heading in this chapter for our easy understanding. We will discuss the SOC dynamics under those two broad headings in subsequent sections. India has a long coastline of about 7500 km including its island territories (Draft National Land Utilization Policy 2013). In India, coastal zone is very important because of its high ecosystem services, productivity, natural resource exploitation, waste effluent and municipal waste discharge, petroleum exportation activities, etc. The coastal region of India consists of Pondicherry, coastal area of Odisha, West Bengal, Andhra Pradesh, Tamil Nadu, Kerala, Goa, parts of Karnataka, and Maharashtra. In the present context, we will discuss the overall impact of land use and its management in relation to soil C dynamics in the coastal regions of India.

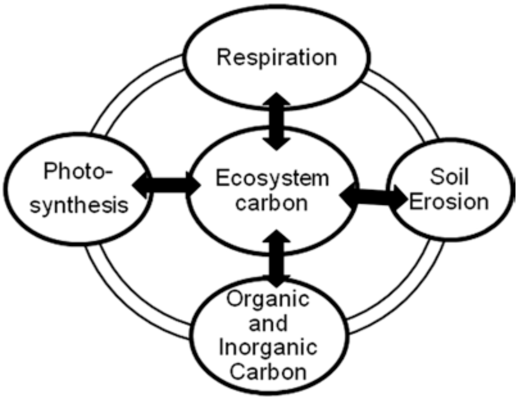


Fig. 6.1 Carbon dynamics in ecosystem

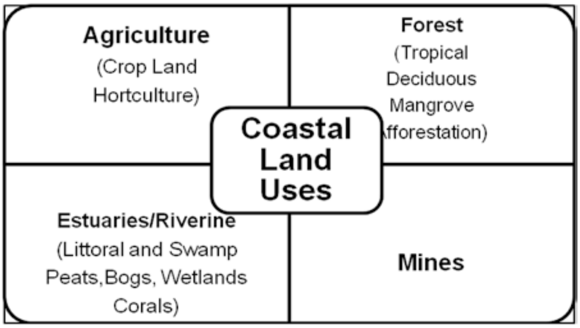


Fig. 6.2 Major coastal land-use practices

6.2 Land-Use and Terrestrial Carbon Sequestration

Terrestrial C sequestration can occur if the losses (emissions, erosion, leaching, etc.) are less than the gains of C by photosynthesis and deposition (Fig. 6.1). Land-use and management practices regulate net sequestration of terrestrial C vis-à-vis those which exacerbate its emission and transfer (Fig. 6.2). Therefore, the strategy is to enhance biomass production, humification, and transfer of C deep into the subsoil through bioturbation as well as simultaneous formation of organo-mineral complexes leading to improvement and stabilization of soil structure. Impact of land use and management must be assessed on the basis of net C sequestration. However, this implies that the gross C sequestration in terrestrial ecosystems must be adjusted for hidden C costs in all input of fertilizers, pesticides, tillage operations, etc. Few mitigation strategies may also lead to enhance emission of CH_4 and N_2O in excess to hidden C costs. Application of nitrogenous fertilizers may exacerbate emission of N_2O. Addition of biosolids, manure, and compost can also enhance emissions of N_2O and CH_4. Therefore, improving use efficiency of these inputs is important for increasing the net C sequestration (Smith et al. 2000).

6.3 Carbon Dynamics Under Different Coastal Land-Use Systems in East Coast Region

6.3.1 Agricultural Systems

6.3.1.1 Carbon Dynamics in Coastal Saline Rice Soil

The coastal region of Bay of Bengal, Sundarbans, India, typically represents coastal saline rice soil. The effects of salinity on the microbial and biochemical characteristics of the salt-affected soils were elucidated in nine (9) different types of soils having electrical conductivity (EC), 2.2–16.3 (Tripathi et al. 2005). The average microbial biomass C (MBC), average basal soil respiration (BSR), and average fluorescein diacetate hydrolyzing activity (FDA) were lowest in the summer season, indicating a negative influence of soil salinity. About 59%, 50%, and 20% variation in MBC/organic C (OC), FDA/OC, and metabolic quotient, (qCO_2), respectively, were due to variation in EC. The decrease in MBC (Fig. 6.3), OC (Fig. 6.4), and microbial activities with a rise in salinity may be the probable reasons for the poor crop growth in salt-affected coastal soils.

6.3.1.2 Carbon Dynamics Under Integrated Nutrient Management in Irrigated Rice-Rice System

At East coast region of Odisha, Bhattacharyya et al. (2012a) reported the effect of integrated nutrient management (with rice straw, green manure, urea) on SOC fractions in soil. A 4-year study on soil labile C fractions including MBC, water-soluble carbohydrate C (WSC), $KMnO_4$ oxidizable organic carbon ($KMnO_4$-C), carbon management index (CMI), and soil C storage in irrigated rice-rice system (Bhattacharyya et al. 2012a) revealed that the rice straw + urea significantly increased soil labile carbon fraction over the unfertilized soil. The MBC accounted for 3.9–5.7% of the total carbon in the soils under study. The application of rice straw + green manure resulted in a significantly ($p < 0.05$) higher (416.9 mg kg^{-1}) accumulation of MBC (Fig. 6.5). Similarly, the readily mineralizable carbon (RMC) content was also highest (188.8 mg kg^{-1}) under rice straw + green manure (Fig. 6.5).

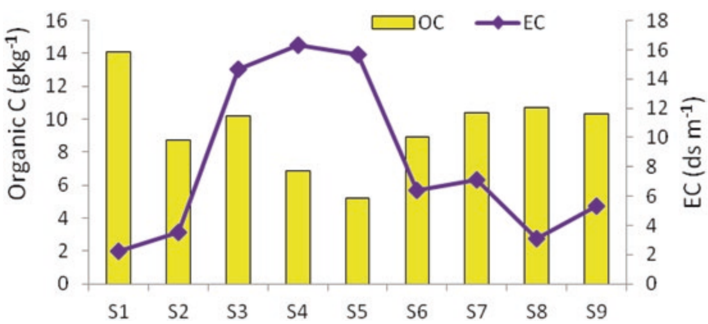


Fig. 6.3 Variations in organic C content in different saline soils growing rice

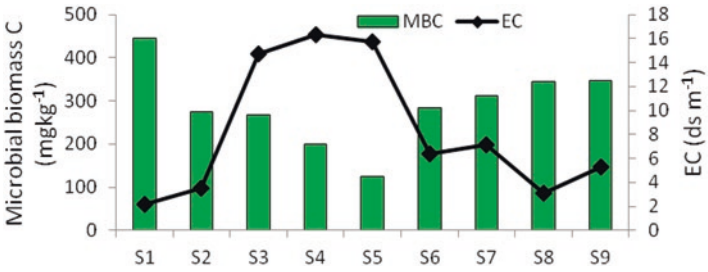
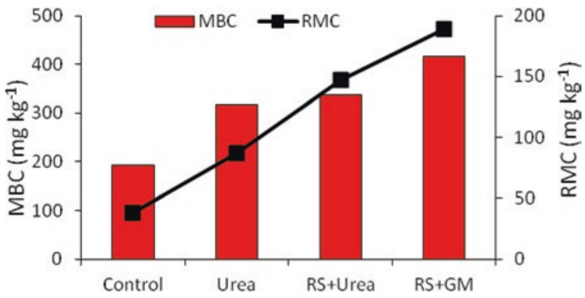


Fig. 6.4 Variations in microbial biomass C content in rice growing saline soils

Fig. 6.5 Microbial biomass carbon (MBC) and readily mineralizable carbon (RMC) in different treatments under irrigated rice-rice cropping system. [Rs, rice straw; GM, green manure]



The water-soluble carbon (WSC) varied from 11.1 to 48.3 mg C kg^{-1}, whereas permanganate oxidizable carbon ($KMnO_4$-C) varied from 315.2 to 472.7 mg C kg^{-1} (Fig. 6.6). Importantly, the combined application of rice straw + urea significantly increased the total carbon content (7.49 g kg^{-1}) as well as total nitrogen content compared to the unfertilized soil (Fig. 6.7).

Hence, the global warming potential (GWP) (10,188 kg CO_2 equivalent ha^{-1}) and carbon emission (CEE) were also higher in combined application of rice straw and green manure. The soil carbon management index (CMI) showed a significant decline in the order of rice straw + green manure (150.2) > rice straw + urea (137.1) > urea (116.4) > control (100.0) (Table 6.1). However, the combined application of rice straw with inorganic fertilizer was proved more effective in sequestrating soil organic carbon (1.39 Mg ha^{-1}) and sustaining grain yield in coastal area of Odisha.

6.3.1.3 Carbon Dynamics in Organic Manurial Management in Rice

The impact of long-term organic amendments in rice on soil carbon dynamics, C storage, and microbial activities in relation to greenhouse gas (GHG) emission was reported in coastal Odisha of Mahanadi basin (Bhattacharyya et al. 2012b). The manurial management system included unamended control, farmyard manure (FYM), green manure (GM) (*Sesbania aculeata*), FYM + GM, and rice straw (RS) + GM combination. The FYM + GM treatment has increased the labile C pools including MBC, RMC, and WSC. On the other hand, under RS + GM system, the soil organic C and total C contents were significantly higher to the tune of 34% and

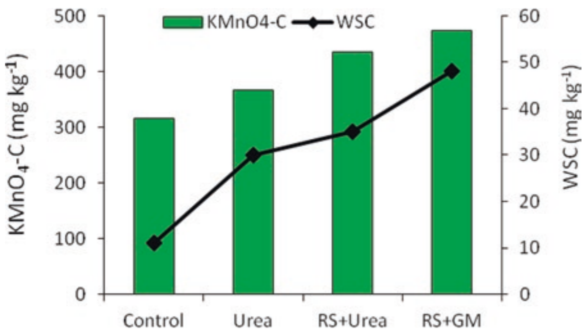


Fig. 6.6 $KMnO_4$-C and WSC in different treatments under irrigated rice-rice cropping system

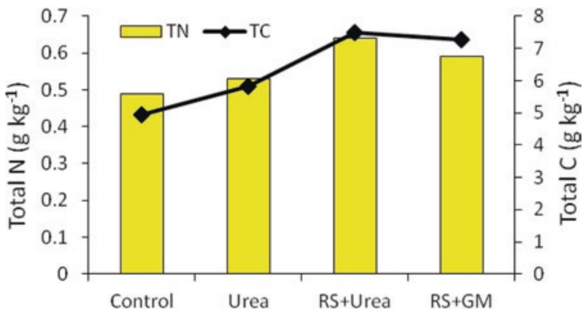


Fig. 6.7 Total C and N in different treatments under irrigated rice-rice cropping system

Table 6.1 Global warming potential (GWP), carbon emission (CEE), C storage, and C management index (CMI) under different treatments in irrigated rice-rice cropping system

Treatment	GWP (Mg CO_2 ha^{-1})	CEE (Mg Cha^{-1})	C storage (Mg C ha^{-1})	CMI
Control	5.86a	1.59a	−1.63a	100a
Urea	8.08b	2.21b	0.29b	116b
Rice straw + urea	9.41c	2.57c	1.39d	137c
Rice straw + green manure	10.18d	2.78d	0.88c	150d

Values followed by different letters are not significantly ($p < 0.05$) different by Duncan's multiple range test

53%, respectively (Fig. 6.8). The study clearly revealed that the application of RS + GM at 1:1 (nitrogen basis) could probably be the best soil amendment to sequester soil organic C (SOC). Such amendments not only have the practical application value but also lead to a higher yield capacity and minimize emission of GHGs in coastal tropical rice soil systems.

6.3.1.4 Carbon Dynamics in Rice-Fish Farming System

Four fish species, namely, *Cirrhinus mrigala* H. (mrigal), *Labeo rohita* H. (rohu), *Cyprinus carpio* L., (common carp), and *Catla catla* H. (catla), were introduced along with rice (*Oryza sativa* L.) cv. Varshadhan, in a coastal rainfed shallow

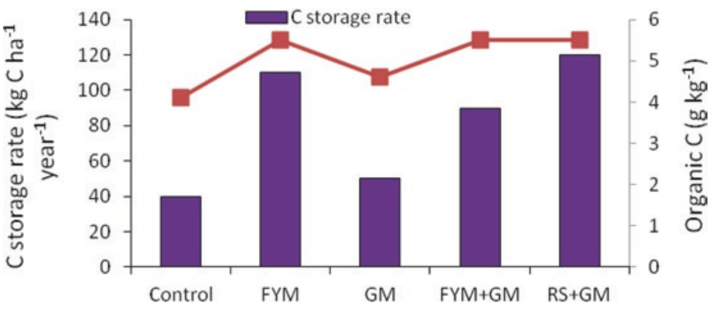


Fig. 6.8 Rate of C storage and organic C content in different organic manurial treatment in rice

Table 6.2 Cumulative CH_4, N_2O-N, GWP, CEE, and yield in rice-fish farming system

Treatment	CH_4 emission (kg ha^{-1})	N_2O-N emission (kg ha^{-1})	GWP (kg ha^{-1})	CEE (kg ha^{-1})	Rice + Fish yield (Mg ha^{-1})
R	109.3[a]	0.89[c]	3126[a]	853[a]	4.1[a]
RF-A	125.6[b]	0.78[a]	3470[b]	946[b]	4.8[bc]
RF-B	136.0[bc]	0.79[a]	3730[bc]	1017[bc]	4.3[ab]
RF-C	148.5[d]	0.82[b]	4051[c]	1105[c]	5.4[c]
RF-D	141.5[cd]	0.81[b]	3873[c]	1056[c]	4.5[ab]

Here, R = Rice only; RF-A = Rice + Fish (mrigal); RF-B = Rice + Fish (rohu); RF-C = Rice + Fish (common carp); RF-D = Rice + Fish (catla). Note: In each column the mean values (three replicated observations) followed by common letters are not significantly different ($p < 0.05$) between treatments by Duncan's multiple range (DMRT) test

(0–25 cm water depth) land, to evaluate the effect of fish species on soil C dynamics in a rice-fish farming system (Bhattacharyya et al. 2013). On seasonal basis, the emission of CH_4 was significantly higher by 26% under rice-fish co-culture compared to rice alone. The maximum emission of CH_4 (36% higher) was found under rice + common carp farming. On the contrary, the emission of N_2O was significantly lower by 9% under rice-fish compared to rice alone. Although the GWP was highest (29.5% more) in rice + common carp, the CH_4 and N_2O emission from this treatment per unit of total yield (rice + fish) were at par and significantly lower, respectively, compared to rice alone (Table 6.2). The labile C pool, viz., MBC, ranged from 277.9 to 743.2 μg g^{-1}, and the highest value was noted in rice + fish (common carp). Most of the labile carbon fractions (RMC, $KMnO_4$-C, and WSC) were also found more in rice + fish (common carp).

6.3.2 Horticulture Systems

6.3.2.1 Carbon Dynamics in Cover Crop-Plantation System

Carbon dynamics was assessed under four leguminous crops, viz., *Atylosia scarabaeoides*, *Centrosema pubescens*, *Calopogonium mucunoides*, and *Pueraria phaseoloides*, grown as soil cover individually in the interspaces of a 19-year-old coconut

(*Cocos nucifera* L.) plantation in Andaman (India). The impacts of above mentioned land uses on C stock of a sandy clay loam coastal soil were assessed at the end of 10 years (Dinesh et al. 2004). The total C, N, and carbohydrate accumulation for the 10-year period exhibited marked variations and was significantly higher under *P. phaseoloides* followed by *A. scarabaeoides*. In general, incorporation of leguminous cover crops significantly enhanced organic C by 1.9–4.6 g kg^{-1} and total N by 0.52–0.78 g kg^{-1} after the 10-year period. Consequently, all the biochemical variables related to microbial activity (biomass C and N, CO_2 evolution, and activities of dehydrogenase) were found significantly higher, thereby reflecting the response of greater organic matter inputs to the soil. Similarly, all the hydrolytic enzymes (acid phosphomonoesterase, phosphodiesterase, casein-protease, BAA-protease, glucosidase, CM-cellulase, invertase, urease, and arylsulfatase) were activated to varying degrees in soils with cover crops, suggesting the role of cover cropping on enhancing microbial activity, enzyme synthesis, and accumulation due to increased C turnover and nutrient availability. The study further revealed that *P. phaseoloides* and to some extent *A. scarabaeoides* were better suited as cover crops compared to *C. pubescens* and *C. mucunoides* for the coastal coconut plantation.

6.3.3 Forest Systems

6.3.3.1 Carbon Dynamics in *Eucalyptus* Plantation

Soil labile C dynamics under 15-year *Eucalyptus* plantations in coastal region of Tamil Nadu state, India (Murugan et al. 2014), were studied in both clay loam and sandy loam soils to assess its C sequestration potential. The understory ground cover includes *Andrographis paniculata Nees*, *Scoparia dulcis L.*, *Hemidesmus indicus (Linn) Shultz*, and *Wikstroemia indica*, with *Andrographis paniculata* as the dominant understory species. The dissolve organic C was significantly lower in stem girding compared to understory removal both in clay loam soil and in sandy loam soil (Fig. 6.9). Despite different magnitudes of pool sizes in both soil types, the MBC and N pools were about 37% and 17% lower in the stem girding treatment,

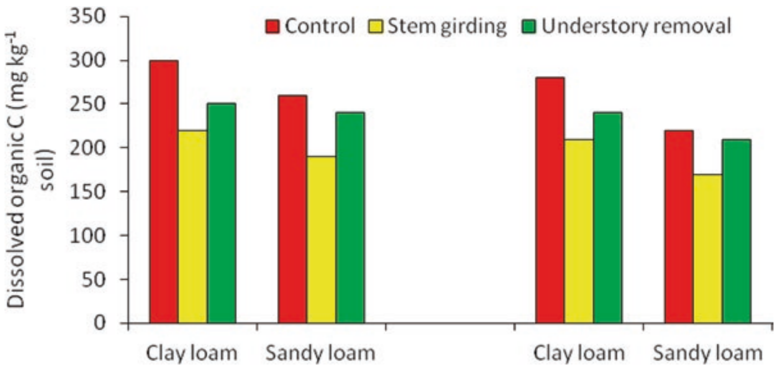


Fig. 6.9 Dissolved organic C in different textured soil under *Eucalyptus* plantation

while, 28% and 14% lower in the understory removal treatment, respectively, compared to control (where neither stem girding nor understory removal was performed). The ratio of microbial biomass C and N was also found lowest in stem girdling treatment. Girdling of trees and understory vegetation removal have been reported to diminish inputs of organic matter from net primary production (NPP) and microbial activity, due to the loss of plant biomass, root exudation, and labile C input, which exert a bottom-up control on soil organisms.

6.3.3.2 Carbon Dynamics in Deciduous Forest

An investigation on soil respiration rate and its relationship with microbial population in natural tropical deciduous forest soil, deforested soil, and deforested-and-cultivated soil in the coastal region of Orissa, India (Mohanty and Panda 2011), revealed distinct seasonal variation of respiration. Depending on season, the rate of respiration varied from 124 to 360 mg CO_2 m^{-2} h^{-1}, with a mean value of 237 mg CO_2 m^{-2} h^{-1}, in the forest site, from 55 to 205 mg CO_2 m^{-2} h^{-1} (with a mean value of 134 mg CO_2 m^{-2} h^{-1}) in the deforested site, and 73–249 mg CO_2 m^{-2} h^{-1}, with a mean value of 169 mg CO_2 m^{-2} h^{-1}, in the deforested-and-cultivated site. The highest rate was observed towards the end of the rainy season, and lowest values occurred during the summer months (Fig. 6.10). The microfungal population showed positive relationship with the rate of soil respiration. The study revealed that conversion of natural forest led to a reduction of soil microbes and rate of soil respiration. Considering the importance of the microbial component in soil, it could be stated that the conversion of natural forests to different land uses leads to the loss of biological stability of the soil.

6.3.3.3 Carbon Dynamics in Horti-silvi-pastoral System

Soil carbon buildup, soil aggregation, and soil moisture retention were studied in degraded sloping land of coastal region in Eastern India under horti-silvi-pastoral systems. Hedge rows of *Indigofera teysmannii* (silviculture component) were used uniformly for all the treatments. The effect of fruit tree component was visible during the 6th year of study in terms of SOC only. After 6 years, the average increase in SOC and water-stable aggregates in the 0–30 cm profile was 89% and 46% under rehabilitation treatments, respectively (including fruits, grasses, and trenching treatments). The SOC stock at the end of 6 years was 34–40 Mg ha^{-1} in the 0–30 cm profile under treatments as compared to 21 Mg ha^{-1} under control (where only hedge species are there). The SOC buildup rate increased linearly with time, and the

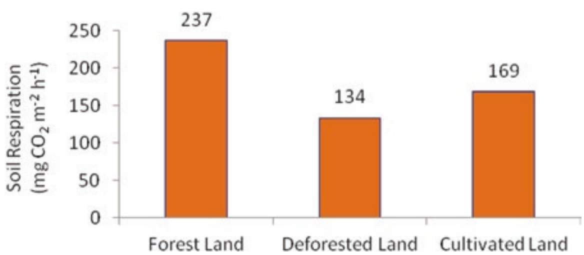


Fig. 6.10 Soil respiration in forest land, deforested land, and cultivated land

average rates were 4.5, 3.5, and 0.64 Mg ha^{-1} $year^{-1}$ for *Stylosanthes* and natural grass-based treatments and control, respectively. In all the systems, macroaggregates (>250 μm) were higher in proportion and contained higher organic carbon. Guava + *Stylosanthes* + trench system proved better in terms of soil carbon buildup, soil aggregation, and soil moisture retention (Lenka et al. 2012).

6.3.4 Carbon Dynamics in Mangrove Ecosystem

6.3.4.1 Carbon Dioxide Exchange

The Sundarban mangrove forest (4264 km^2) constitutes about 3% of the total area of the world mangrove. Diurnal variations of airflows showed that the minimum and maximum CO_2 flux of 216.2 μmol m^{-2} h^{-1} and 49.9 μmol m^{-2} h^{-1}, respectively, occurred during the higher sea breeze. The average ratio of dissolved inorganic nitrogen to dissolved inorganic phosphorus was 11 ± 4, and the surface water was under saturated with respect to dissolved oxygen (Biswas et al. 2004).

6.3.4.2 Carbon Storage

Carbon stocks were quantified in aboveground biomass (AGB) in three dominant mangrove species (*Sonneratia apetala*, *Avicennia alba*, and *Excoecaria agallocha*) in the Indian Sundarbans by Mitra et al. (2011). The carbon stocks varied with spatial locations (western region vs. central region) and with seasons (premonsoon, monsoon, and post-monsoon). Among the three species, the carbon storage was in the order of *Sonneratia apetala* > *Avicennia alba* > *Excoecaria agallocha*. However, aboveground biomass (AGB) varied significantly with locations but not with seasons. Such variation may be attributed to different environmental conditions to which these areas are exposed to, such as higher siltation and salinity in central region compared to the western region. The relatively higher salinity in central region caused subsequent lowering of biomass and stored C of the mangrove species.

6.4 Carbon Dynamics Under Different Coastal Land-Use Systems in West Coast Regions

6.4.1 Carbon Dynamics in Rice Soil

Impact of organic and inorganic sources of nutrient application on soil organic carbon (SOC) stock and its buildup rate in flooded rice soils was tested in the west coast of India. The different nutrient sources tested were farmyard manure (FYM), vermicompost (Verm), *Gliricidia* (*Gliricidia maculata*) and *Eupatorium* (*Chromolaena adenophorum*, as green manure) (GE), paddy straw (dry biomass), and water hyacinth (PsWh), dhaincha (*Sesbania rostrata*) (SR), recommended dose as NPK (RDF), and control. The SOC content, stock, and buildup rate significantly differed by the application of different organic and inorganic nutrient sources after

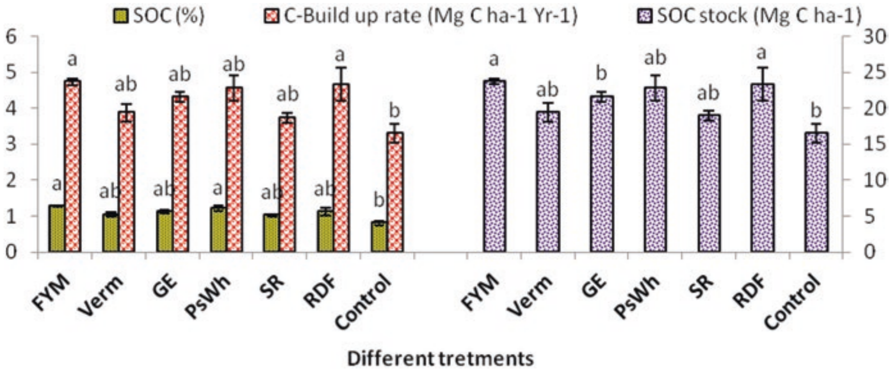


Fig. 6.11 Effect of different nutrient management practices on SOC, SOC stock, and C buildup rate. [Here: values presented in mean ± SE, $n = 3$, and values followed by similar letters indicate nonsignificant difference at 5% level of significance based on Tukey's honest significant difference (HSD) test]

5 years (Fig. 6.11). Application of organic sources, like FYM and paddy straw, combined with water hyacinth had higher SOC over control. The highest SOC stock (23.7 Mg C ha^{-1}) was observed in FYM-based system followed by that of RDF (23.2 Mg C ha^{-1}) while the lowest (16.5 Mg C ha^{-1}) in control.

6.4.2 Carbon Dynamics in Natural Forest

Carbon dynamics and stocks in natural forests, plantation, and trees outside of the forests (TOFs) of Gujarat using pilot enumeration technique were reported by Pandya et al. (2015). Banaskantha forest division management plans of reserved as well as protected areas were surveyed. Mature and large trees resulted 90 times higher C sequestration rates than the healthy small trees. Growing stock in forest cover and trees outside of the forest in Gujarat stored 185.14 and over 78.46 million tons carbon, respectively (FSI 2013). If soil carbon is added to this value, the carbon store in the Gujarat forests may be estimated about 88.62 million tons. The ratio of belowground biomass to the aboveground biomass was about 0.27, whereas biomass expansion factor, the factor multiplying growing stocks, gave AGB of 1.575. The growing stock in these forests is about 66.81 million cubic meters against the estimate of 48.28 million cubic meters in the entire forest of Gujarat. This does not include growing stock of tropical thorn forest. Overall, carbon store in the forest cover of Gujarat is above 78.47 million tons (Singh 2011).

6.4.3 Carbon Dynamics in Sediments

Carbon dynamics in sediment were studied under Pichavaram mangrove ecosystem along the Chapora and Mandovi estuaries at the southwest coast of India (Bala

Krishna Prasad and Ramanathan 2008). The levels of organic carbon at offshore and Chapora and Mandovi estuaries (direct influence of ferro-manganese ore mining) ranged from 0.02% to 6.9% and 0.1% to 6.5%, respectively, and there was a marked seasonal variation. The offshore and experimental sites exhibited lowest values of SOC contents 1.2% ± 0.1% and 1.9% ± 0.3%, respectively, during the monsoon season. Both the sites showed differences in pre- and post-monsoon OC accumulation. Highest accumulation at the control (sites free from metal pollution) site was found in the pre-monsoon season (3.1% ± 0.8%) and at the experimental site in the post-monsoon season (3.4% ± 1%). Though, there was no monthly variability at the control and experimental sites, there was considerable inter-seasonal variability at both the sites.

In another study in a hilly forested terrain situated at Uttar Kannada district, Western Ghats in south India, aboveground standing biomass and carbon-stock dynamics were monitored for 25 years (from 1984 to 2009) by Bhat and Ravindranath (2011) from six permanent forest sites such as Chandavar, minor forest (MF); Bidralli, reserve forest (RF); Nagur, reserve forest; Sonda, reserve forest; Sugavi, minor forest; and Santgal, reserve forest subjected to different levels of anthropogenic pressure. Carbon stock was observed lowest in Nagur RF (93.63 t ha^{-1}) and the highest in Sonda RF (131.67 t ha^{-1}). In spite of natural disturbances and harvest of trees by local communities, increase in basal area, biomass, and carbon stocks in forest plots is on the account of stimulatory growth of surviving trees. Restocking of tree density, increase in basal area, aboveground standing biomass, and carbon stock over a period of 25 years indicates that the forests are in the process of recuperation, sequestering atmospheric carbon and providing environmental service.

6.5 Conclusion

Coastal land-use practices including agriculture, forest, and plantations have an important role to play to mitigate the climate change due to atmospheric enrichment of CO_2 and other greenhouse gases. Scientific management of coastal land uses could provide solution to environmental issues, especially to reduce rate of CO_2 enrichment in the atmosphere. Recommended management practices included conversion from plow till to no till, incorporation of cover crops and forages in the crop rotation, liberal use of crop residues and biosolids like mulch, integrated nutrient management including compost/manures and judicious use of fertilizers, and integrated pest management. However, there are hidden C costs of fertilizers and pesticides and risks of increasing emissions of gaseous C. Therefore, enhancing use efficiency of these inputs is important. Restoration of degraded coastal soils and ecosystems is important for SOC sequestration. Degraded coastal soils already have lost a large fraction of the original SOC pools and hence, need to be restored through suitable land-use practice coupled with soil conservation measures. Soil erosion by water and wind is the most widespread degradative process in coastal regions. Therefore, adoption of conservation-effective measures can curtail erosion-induced emissions and replenish the depleted SOC pool and thereby quality and resilience of coastal soils.

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7 Soil Carbon Dynamics Under Different Land-Use and Management Systems

Shrikant Badole, Ashim Datta, A. Krishna Chaitanya, Sham Prasad Majumder, and Biswapati Mandal

Abstract

Soil organic carbon (SOC) is an important component of soil that maintains soil fertility, productivity, as well as overall sustainability. Low SOC status in tropical soils, particularly those under the influence of arid, semiarid, and subhumid climates, is a major factor contributing to their poor productivity. Land-use change (LUC) is the second most important factor contributing about 20% of global emission after fossil fuel burning. To feed the growing world population, more and more natural or forest area has brought under agricultural uses particularly intensive crop cultivation. Such conversion from natural to agricultural ecosystems has led to an average decrease in C stocks of 25–30%. Soil C pools change rapidly in response to land-use change; intensive cropping/cultivation might disturb soils leading to more oxidative loss of SOC; on the other hand, it leads to huge additions of carbon as crop residue biomass and results in either a net buildup or depletion of SOC stock in soils. Cropping systems, management practices, and soil environment play an important role in C stabilization and maintaining the SOC stock. The cereal-based cropping systems such as double rice as well as forestry (*Madhuca longifolia* and *Diospyros melanoxylon*) or horticulture (guava) system conserve organic carbon in soil at a desirable level for performing ecosystem functions that would help to increase food/timber production. Soil C sequestration research has historically focused on the top 0–30 cm of the soil profile, ignoring subsoil horizons that might also respond to management. Despite their low C content, most subsoil horizons contribute to more than half of the total soil C stocks, and therefore, subsoil C may be even more important in

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terms of source and sink for CO_2 than topsoil C. Therefore, the knowledge of SOC distribution and controls on C sequestration within soil profiles are used to predict the effect of land-use changes on C emission. An attempt has been made in this chapter to synthesize the land-use effects on SOC dynamics under different management scenarios.

Keywords
Carbon dynamics · Cropping systems · Forestry · Horticulture system · Land-use change

7.1 Introduction

SOC is an important component in soil that maintains soil fertility, productivity, as well as overall sustainability. Low SOC content in tropical soils, particularly those under the influence of arid, semiarid, and subhumid climates, is a major factor contributing to their poor productivity (Mandal et al. 2007). Maintaining or improving organic C levels in tropical soils is more difficult because of rapid oxidation of organic matter under the prevailing high temperature and thus have poor structure, low water retention capacity, and low fertility (Lal et al. 2003; Mandal et al. 2007). Poor agriculture management and climate extremes have significantly contributed toward the land degradation and deterioration of soil quality in these regions. However, improving soil organic matter (SOM) is a prerequisite to ensure soil quality, productivity, and sustainability (Mandal et al. 2007).

The organic carbon pool in agricultural land uses is capable of enhancing agricultural sustainability and serving as a potential sink of atmospheric carbon dioxide (Gnanavelrajah et al. 2008). About 20% of the global emission presently comes from land-use change (IPCC 2001). Soil C pools change rapidly in response to land-use change (Guo and Gifford 2002). Changes in vegetation cover are expected to modify soil C content and nutrient cycling (Li and Mathews 2010), thus impacting environmental equilibrium and sustainability (Bastida 2006). Poor soil management and the replacement of native forests by farmland or exotic timber species may compromise soil health. Management-based soil C sequestration strategies were significantly more effective at reducing global warming due to the atmospheric saturation of CO_2 in high-emission scenario (Mayer et al. 2018). The knowledge of SOC distribution and controls on C sequestration within soil profiles are used to predict the effect of land-use changes on C emission. The importance of SOC sequestration in subsoil to mitigate the greenhouse effect is related to the increase turnover time of SOM with increase in depth and to the fact that subsoil SOC occurs in fairly stable and most probably highly recalcitrant forms to biodegradation (Nierop and Verstraten 2003). Subsoil SOC stocks become additionally important because they primarily constitute the intermediate and passive SOM pools (Lutzow et al. 2008). The lack of fresh organic C in deeper soil layers and restricted energy supply to microbes are the main causes of reduced decomposition rate at depth

(Fontaine et al. 2007). Therefore, an attempt is made to collate information on SOC dynamics under different land uses such as cereal-based cropping systems, forestry, horticulture in surface, as well as deep soil layers.

7.2 Land-Use Change (LUC) and Global Warming

Anthropogenic LUC affects global climate through biophysical and biogeochemical pathways. Land-use changes alter biophysical characteristics of land surface (albedo, leaf area index, rooting depth), hence leading to disequilibrium in net radiation and heat fluxes along with changes in precipitation and evapotranspiration. Biogeochemical changes associated with CO_2 emissions are mainly through deforestation, devegetation, draining of peat lands, and cultivation of these lands by burning and rapid oxidation of litter.

According to the IPCC (2013) report, the rise in global average temperature between 1880 and 2012 was 0.9°C (1.5°F). Moreover, the raised temperature warms soil, could make soil flora and fauna less efficient in digesting the C from organic matter, and further emits CO_2. Abandoned agricultural fields are active C sinks (Vaccari et al. 2012) with mean annual uptake of 281.7 ± 39.0 g C m^{-2} $year^{-1}$. In the initial years of abandonment, C uptake was rapid because of herbaceous growth of vegetation due to residual soil fertility. Moreover, absence of tillage and growth of woody vegetation support more C input into soil and enhance SOC buildup.

Grassland and forest systems tend to have largest C input to the soil; often these materials are more recalcitrant, while small C inputs are found in croplands, so conversion of croplands to forest may increase SOC stock. Hence, abandonment of croplands may lead to global food insecurity. Instead of adopting new cropping systems, proper crop management practices may take care of crop production and global warming. Conversion of sole cropping system to agroforestry and agro-horticulture has increased SOC around two times from 4.2 g kg^{-1} to 7.1 g kg^{-1} and 7.3 g kg^{-1}, respectively, within 6 years of plantation (Das and Itnal 1994). Inclusion of submerged rice in cropping system has tremendous potential to sequester C in soil (Mandal et al. 2008).

Land-use and management practices are net sink, rather than sources of GHG emissions (Lal 2007). Despite its importance, size, and dynamics, SOC in soils of the tropics is still poorly known (Batjes 1996). Land-use change has a large impact on many of the biological and chemical processes of terrestrial ecosystems, and the most prominent of these changes is the modification of global terrestrial C cycling (Montane et al. 2007; Li and Mathews 2010). Soils of the tropics contain one-third of the global SOC pool, with about 128, 151, 136, and 56 Pg C stored in tropical wet, moist, dry, and mountain regions, respectively (Hiederer and Köchy 2011). The SOC stock can be significantly modified by the impact of anthropogenic activities such as deforestation and land-use change (Scharlemann et al. 2014). Several studies have demonstrated that SOC is highly sensitive to LUC (Smith 2008; Parras-Alcántara et al. 2013). Worldwide, LUC is responsible for estimated net emissions of 1.1 ± 0.7 Pg C $year^{-1}$ during the first decade of the 2000s. This is mainly due to

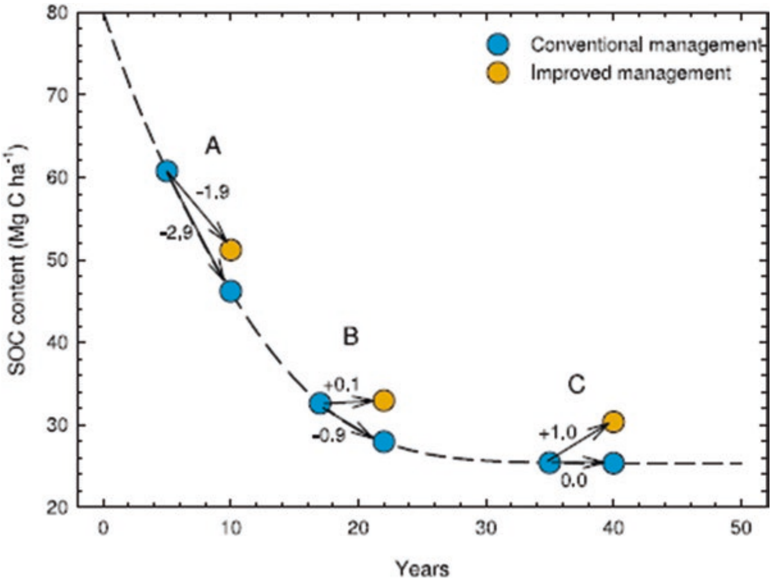

Fig. 7.1 Relationship between SOC content and aging by hypothetical field trial

deforestation and the conversion of natural vegetation into cropland in the tropics (Don et al. 2011; Houghton 2003). Tropical ecosystems are known for high biodiversity and for important effects on global climate and biogeochemical cycles, especially on C turnover and sequestration (Katovai et al. 2012; Malhi and Phillips 2004). Due to faster transformation processes during litter decomposition, tropical soils have higher turnover rates than soils in colder climates (Zech et al. 1997). Conversion from natural to agricultural ecosystems led to an average decrease in C stocks of 25–30% (Don et al. 2011; Houghton and Goodale 2004). LUCs are acknowledged as a measure to mitigate climate change if the depleted cropland pools are refilled with carbon (The Terrestrial Carbon Group 2010). However, carbon loss from soils due to LUC is still going on. Sanderman and Baldock (2010) conducted a hypothetical field trial by converting a natural ecosystem to agricultural production in year zero; comparing conventional and improved management practices initiated at three different times (A, B, and C) showed SOC content reduction by aging and slightly improved by better management practices (Fig. 7.1).

7.2.1 Cereal-Based Cropping

Cropping system, management practices, and soil environment play an important role in C stabilization and maintaining SOC stock. For better understanding of C stabilization or loss in soil, we must have an idea of labile and recalcitrant pools of carbon and their equilibrium/relationship. Labile pool of SOC has rapid turnover rate and is important for soil food web, hence greatly influence nutrient cycling in soil for maintaining soil quality and productivity (Majumder et al. 2007, 2008a, b). Recalcitrant pool is tardy altered pool, so it helps in buildup of SOC stock.

Both quality and quantity of crop residue affect their turnover time in soil and rate of conversion to SOC. Moreover turnover time and conversion rates, resulting in stabilization of SOC, are ecosystem properties (Schmidt et al. 2011) including biochemistry of substrate, associated niche, climate variability, etc. and as such affect soil health, crop productivity, and climate change mitigation. The rate of conversion of crop residue C to SOC was about 1.6 times more in presence of organic application compared to that in its absence (Fig. 7.2) suggesting that organics might have somehow facilitated this conversion (Mandal et al. 2007). Such influence of organics, however, varied among cropping systems, being higher where legume is included. Carbon depletion is influenced by the amount of crop residue C inputs to the soil (Fig. 7.3), by the different species of crops grown. In double rice system, amount of crop residue is more; therefore, depletion is lower than single rice-based cropping systems. In a rice-rice cropping system, the soil remains under submergence for almost 7–8 months in a year, while the crops are growing and under saturated/field moist water regime for almost a month before and after the growing period of the crops. This prolonged submergence may retard oxidation, enhance the character of recalcitrance to SOC (Olk et al. 2002), and help in stabilization of SOC (Mandal et al. 2008). Mandal (2011) estimated carbon balance in rice-rice cropping system; total carbon cost for cultivation (inputs, CH_4, N_2O, total – 1250, 1575, 775 kg CE ha^{-1} year^{-1}, respectively) was lower than carbon output from rice cultivation (grain, straw, root, husk –1350, 1620, 250, 520 kg CE ha^{-1} year^{-1}, respectively);

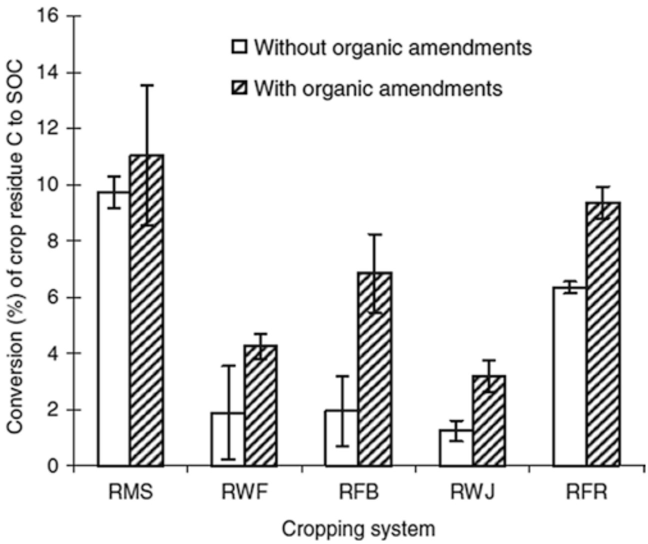

Fig. 7.2 Organic amendments influence conversion of crop residue C to SOC under rice-mustard-sesame (RMS), rice-wheat-fallow (RWF), rice-fallow-berseem (RFB), rice-wheat-jute (RWJ), and rice-fallow-rice (RFR) systems (Mandal et al. 2007)

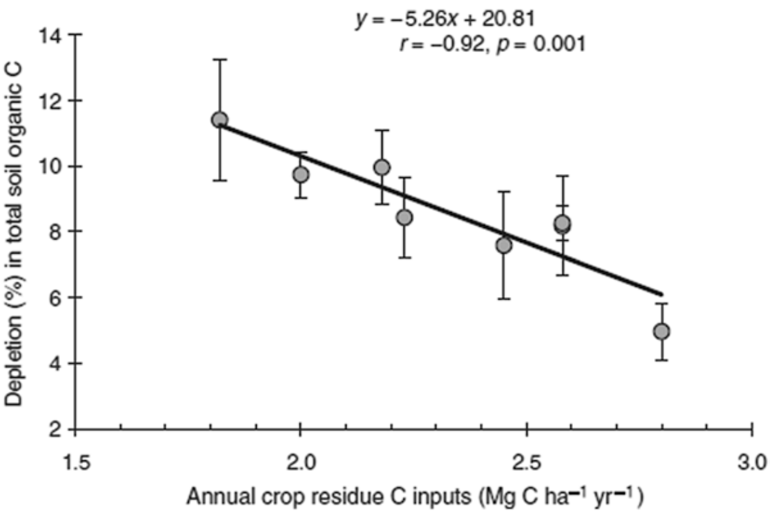

Fig. 7.3 Inverse relationship of depletion of SOC with crop residue C input (error bars present the standard error of mean)

hence, we can consider rice crop as a carbon-negative budgeting crop rather C neutralizing crop.

Sewage-irrigated rice-wheat had significantly higher SOC content than tube-well-irrigated rice-wheat as well as vegetable field soil at 0–20 cm soil depths (Purakayastha et al. 2007). Datta et al. (2018) studied dynamics of SOC, and its pools under 28-year-old sorghum-wheat cropping system in Vertisols and found that of the several pools of SOC analyzed, a higher proportion was found in non-labile (47.3%) followed by less labile (22.1%), labile (18.4%), and very labile (12.1%) ones (Fig. 7.4). A higher proportion (70% of TOC) of SOC resided in passive pool (less labile + non-labile) than active one (very labile + labile) throughout the profile. The proportion of active pool was, however, higher under balanced (NPK) and integrated nutrient management practices (NPK + FYM) over the others (Fig. 7.5). Long-term intensive cropping with NPK (15.1%) and NPK + FYM (22%) caused a net enrichment in SOC stock over the control. To offset the loss of C and maintain the SOC level, a critical amount of 0.96 Mg C ha^{-1} year^{-1} was needed to be incorporated into the soil (Fig. 7.6). Therefore, balanced fertilization with organics provided not only higher yield but also increased C sequestration in Vertisols even with intensive cropping of sorghum-wheat system under hot semiarid conditions (Datta et al. 2018). Datta et al. (2017) also studied the dynamics of SOC pools in soils under a 26-year-old long-term experiment with rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) cropping system on Inceptisols under humid agroclimatic region in India with various soil management practices. They reported that labile C pool (46%) was highest followed by very labile (26.5%), non-labile (20%), and less labile (7.3%) of the total organic C at 0–15 cm soil depth. The NPK + FYM treatment was found to have higher SOC pools, and lability index (LI), as compared to

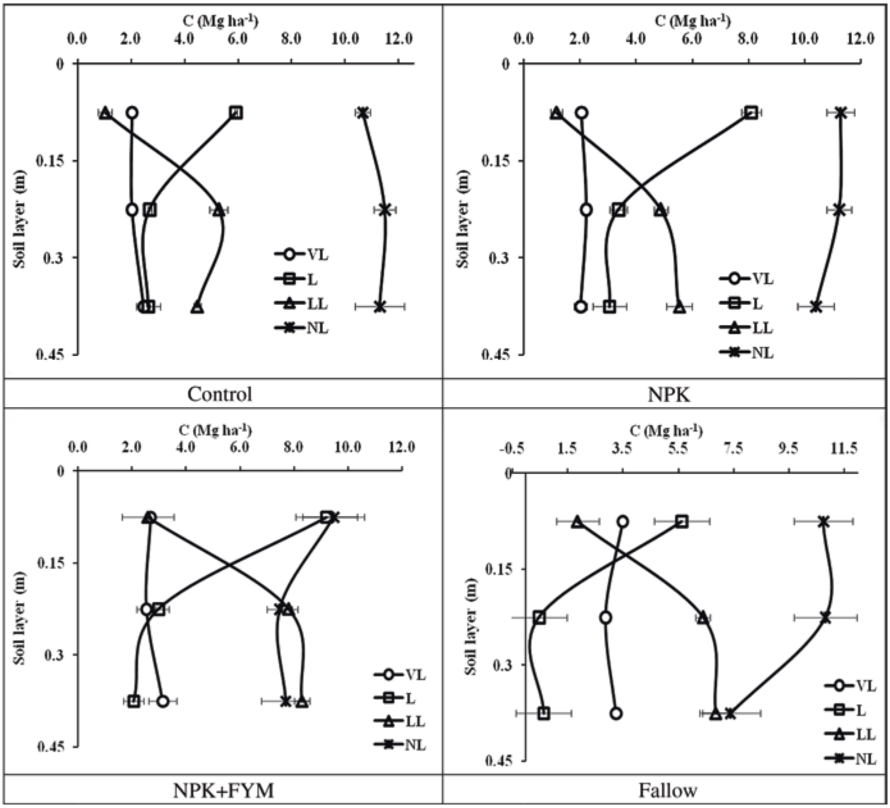

Fig. 7.4 Depth-wise variation in very labile (VL), labile (L), less labile (LL), and non-labile (NL) pools of organic C in soils under different treatments (control, NPK, NPK + FYM, and fallow) used for the sorghum-wheat cropping system. Horizontal bars indicate ±S.E. of mean of the observed values (Datta et al. 2018)

others. They again reiterated the importance of balanced fertilization with inorganic and organics for maintaining overall sustainability of the rice-wheat system. Krishnachaitanya et al. (2018) studied carbon dynamics, in double rice cropping system, in a 14-year-old experiment in semiarid southern India and found that total organic carbon was allocated into different pools in order of very labile > less labile > non-labile > labile, constituting about 41.4, 20.6, 19.3, and 18.7%, respectively. In comparison with control, system receiving farmyard manure (FYM-10 Mg ha^{-1} season^{-1}) alone showed greater C buildup (40.5%) followed by 100% NPK + FYM (120:60:40 kg N, P, K ha^{-1} + 5 Mg FYM ha^{-1}season^{-1}) (16.2%). Actually, a net depletion of C stock was observed with 50% NPK (−1.2 Mg ha^{-1}) and control (−1.8 Mg ha^{-1}) treatments. Only 28.9% of C applied through FYM was stabilized as SOC. A minimal input of 2.34 Mg C ha^{-1} year^{-1} is needed to maintain SOC level.

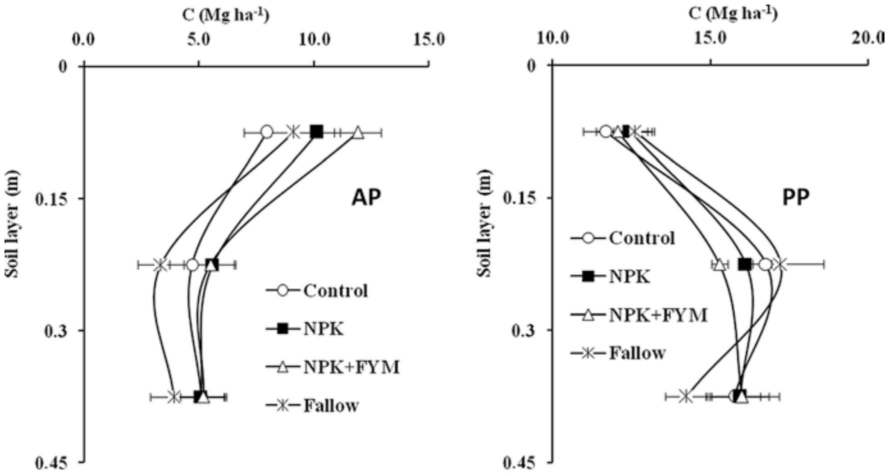

Fig. 7.5 Depth-wise distribution of active (AP) and passive pool (PP) of organic C in soils under different treatments used for the sorghum-wheat cropping system. Horizontal bars indicate ± S.E. of mean of the observed values (Datta et al. 2018)

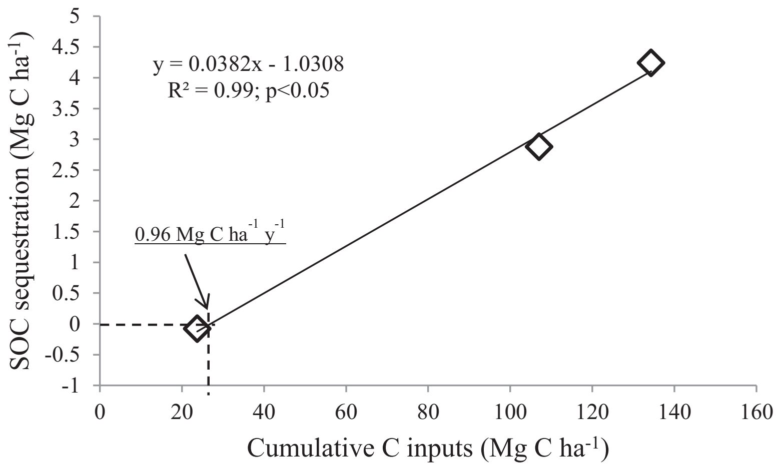

Fig. 7.6 Relationship between cumulative C inputs and SOC sequestration and the critical C input value obtained (Datta et al. 2018)

7.2.2 Forestry

Changes in land-use pattern severely reduce sink capacity of soils. Forest soils play an important role in the global C cycle (Detwiler and Hall 1988; Jobbagy and Jackson 2000), covering about 4.1 billion hectares globally (Dixon and Wisniewski 1995). Forest vegetation and soils contain about 1240 Pg of C (Dixon et al. 1994), and the C stock varies widely among latitudes. Of the total terrestrial C stock in forest biomes, 37% is in low latitude forests, 14% in mid-latitudes, and 49% in high latitudes. The global potential of C sequestration by forests is high. In forest soils it is about 0.4 Pg C year^{-1}and overall 1–3 Pg C year^{-1} in forest biomes (Lal 2005). Proper management of forests would result in significant quantities of C sequestration in both below- and aboveground biomass in addition to serving other ecosystem functions.

Globally highest area (1.76 Mha) was reported under tropical forests followed by boreal (1.37 Mha) and temperate (1.04 Mha) forests (Prentice 2001) (Table 7.1). Highest carbon stock in plant (340 Mha) was found in tropical forests, whereas soils under boreal forest (338 Mha) stored highest C stock. Highest C density was also observed under soils of boreal forest (296 Mha) (Table 7.1).

The conversion of forest reserve to other land uses in recent times has caused many complex changes in the forest ecosystem whose impact raises diverse ecological problems (Bhattacharyya et al. 2008; Henrik et al. 2010). Historically, when croplands have been established on land previously used for native vegetation, the soil C pool has been a major source of atmospheric CO_2, contributing about 180–200 Pg C over the last two centuries (DeFries et al. 1999) which is about 40% of the total anthropogenic CO_2 emissions (Marland et al. 2000). The conversion from natural vegetation to cropland often leads to a depletion of the SOC stock due to decrease in the amount of biomass (above and belowground) returned to the soil, change in soil moisture and temperature regimes which accentuate the rate of decomposition of organic matter, high decomposability of crop residues due to differences in C:N ratio and lignin content, tillage-induced perturbations, decrease in soil aggregation and reduction in physical protection of the soil organic matter, and increase in soil erosion (Lal 2005; Poeplau et al. 2011). SOC stocks under undisturbed, native vegetation are usually considered to be in dynamic equilibrium with other terrestrial carbon pools; they are largely controlled by climate, terrain, vegetation, soil mineralogy, particle/aggregate size, and their interactions (Watson et al. 2000; Canadell et al. 2007).

The deforestation and conversion of tropical rain forest into agricultural ecosystems result in emission of 1.6–1.7 Pg C year^{-1} into the atmosphere (about 20% of the anthropogenic emissions) (Watson et al. 1995; IPCC 2000). Thus, understanding the mechanisms and factors of SOC dynamics in forest soils is important in identifying and enhancing natural sinks for C sequestration to mitigate the climate change.

Table 7.1 Estimation of terrestrial carbon stock in world's forest zones (Prentice 2001)

		Terrestrial carbon stock (Pg)			Carbon density (Mg C ha^{-1})	
Biome	Area (Mha)	Plant	Soil	Total	Plant	Soil
Tropical forests	1.76	340	213	553	157	122
Temperate forests	1.04	139	153	292	96	122
Boreal forests	1.37	57	338	395	53	296
Total	4.17	536	704	1240	–	–

Although forestland management is generally less intensive than cropland management, there are several management options such as a change in tree species composition, afforestation, thinning, drainage, fertilization, liming, site preparation, and harvest management which are associated with an increase in SOC stocks and are consequently viewed as having a high potential for soil C sequestration (Lal 2005). The most common forest management activities are harvesting and site preparation. Because the forest floor comprises the most dynamic part of SOC stock, estimating the effects of these activities on SOC dynamics is critical to predicting the local effects on ecosystem sustainability and global C exchange with the atmosphere (Yanai et al. 2003). Numerous studies have shown that decomposition rates of surface litter generally decrease after clear cutting because of the reduction in biotic activity and decrease in soil moisture content. Consequently, some studies have documented an increase in forest floor carbon several years after harvest (Mattson and Swank 1989; Johnson and Todd 1998). If forest harvesting is done with sufficient care, and does not result in disruption of natural processes, there may be a little or no effect on SOC stock (Fig. 7.7). Further, any decline in biomass input may be compensated by the large amount of harvest residues left behind (Post 2003; Yanai et al. 2003).

Carmean (1970) observed low tree growth in soils of low available water capacity. Improving subsoil drainage can also enhance tree growth. In addition to N, biomass production in forest ecosystems may also be limited by deficiency of some micronutrients. Benemann (1992) suggested that fertilizing forests with Fe and other trace elements might enhance primary productivity. Application of biosolids (e.g., sludge and compost) to forest soils may also increase the soil C sequestration. Application of biosolids increased SOC concentration to 45 cm depth and also decreased soil bulk density to 17 cm depth (Harrison et al. 1995). Establishing bioenergy plantation crops is another option for enhancing SOC stock and offsetting fossil fuel combustion. Jha et al. (2012) studied different land uses in Vertisols of

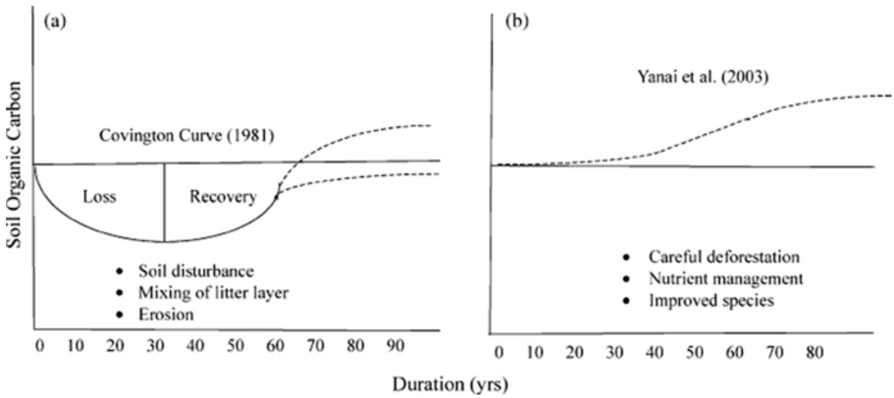

Fig. 7.7 A schematic diagram showing the effect of timber harvest and logging on soil organic carbon stock (**a**) with soil disturbance and mixing of litter layer and mineral soil and (**b**) without soil disturbance and adoption of improved management practices. (Yanai et al. 2003)

Central India and found highest and lowest SOC under forest (38.0 g kg^{-1}) and agriculture (8.9 g kg^{-1}) land-use system, respectively, at 0–15 cm soil depth. High above- (leaf litter) and belowground (root biomass) input to soil might have resulted in higher SOC content under the forest land-use system. Forest land uses (*Madhuca longifolia* and *Diospyros melanoxylon*) showed three- to sixfold more SOC content as compared to the agricultural land use. Mishra et al. (2004) also observed higher SOC under 6-year-old plantations of *P. juliflora*, *Dalbergia sissoo*, and *Eucalyptus tereticornis*.

7.2.3 Horticultural Land Use

Land-use and soil management practices can significantly influence SOC dynamics and carbon flux of the soil (Batjes 1996; Tian et al. 2002). Tree growth serves as an important means to capture and store atmospheric carbon dioxide in vegetation, soils, and biomass products (Makundi and Sathaye 2004). Bulk of the carbon enters the ecosystem through the process of photosynthesis in the leaves. After litter fall, the detritus is decomposed and forms soil organic carbon by microbial process. A lot of studies have been carried out on the soil physicochemical and biological changes over the humid tropical regions of the world (Awotoye et al. 2013). Though horticultural land uses are economically important for the livelihood security of the farmers, very limited information are available on SOC distribution under land uses of fruit trees such as guava, litchi, mango, jamun, etc.

There is great variation on the vegetation dynamics of the land uses and biomass litter levels reaching the soil (Laganiere et al. 2010). Gupta and Sharma (2011) studied the soil organic carbon (SOC) pool up to 30 cm of soil layer and observed maximum SOC in the forest lands followed by grasslands, orchards (mango, guava, litchi), and plantation (*Eucalyptus*) areas. SOC pool under different orchards was estimated, and it was found maximum in *Pyrus malus* (105.2 t ha^{-1}) followed by *Mangifera indica* (53.24 t ha^{-1}), *Litchi chinensis* (45.47 t ha^{-1}), *Citrus* spp. (43.10 t ha^{-1}), and the *Psidium guajava* (38.88 t ha^{-1}). Maximum share of total SOC pool was contributed by *Pyrus malus* (36.80%) followed by *Mangifera indica* (18.62%), *Litchi chinensis* (15.90%), *Citrus* spp. (15.08%), and *Psidium guajava* (13.60%) (Fig. 7.8a). *Pyrus malus* has high mitigation potential (2.71) which

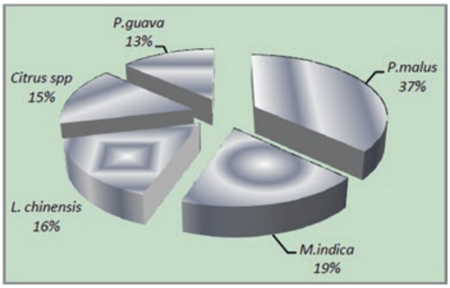

Fig. 7.8a SOC percent share of different orchards under horticulture land use (Gupta and Sharma 2011)

indicates that it can store more than double SOC pool as compared to *Psidium guajava*. Mitigation potential of *Litchi chinensis*, *Citrus* spp., and *P. guajava* was not much different (Gupta and Sharma 2011).

Gupta and Sharma (2013) also studied SOC pools up to 30 cm soil depth under different orchards in Uttarakhand state of India and found that maximum SOC pool was estimated under apple orchard followed by mango, litchi, and guava (Fig. 7.8b) and they significantly differed from each other. The impact of different horticultural land uses, namely, guava (*Psidium guajava*), litchi (*Litchi chinensis*), mango (*Mangifera indica*), and jamun (*Syzygium cumini*), on distribution of SOC in soil layers in a reclaimed sodic soil showed that carbon content in passive pool along with its recalcitrant nature was increased with depth in all the land uses and overall highest SOC storage (133 Mg C ha^{-1}) as well as maximum passive pool C (76 Mg C ha^{-1}) was maintained in guava land use (Datta et al. 2015).

Datta et al. (2015) studied oxidizable organic C under different land uses in a reclaimed sodic soil of northwest India. Highest oxidizable organic C was observed under *Eucalyptus* (33.5 Mg C ha^{-1}) followed by guava (25.9 Mg C ha^{-1}) > jamun (25.1 Mg C ha^{-1}) > litchi (25.0 Mg C ha^{-1}) > rice-wheat (19.4 Mg C ha^{-1}) > mango (16.5 Mg C ha^{-1}) > *Prosopis* (15.1 Mg C ha^{-1}) at 0–0.2 m depth of soil, respectively. Oxidizable organic C content in subsurface soil (1.0–1.5 m) varied from 6.3 to 17.0 Mg C ha^{-1}. The highest and lowest values of OC were associated with litchi (17.0 Mg C ha^{-1}) and jamun (6.3 Mg C ha^{-1}) (Datta et al. 2015). Novara et al. (2019) studied SOC sequestration rate after 5 years of cover crop soil management in Mediterranean vineyards of Sicily, Italy. They observed highest SOC content in cover crop (*Vicia faba*) management in the slope area with an average value of 9.52 ± 0.34 g kg^{-1}, whereas the SOC content under conventional tillage was 8.74 g kg^{-1}. SOC varied from 9.88 to 10.47 g kg^{-1} in flat vineyard under conventional tillage and cover crop, respectively. Verma et al. (2017) studied four land uses, namely, hedge-based, alder-based, and guava-based agroforestry system and control plots in acid soils of the eastern part of the Indian sub-Himalayas, and found that plots under hedge and alder-based AFS had about 62 and 59% higher SOC concentrations compared with the control plots (mean of 0–10, 10–20, and 20–30 cm soil depth = 16.0 g kg^{-1}) in the 0–30 cm soil layer. For all land-use systems (except control plots), SOC contents in the 10–20 cm depth were significantly higher than

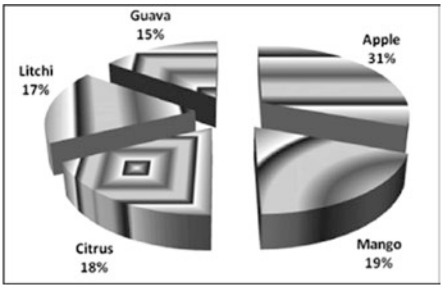

Fig. 7.8b Share of total SOC pool occupied by different orchards in Uttarakhand (Gupta and Sharma 2013)

the other soil layers, indicating the importance of the middle layer for SOC sequestration.

7.3 Deep Soil C Sequestration

Soil C sequestration research has historically focused on the top 0–30 cm of the soil profile, ignoring deeper portions that might also respond to management (Syswerda et al. 2011). It has been showed that significant amounts of stable SOC are also stored at greater depth (Meersmans et al. 2009). There is a 60% increase in the global SOC budget when the second meter of soil was included (Batjes 1996). Despite their low C content, most subsoil horizons contribute to more than half of the total soil C stocks, and therefore, subsoil C may be even more important in terms of source and sink for CO_2 than topsoil C.

Best management practices can help to achieve SOC sequestration through increasing C stocks by improving depth distribution of SOC and by stabilizing the SOC as recalcitrant C with long turnover time (Lorenz and Lal 2005). Strategies which help to increase the deep soil C sequestration are (1) increase in C inputs into the zones of the soil profile that have slower decomposition rates (Lal 2004); (2) selection of plants and cultivars with a belowground biomass higher in biochemical recalcitrant compounds; (3) growth of leguminous cover crops which help to preserve SOC due to residue inputs from root biomass (Gregorich et al. 2001); (4) manipulation of the quality and quantity of subsoil OM inputs from roots which can be achieved by selection of plant species and cultivars (Batjes 1998); (5) the transfer of SOC to deeper soil layers and increase in SOM stability may also be promoted by manipulating the soil fauna (Wolters, 2000); and (6) managing microorganisms that carry out the decomposition of plant litter in the subsoil may promote C sequestration as the contribution of microbial products to SOC vs. plant inputs increase with soil depth (Martens et al. 2003; Rumpel et al. 2002).

Most of these estimates of sequestration capacity are based on studies of soil C change in surface soils and recent concerns that similar gains may not be occurring or that soil may be closing C at depth (Carter 2005; Baker et al. 2007). Subsoil SOC stocks become additionally important because they primarily constitute the intermediate and passive SOM pools (Lutzow et al. 2008). Lack of fresh organic C in deeper soil layers restricts energy supply to the microbes leading to reduced decomposition rate at depth (Fontaine et al. 2007). It has been showed that vertical distribution of C in the soil is much deeper than the vertical distribution of roots, suggesting a decrease of SOC decomposition rate with depth (Gill et al. 1999; Gill and Burke 2002). Radiocarbon ^{14}C dating studies confirmed more stable C with greater turnover times in deeper soil layers (Rumpel et al. 2002; Baisden and Prafitt 2007). To date, most studies have concluded that SOM at depths greater than 30 cm is composed more of microbially derived materials than of plant-derived materials and are associated primarily with soil minerals (Schmidt et al. 2011; Schrumpf et al. 2013).

Conversion of land from its natural state to agriculture generally leads to losses of soil organic carbon. It may take about 50 years for the organic carbon of soils in the temperate climate to reach a new equilibrium level following a change in management, but this period is much shorter in a semiarid and tropical environment like India (Swarup 2008). Under natural vegetation, SOC values tend to attain quasi-equilibrium with varying duration of 500–1000 years in a forest system (Dickson and Crocker 1953), 30–50 years in agricultural systems after forest cutting (Batjes 2001; Naitam and Bhattacharyya 2004), and 5–15 years in agricultural systems after forest cutting in red soils in Orissa (Saikh et al. 1998). Such reports confirm changes in SOC due to changes in land-use systems. After each change in the land-use system, a new quasi-equilibrium stage is arrived over a period of constant management in terms of new land-use pattern, vegetation cover, and management practices (Bhattacharyya et al. 2008). Thus, the conversion of farmland system into forest and grassland ecosystems is favorable for the accumulation of soil organic carbon and much more favorable for carbon fixation and ecological environment improvement where the capacity of soil functioning as a carbon sink is increased.

Few studies have assessed the impact of cropping on deep SOC stocks, and these have shown that some soils lose deep SOC under cultivation, though these losses are lower than in surface layers (Guo and Gifford 2002). Hence, research dealing with SOC depth distribution is gaining interest as the identification of a stable SOC reservoir at greater depths is essential for understanding the influences of climate and human activities on the terrestrial C cycle (Wang et al. 2004). Therefore, agricultural soils are particularly important for C storage because of their potential for C sequestration both now and in the future (Murty et al. 2002). Datta et al. (2015) studied the percent of TOC in individual soil layer with respect to the whole soil profile under different land uses in a reclaimed sodic soil. Highest percentage of TOC at 0–0.2 m soil layer was observed under jamun land use (32.7%) followed by *Eucalyptus* (31.1%), litchi (27.3%), rice-wheat system (22.6%), mango (21.9%), guava (21.8%), and *Prosopis* (21.6%) land uses. The percentage of TOC in each soil layer decreased significantly ($p < 0.05$) with depth increment. At lower depths, percent of TOC with respect to the whole profile TOC decreased significantly (Fig. 7.9). Although below 1.0 m depth, there was an apparent increase in percent of TOC which was due to the increase in depth interval (0.5 m) than the upper layers (0.2 m interval). For that reason, TOC stock as well as percent of TOC was increased below 1.0 m depth of soil (Datta et al. 2015).

7.4 Conclusion

Land uses significantly influence SOC sequestration and depth distribution in soil. In the present context of climate change, proper land-use management can help to sequester SOC and mitigate the harmful effects of extreme climate events. In India, there are significant areas under degraded wasteland category if rehabilitated through suitable tolerant tree species not only it may increase the area under forest but subsequently fixes atmospheric CO_2 besides performing many ecosystem

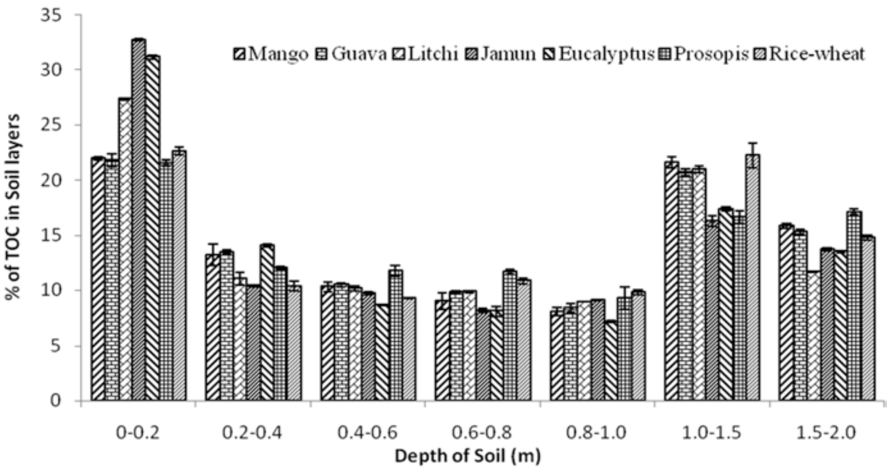

Fig. 7.9 Distribution of TOC in different depths under various land uses. Vertical bars indicate ± S.E. of mean of the observed values (Datta et al. 2015)

functions. The income of the resource poor farmers would also increase. Forest or horticultural land uses with deep root system can have the potential to sequester significant amount of SOC at deep soil layers with higher turnover time. For overall sustainability of the cereal-based cropping system as well as forestry or horticulture system and improving soil health, we have to maintain organic carbon in soil at a desirable level. This will also help to increase food grain production that ultimately helps to feed the burgeoning population of the country.

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Carbon Management in Diverse Land-Use Systems of Eastern Himalayan Subtropics

8

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Abstract

The north eastern region (NER) of India has ~48% degraded land of its total geographical area of 26.23 m ha. Shifting cultivation, cultivation along the slope, poor soil conservation measures, extractive farming practices like excessive disturbance of soil in sloping lands, no or very low application of organic manure and fertilizer, residue burning, deforestation, etc., are the major causes of land degradation in the NER. Improving carbon (C) status of the soil and maintaining it at critical level (1.5% or more) through Good Agricultural Practices (GAP) in subtropical hill ecosystems offers an opportunity for sustainable agriculture and environmental security. Among the NER states, Tripura has highest area (>89%) under relatively low soil organic carbon (SOC) content (1.0–1.5%) followed by Assam (62.83%) and Meghalaya (19.9%). Whereas, SOC content in mid and high attitude areas of the NER ranges from 1 to 3.5% or more with trend of increasing SOC as altitude increases. In general, soils in the tropical and subtropical ecosystems of the NER have lower SOC than those of temperate and alpine ecosystems. Practising Integrated Farming System, conservation agriculture, location-specific

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agroforestry system, multiple cropping, crop intensification and diversification, rehabilitation of degraded lands through appropriate amelioration measures like liming, organic amendments, etc. have the potential to restore SOC content, improve agricultural productivity and will help in the advancement of food and nutritional security in the region.

Keywords
Conservation agriculture · Eco-restoration · Hill ecosystem · Land use · Soil organic carbon

8.1 Introduction

The North Eastern Region (NER) of India, a fragile ecosystem with diverse agro-climatic and geographical conditions, comprises the states of Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura, and lies between 22°05′ and 29°30′ N latitudes and 87°55′ and 97°24′ E longitudes. Approximately 56% of the area is under low altitude (valley or lowland), 33% is under mid-altitude (flat-upland) and the rest is under high altitude (upland terrace). The hills, mountains and undulating plateau account for 72% of the total geographical area of the region. Valleys are rich in organic matter (OM) but on steep slope, because of continuous removal of topsoil, the organic matter status is poor to medium. The region has remained economically backward, though there is an ample potential for development due to the presence of abundant natural resources. Traditionally, based on rainfall, farmers both at upland terrace and valley lands follow the mono-cropping practice. Rice is the staple food of the people occupying more than 80% of the cultivated area followed by maize. Therefore, the cropping intensity of the region is also low (134%). Farming in the rainfed North-East India is a high-risk venture. Intensive natural resources mining and continuous degradation of natural resources (soil, water, vegetation) under existing management practices will not ensure a sustainable farm productivity and food security for the coming years. Yet, jhum (shifting cultivation) is practised in about 0.76 m ha in the region, causing severe degradation of land and biodiversity and has made the production system unsustainable. In addition, the topography of the region is such that it is difficult to promote mechanized agriculture. In spite of its total geographical area of 26.2 m ha, which is 8% of the total area of the country, the region contributes only 3% to the country's total food production.

Improving carbon (C) status of the soil through Good Agricultural Practices (GAP) in subtropical hill ecosystems offers an opportunity for sustainable agriculture and environmental security in the region to cope with changing climate (Das et al. 2017). Watershed-based farming system approach, site-specific soil conservation measures, mixed land use of agri-horti-silvi-pastoral system, multipurpose tree (MPT) based agroforestry systems (AFS), bio-resource recycling for soil health management, residue recycling, integrated nutrient and water management, subsidiary source of income through rearing of livestock, creation of water harvesting and

Table 8.1 Extent of land degradation (based on 1:250,000 resource mapping) in NE region (000 ha; NBSS & LUP 2004)

State	Erosion	Water-logging	Acidity	Complex problems	Total degraded land	% of TGA
Arunachal Pradesh	2372	176	1955	–	4503	53.8
Assam	688	37	612	876	2213	28.2
Manipur	133	111	481	227	952	42.6
Meghalaya	137	07	1030	34	1208	53.9
Mizoram	137	–	1050	694	1881	89.2
Nagaland	390	–	127	478	995	60.0
Sikkim	158	–	76	–	234	33.0
Tripura	121	191	203	113	628	60.0
Total	4136	522	5534	2422	12,614	47.5

silt retention structure at lower reaches are more pertinent agricultural strategies for sustainable agriculture and ecosystems in the region.

8.2 Land Degradation

In the NER, degradation of agricultural lands is said to have begun with the inception of shifting cultivation around 7000 BC. With increase in population (>40 million), soil degradation has increased many folds in the last few decades. Among the states of the NER, Arunachal Pradesh ranked first in terms of total amount of degraded land (Table 8.1). Various types of degradation such as water erosion, waterlogging, acidity, reduced infiltration, nutrient leaching, burning of vegetation, decline in vegetation covers and loss of biodiversity are alarming in the region. The loss of nutrient loaded soil through runoff because of high rainfall has more implication for the natural resource base and environment in the region. The extent of soil and nutrient transfer in the region has been estimated to be about 601 Tg of soil and 685.8, 99.8, 511.1, 57.1, 43, 22.6 and 14 thousand Mg of N, P, K, Ca, Mg, Mn and Zn, respectively. Unceasing degradation of land has affected the land, water and biodiversity resources, which may lead to a crisis of enormous magnitude for these resources in the future. Effective planning for soil and land resources, therefore, assumes a great significance in the region.

8.3 Factors Responsible for Low C Status

There are various factors responsible of land degradation, e.g. mining forests for fuel, timber and fodder by surrounding human settlement, high rainfall, undulating topography, infrastructure development and tenant system of land management by different ethnic tribes. In the NER, there is a high percentage of area under

Table 8.2 Soil erosion hazards associated with various land-use practices (Prasad et al. 1986)

Land-use system/practices	Experimental plot size	Soil loss (Mg ha^{-1} $year^{-1}$)
Shifting cultivation	Small	30.20–170.20
Tuber crops on raised bed (Bun)	Medium	40.00–50.00
Pineapple cultivation along the slope (First 2 years)	Small	24.00–62.60
Mixed crop of maize and rice	Small	19.70–21.00
Rice crop on slope	Small	32.90–45.00
Bare/fallow	Small	83.80
Cropping systems	Medium	51.00–83.80
Natural bamboo forest	Field	0.04–0.52

Note: Area of small, medium and field size plots were in ranges of 5, 16 and 69,000 m^2, respectively

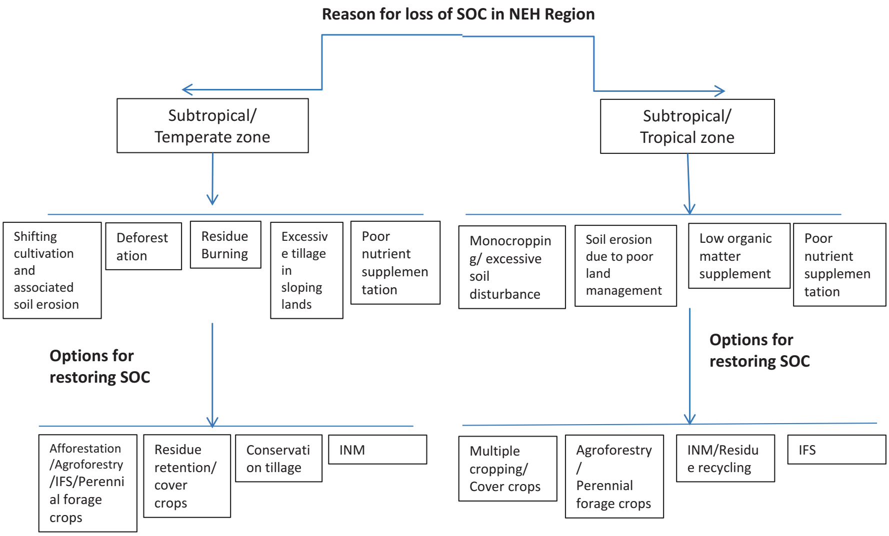

Fig. 8.1 Flow chart showing reasons for loss and options to restore SOC in NEH region

wasteland due to shifting cultivation (*jhum*) in Nagaland, Assam hills, Manipur, Meghalaya and Mizoram. On such lands, soil erosion through running water is the main agent of land degradation (Table 8.2). As per a recent estimate, the region has ~12.6 m ha of degraded land. The existing community/private land system has been excessively exploited for survival and the realization of short-term objectives without caring for the long-term health of the soil. The major cropland areas of hill agriculture are eroding faster than natural processes and have been significantly degraded due to various problems (Fig. 8.1). Some of the major contributing factors to land degradation and low SOC in the region are described below.

8.3.1 Deforestation

As per government policy two-thirds of the hills should be under forest cover to prevent land degradation and impart stability to the fragile hill ecosystem. The majority of the hill districts of Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram and Nagaland are under more than 66% forest cover. Forest ecosystems of hills are being threatened by loss of forest lands due to agricultural practices (mainly shifting cultivation), industries, infrastructures and human settlements, illicit felling, lopping for fodder and fuel wood, overgrazing, removal of forest floor litter, forest fires, over-felling, etc. Population explosion and encroachment of forest land are also a serious concern. The deforestation of hill slopes has resulted in increase in sediment load of rivers emerging from the hill and mountains, causing greater sedimentation load in the Brahmaputra and its tributaries as compared to the Ganges. The damage is proportional to the angle of slope.

8.3.2 Cultivation along the Slopes

Most of the lands in the NER belong to VI and VII classes of land capability and are used for agricultural crops production along slopes. A continuous increase in population has resulted in further spread of cultivation on steeper slopes, with much less fertile soil and is one of the major causes of degradation and poor land productivity. All field operations are done along the slope instead of across the slope, thereby encourages huge soil loss through runoff. The loss of soil through runoff on such lands varies from 10.8 Mg ha^{-1} to as high as 62 Mg ha^{-1} depending upon type of land use (Prasad et al. 1986). The loss of topsoil reduces the inherent productivity of land through loss of nutrients and degradation of physical structure of the soil. It also increases the cost of food production.

8.3.3 Shifting Cultivation

Shifting cultivation, popularly known as *Jhum*, is a common practice on hill slopes and is the single largest factor contributing to the reduction in forest cover in the region. A quantum jump in population of tribal societies practising shifting cultivation and the declaration of reserve forests by the government have shortened the fallow periods, which on an average at present is 3–5 years compared to 15–20 years half a century ago. Such reduction in fallow periods has decreased the time for soil health build-up and hastened the process of soil degradation. The loss of soil under shifting agriculture has been reported to the tune of 5–83 Mg ha^{-1} depending upon crops grown and slope of the land (Prasad et al. 1986). Consequently, 80% of the cultivated area of the region is under moderate to severe level of erosion, threatening ecological balance and food security for future generations. The productivity of lands under shifting cultivation are directly dependent on the rest or fallow periods, during which such lands are rebuilt up by organic matter and essential nutrients for remunerative agricultural yields predominantly stored in the forest ecosystem rather than the soil. Burning of above-ground biomass increases pH and cations and decreases carbon (C) and N contents in surface soils. The SOC content decreases after burning because of oxidative loss of CO_2. Soil loss to the tune of 40.9 Mg ha^{-1} and corresponding nutrient loss of 703 kg SOC, 63.5 kg P and 6 kg K ha^{-1}have been reported from shifting cultivation on steep slopes of 44–53%. Annual loss of top soil, N, P and K to the extent of 88,346, 10,669, 372 and 6051 Gg from the region had been reported (Sharma et al. 2006).

8.3.4 Bun Cultivation

Bun cultivation is a local system of *jhuming*, developed by tribal families of East and West Khasi Hills and Ri-Bhoi districts of Meghalaya. About 15,062 families of Meghalaya practise this method of modified *jhuming* for cultivation of crops such as potatoes, sweet potatoes, ginger, vegetables, etc., on a series of beds formed along the slopes of the hills. During December to March, raised beds of approximately 5 m × 1–1.5 m × 0.3–0.5 m height are prepared. This system of *jhuming* involves cutting of shrubs and grasses, putting of locally available dried vegetation @ 40–50 Mg ha^{-1} (as needles of pine species and some weed flora, e.g. *Lantana camera*, *Eupatorium odoratum, Setaria glauca*, grass mixtures) on the form of raised beds (0.02–0.05 m layer) along the slopes and covering the same with the soil collected from the surroundings, burning of covered vegetation and planting in the soil afterwards. This plant biomass is burnt as such for quick release of nutrients and the crops are sown in the bun after 1 month of burning (Majumdar et al. 2004).

8.3.5 Poor Management Practices

Agriculture in the NER is subsistence by nature. Hill farmers hardly apply nutrients to any crops. Rather, they mostly rely on inherent nutrient supplying capacity of soil. Residues are either burnt or removed from the field. Monocropping is prevalent in hills, while double cropping is practised in certain areas especially in the plains and valleys. Therefore, nutrient mining due to very low or no application of nutrients, erosion, low biomass production, etc. are the major causes of low SOC in mid- or high-altitudes areas. Relatively higher temperature and low biomass input due to monocropping in subtropical areas lead to depletion of SOC due to oxidation (Kuotsu et al. 2014).

8.4 The Necessity of Maintaining a Minimum SOC in Himalayan Subtropics

Concentration of greenhouse gases (GHGs) in the atmosphere has increased over the years due to large-scale combustion of fossil fuels, deforestation, and poor agricultural management and subsequently it increased the global average temperature. Carbon storage in soils for longer periods and in deeper layers has been considered as an important strategy to combat increasing level of CO_2 concentration in the atmosphere. In addition, soil organic carbon (SOC) helps in maintaining soil productivity and the natural ecosystem (Yadav et al. 2017a). Maintaining and improving SOC level is a pre-requisite to ensure soil quality, crop productivity and sustainability of agricultural ecosystems. The extent of variation in SOC content and stock relies on the land-use type and land-use change and post-conversion land management (West et al. 2010; Post and Kwon 2000). Increase in SOC content by 0.01% can substantially reduce the adverse consequences of annual increase in atmospheric carbon dioxide concentration (Lal et al. 1998). It is reported that soil contains a significant part of the global carbon stock (3.5%, Batjes 1998). The NER is highly variable in climatic conditions (tropical to alpine climate), topography, rainfall pattern, vegetation, land use and cultural diversity and ethnicity; the SOC content is also expected to be highly variable across the region (Choudhury et al. 2015). SOC in the humid subtropical climate becomes more important in view of undulating hilly terrains (Yadav et al. 2017b). Since soils contain (1505 Pg C) more than twice the C found in the atmosphere (560 Pg C), loss of C from soils can have a significant effect on atmospheric CO_2 concentration and thereby on climate. Halting land-use conversion would be an effective approach to reduce soil C losses, but with a growing population and changing dietary preferences in the developing world, more land is likely to be required for agriculture. Maximizing the productivity of existing agricultural land and applying best management practices to that land would slowdown the loss, or in some cases even restore soil C. However, there are a number of obstructions to implementing best management practices, the most significant of which are driven by poverty in developing countries. Management practices that also improve food security and profitability are most likely to be adopted. Soil C management needs to be considered within a broader framework of sustainable development. Policies to encourage fair trade, reduced subsidies for agriculture in developed countries and less interest on loans and foreign debt would encourage sustainable development, which in turn would encourage the adoption of successful soil C management practices in developing countries. If soil management is to be used to help address the problem of global warming, priority needs to be given to implementing such policies.

8.5 Soil Fertility and Soil Organic Carbon Status

Most soils of the NER are rich in SOC and nitrogen (N) content, except those under shifting cultivation, but are low to medium in phosphorus (P) and medium to high in potassium (K). Soils of the humid subtropical regions (e.g. Tripura, Assam and other foothills) are deficient in SOC and K. More than 85% of soils are acidic, and have mild to severe acidity attributable to the leaching of basic cations due to heavy rainfall. Phosphorus fixation is a problem in these soils and substantial part of the P from applied phosphatic fertilizer gets immediately fixed, and unavailable. Soils of the region are broadly classified under five orders, namely Inceptisols, Entisols, Alfisols, Ultisols and Mollisols (Sharma et al. 2006).

In Arunachal Pradesh, SOC concentration ranges from 14 g (mid altitude) to 59 g kg^{-1} (high altitudes). In Manipur, SOC concentration ranges from 1–34 g/kg in Bishnupur valley to 5.1–36.6 g kg^{-1} in Imphal valley. Conversely, in the hill districts of Manipur the SOC concentration is much higher (14.4–51 g kg^{-1}) than valleys. In Meghalaya, the SOC concentration ranges from 5.2 to 43.0 g kg^{-1}in East Khasi Hill and 5.2 to 31.3 g kg^{-1}in West Khasi Hill districts. About 13% soils in the valleys and 5.5% in the high altitude (>1700 m MSL) are low in SOC in Meghalaya. The soils of Mizoram are low to medium in SOC (4.2–13.4 g kg^{-1}) concentration. In Sikkim, the SOC concentration is high to very high in most of the soils ranging from 23.5 to 44.5 g kg^{-1}. However, SOC concentration is low in low altitude areas (<600 m MSL) ranging from 23.5 to 31.5 g kg^{-1} (Sharma et al. 2006; Das et al. 2011). The SOC content in soils of Tripura ranged from 0.5% to 2%. SOC content in majority of land area is in the range of 0.75–1.5% (~77%) and about 12 and 11% land area fall under <0.75% and > 1.5% range of organic carbon, respectively (Bhattacharyya et al. 1998).

8.6 Different Approaches for Managing SOC

Mismanagement of land accelerates the soil organic matter (SOM) decomposition and affects the carbon cycle due to imbalance between carbon emissions and sequestration (Choudhury et al. 2015). SOC is influenced by the dynamic interaction of climate, vegetation, land use, soil type, topography and management practices (Jaiarree et al. 2014). Rapid land-use and land-cover change owing to large-scale deforestation, conversion of natural ecosystem to human managed ecosystem (temporary agriculture) through various production practices, plantations and other forms resulted in a colossal loss of plant biomass in the region. More than 8.5 million tonnes of plant biomass is burnt annually under shifting cultivation alone. Conversion of primary or secondary forests to crop lands and perennial crops/plantations in the tropics always results in 25–30% loss of SOC stock (Don et al. 2011). It is widely reported that cultivation practices in hill slopes under an agriculture system degrade soil structure, reduce the aggregate stability and make the soils more prone to soil erosion (Choudhury et al. 2015). A schematic diagram showing approaches for restoring SOC in valleys and hills under subtropical ecosystems are presented in Fig. 8.1.

8.6.1 Indigenous Carbon Management in NER

A number of indigenous farming systems are being practised in the NER and production is maintained only through organic nutrition. These are: Zabo systems, which are practised in Phek district of Nagaland and have a combination of forest, agriculture, livestock and fisheries; Rice (*Oryza sativa* L)-Based Farming System of Apatani Plateau occupying a stretch of 26 sq. km area in Subansiri district of Arunachal Pradesh which is inhabited by the “Apatani” tribe; Bamboo Drip

Irrigation System followed mainly in Jaintia and Khasi Hills of Meghalaya; Agriculture with Alder in Nagaland; Rice Cultivation on Terraces prevalent in Nagaland, Manipur and Sikkim; Taungya System, which is a method of establishing forest species in temporary combination with field crops; Homestead Agroforestry, where farmers of Assam and Tripura grow a number of tree species along with livestock, poultry and fish mainly for the purpose of meeting their own needs.

An analysis of the food grain production indicates that production from the high input belt, viz. from the 37% area has almost reached a plateau as the residual effects of massive use of chemical fertilizers and pesticides along with HYV started manifesting. On the other hand, the rainfed areas of the country, by and large particularly the hill and mountain ecosystem which occupies 30.8 m ha areas, fall under Complex, Diverse and Risk Prone (CDR) areas which depend on the recycling of on- and off-farm wastes. In other words, CDR agriculture aims at production sustainability through crop rotation, mixed farming and intercropping, etc. As stated by Bujarbaruah (2004), the NER has immense potential to promote organic agriculture as the region has 0.76 lakh ha of land under shifting cultivation where no inorganic input and tillage has ever been used. The region has varied agro-climatic zones where the production from tropical to temperate agri–horticultural crops, animals and fishes persists. Inaccessibility, fragility and marginality of the entire area are thought to put a barrier in promotion of the organic agriculture in the region. The need of the hour is to identify a commodity which has the potential to harness both the domestic and the international market.

8.6.2 Perennial grasses and SOC stocks

Perennial forage crops significantly increase concentrations of available N, P, K and that of SOC compared to the antecedent level in a 3-year study at ICAR Complex, Umiam, Meghalaya indicating the importance of forages for improving soil quality (Das et al. 2016). Concentrations of available N, P, K and that of SOC after 3 years were reported significantly higher under organic manure compared to those under inorganic fertilizer and control treatment. Soil bulk density (ρ_b) has been reported to decrease with successive cropping cycles of perennial forage crops in 0–15 and 15–30 cm layers. The average soil microbial biomass carbon (SMBC) and dehydrogenase activity (DHA) under organic manure was 17.9 and 6.21% higher than that under control, respectively.

In Meghalaya, in an experiment the SOC stock (0–15 cm) increased by 5.4–7.5% under forages and by 2.3–10.4% under fertilization compared to the antecedent stock after the third year. Furthermore, soils under Napier had the highest OC stock followed by that under Congosignal grass (Ghosh et al. 2009). Fertilization of grasses with organic sources further accelerates carbon build-up than that fertilized with inorganic fertilizers (Das et al. 2016). Perennial grasses accumulate more SOC over time than other systems because of larger inputs of biomass-C from litter, roots, and the slower rate of decomposition (Zhou et al. 2012). The increase in SOC under forages compared to the initial values was attributed to high root biomass, and addition of OM to the soil through decaying of large volume of dead roots, and return of detritus materials (De Deyn et al. 2008). Perennial grasses have a high root biomass, which is a continuous source of OM to the soil (Bonin and Lal 2014). Thus, grasses improve soil aggregation, water transmission properties and SOC concentrations (Conant et al. 2001). Increase in SOC concentration over time may also be attributed to the minimal disturbance of soil under perennial grasses and to extensive root systems (Gentile et al. 2005). The retention of SOC depends on the quantity of root biomass and its quality (lignin/nitrogen ratio, carbon/nitrogen ratio, cellulose, hemicellulose, etc.) which can vary widely as a function of climate and soil type (Ghosh et al. 2009). Therefore, conversion of degraded land to hybrid Napier grass fields can increase C-sequestration in ecosystems (Nishanth et al. 2013).

Continuous applications of organic amendments can enhance SOC concentration (Jiang et al. 2006), available P and K and improve soil quality (Panwar et al. 2010; Das et al. 2014). Ghosh et al. (2009), from a long-term study (15 years) at ICAR Complex, Umiam, Meghalaya, indicated that soil under perennial grass maintained ~30% higher SOC ($P < 0.05$) than the control (intensive cropping) and initial value. Significantly higher SOC at 0–0.15 m depth ($P < 0.05$) was reported under most perennial fodder species like setaria (*Setaria sphacelata)* (2.4%), *Brachiaria rosenesis* (2.55%), and *Panicum maximum* (2.54%), compared with those under control. The superiority of these grasses was mainly due to higher root biomass generation, constant addition of organic matter to the soil through decaying of large volume of dead roots, and high return of leftover surface plant residue leading to improvement in C-status of the soil (Das et al. 2017). Repeated ploughing, little coverage of soil surface, and no regular addition of organic matter were practised under traditional cultivation over a long period of time; therefore, traditional cultivation tended to deplete the SOC level.

Addition of organic matter through root decay enhances SOC, which directly or indirectly affects soil physical properties and processes such as aggregation, water-holding capacity, hydraulic conductivity, and resistance of soil to water and wind erosion (Franzluebbers 2002; Celik et al. 2004). Hudson (1994) reported that soils high in organic matter had greater available water-holding capacity than soils of similar texture with less organic matter. Grewal and Abrol (1986) reported that surface vegetation protected soils directly against erosive forces of raindrops and surface run-off by improving soil physical and hydrological parameters. Grasses improve water transmission in terms of infiltration rate, hydraulic conductivity and available water content.

8.6.3 Resource Conservation Practices and SOC

Tillage affects soil physical, chemical and biological properties and can play an important role in enhancing the yield potential of crops. Resource conserving practices like zero tillage can help farmers to grow crops sooner after rice harvest so that the grain matures before the onset of pre-monsoon shower starts.

Table 8.3 Organic carbon and biological activity under different tillage practices (Ghosh et al. 2010)

Treatment	SOC (%)	SMBC (μg g^{-1} soil)	Dehydrogenase activity (μg TPF g^{-1} 24 h^{-1})
Conventional tillage	1.47	91.3	29.5
No-till	2.23	128.5	131.5
Double no-till	2.51	134.1	166.6
Minimum tillage	2.17	121.3	127.5
CD (*P* = 0.05)	0.78	12.1	27.5

SMBC Soil microbial biomass carbon, *TPF* Tryphenylformazan

A field study was conducted for 4 years with rice during rainy season and wheat, *toria* and linseed in winter season with four tillage practices, viz conventional tillage, (3–4 passes of power tillage and residue removal), double no-till (NT) and residue retention (1/3), NT for *rabi* crops and residue retention (1/3), residue incorporation (minimum tillage) (one power tillage before sowing). Except double NT plots, puddling was done in other treatments. In double NT, transplanting of 25-day-old 3–4 seedlings/hill was done in moist field with the help of cone of manual dibbler at a spacing of 25 x 10 cm row-to-row and plant-to-plant. The results revealed that maximum grain yield of rice (rainy season) and following crops (wheat, *toria* and linseed) were recorded under double NT plots followed by NT (for *rabi* crop only) along with residue retention (Table 8.3). Significant difference in SOC was found among tillage treatments. In the field study, NT also recorded higher soil microbial biomass carbon (SMBC) and dehydrogenase activity (Table 8.3), which in turn resulted in growth and higher yield of all crops under NT. When NT combined with residue on soil surface, C–sequestration was higher than conventional tillage which favoured more numbers of earthworm population in the field.

8.6.4 Organic Farming and SOC management

The fertilizer consumption in the NER (excluding Manipur and Tripura) is less than 12 kg ha^{-1} (Das et al. 2017). The total potential for nutrient supply through crop residues in the NER has been estimated as 9.86, 2.12 35.5 Mg of N, P and K, respectively, with an average 2.46 kg N, 0.53 kg P_2O_5 and 8.87 kg K_20 per ha. Thus, a good quantity of potash can be added through crop residues (Sharma et al. 2006). Growing leguminous shrubs such as *Crotolaria juncea* and *Tephrosia purpurea* around the farm fences can produce 5–6 Mg ha^{-1} green leaf manure containing 2.4–2.7% N, 0.3–0.6% P and 0.8–2.0% K. A 5-year duration study indicated that application of recommended dose of N through FYM or FYM + vermicompost was equally effective as organic amendment and their continuous application improved soil health and crop productivity (Patel et al. 2015). Organic production of rice, pea, lentil (*Les esculenta*), carrot (*Daucus carota*), French bean (*Phaseolus vulgaris*), tomato

Table 8.4 Soil fertility as influenced by different nutrient management practices under raised and sunken bed system (Hazarika et al. 2006)

Treatments	Available N (kg ha^{-1})		Available P (kg ha^{-1})		Available K (kg ha^{-1})		Organic carbon (%)	
	Raised	Sunken	Raised	Sunken	Raised	Sunken	Raised	Sunken
Natural	166.2	171.3	2.5	1.7	272.3	250.3	3.1	2.9
Organic	181.9	185.0	2.8	1.9	285.1	260.2	3.4	3.1
Integrated	181.9	194.7	2.7	2.3	291.5	264.4	3.4	3.1
In-organic	169.3	178.6	2.3	1.5	282.1	259.2	3.2	2.9
Initial status	144.3	–	1.41	–	246.0	–	1.7	–

(*Solanum lycopersicum*), potato (*Solunum tuberosum*) and okra (*Abelmoschus esculentus*) can sustain soil health and productivity in the NER (Das et al. 2014).

Studies on nutrient contents of soil showed that there was improvement in soil quality due to adoption of organic farming (Table 8.4). Available N, P and K in raised bed were found higher in organic as well as integrated treatment. Lower values of these nutrients were found in the soils of sunken beds compared to raised beds. Population of bacteria, *Rhizobium* and PSM were found more in the soils of organic treatment. Higher microbial populations in organic, natural and integrated treatments probably mineralized the unavailable forms of nutrients enhancing their availability.

Studies on homestead organic farming under raised and sunken bed system with in situ residue management supplemented with FYM, rock phosphate and neem cake as a source of nutrient supply showed that the cropping intensity as high as 300% can be achieved under wetland with proper land configuration along with sustained productivity of crops (Das et al. 2014).

The results of different experiments indicated that organic farming maintained soil quality. Therefore, the productivity of crops under organic farming either maintained or improved over the years.

8.6.5 Alternative Farming Systems

The alternative system (integrated farming systems) to shifting cultivation has been developed in ICAR Research Complex, Meghalaya. After 20 years of research, the highest accumulation of exchangeable K was observed under agri-horti-silvi-pastoral system. The rise in available P in agriculture, livestock-based system could be due to heavy and continuous dressing of cow dung litter for extended periods of time. Available K increased in all the systems except in livestock-based farming system. The overall fertility build-up followed the trend as agriculture > agri-horti-silvi-pastoral > livestock-based farming system. However, livestock-based or horticulture farming systems could be the alternative to shifting cultivation on sloping land under mid- to low-altitude conditions in Meghalaya. This is because of the fact that horticulture and livestock-based farming system can ameliorate acidity by reducing the A1-toxicity as these two systems maintained highest SOM in 20 years, while organic matter build-up was highest in the livestock-based system (1.63%) followed by the agro-forestry system (1.6%).

8.6.6 Integrated Nutrient Management

The hill farmers are mostly small and marginal in nature, having meagre resources and risk bearing ability. Thus, promotion of any system of nutrient management should be of low cost in nature and ecofriendly. The use of N, P and K through fertilizer in the region is only 13.37, 11.12 and 11.10%, respectively, of the crop removal, indicating continuous addition to their deficit in soils resulting in poor productivity. Considering the fertility status of the North Eastern Region, application of macro- and micronutrients is required for various crops as per their need, to obtain higher yield. The requirement of nutrient varies widely for different crops, which is one of the most essential factors to be considered for application of fertilizers. The variation in fertilizer consumption within the region is directly related to the cropped area. Another reason for low productivity is the imbalanced use of different fertilizers. While the optimum ratio for N, P_2O_5 and K_2O is 4:2:1, in many cases the ratio is far diverted. In most cases only N fertilizer is applied and P and K are neglected. In case of Manipur, the ratio is 76.9: 7.5: 1.

To set an optimum yield of crops, it is required that fertilizers be judiciously used based on soil test and crop response. Secondly, organic resources available need to be properly utilized for crop production. Bujarbaruah (2004) reported availability of 8.9 Tg of crop residues and 37 Tg of animal dung giving about 47 Tg of organic manure potential in the region. If these sources are effectively recycled in crop production, nutrient requirement can be reduced substantially. Low rate of fertilizers and other chemicals along with good potential for organic manure offers opportunity for organic farming in the region. Thus, INM and organic farming are the two important areas of soil management in the region.

Integrated use of chemical fertilizers of 60 kg N/ha along with 5 Mg ha^{-1} FYM with seed inoculation of *Azotobacter* was found to enhance rice yield and nutrient uptake with better nitrogen build-up in the soil of the region. Similarly, application of SSP with *Rhizobium* inoculation in black gram produced 69.1% increase in nodulation over control in acidic soil of Tripura. Datta and Dhiman (2001) found that application of lime+ phosphate+ *Rhizobium* + PSB, increased nodulation from 31 to 45%. All these experiments revealed that integrated nutrient management improves soil microbial population and ultimately soil health.

8.7 Managing SOC Under Various Land-Use Systems

Agricultural soils have a large potential of carbon stock and for expended carbon-sequestration. Agricultural soils, thus, provide a prospective way for reducing atmospheric concentration of CO_2 (Lal 2004).

8.7.1 Tripura (Low Altitude)

In soils of different land-use systems of Lembucherra, Tripura, SOC concentrations varied from 8.6 to 16.4 Mg kg^{-1} at 0–15 cm and 7.4 to 15.2 kg ha^{-1} at 15–30 cm layer. Among all the land uses, SOC stock was the maximum under bamboo plantations followed by *Tephrosia purpurea* and duck-based farming system. Mango and areca nut blocks had the lowest SOC stock (Das et al. 2011, 2017).

Agriculture, horticulture and shifting cultivation are the three prominent land uses practised by farmers of Tripura. Soil properties and SOC status of land under these systems are varied. The SOC is highest under agriculture land use (0.82%) from those under shifting cultivation (0.80%) and horticulture (0.67%) land-use systems. Further, SOC content has been reported to vary with land topography among the land-use systems (Fig. 8.2) (Bhattacharyya et al. 1998). The major concern in such landscapes is soil erosion and the necessary conservation practices. From a comparative study of the two contrary processes, viz. soil loss and its formation, it was estimated that Tripura could tolerate a loss of 29 Mg ha^{-1} $year^{-1}$ of soils and 0.5% SOC on the surface as the minimum value to maintain a threshold SOC stock of 0.05–0.06 Pg m ha^{-1}; 0.15 Mgs (~150 kg) SOC ha^{-1} $year^{-1}$ ($29 \times 0.5/100 = 0.145$ Mg ha^{-1} $year^{-1}$) was found to be the tolerable limit of SOC loss in Tripura. The spatial variability of SOC loss in the state indicates that most of the areas in the north, north–south extending further in the southern part are under threat for SOC loss beyond the tolerable limit. Tripura has an area of 20% under valleys and interhill basins. Most of these areas are used for agriculture (submerged paddy). These soils are subjected to erosion within the tolerable SOC loss limit and are also characterized by high SOC buildup due to reduced moisture regime in the soil profile and thus fall under tolerable SOC loss. On the contrary, in the hills and the *tilla*

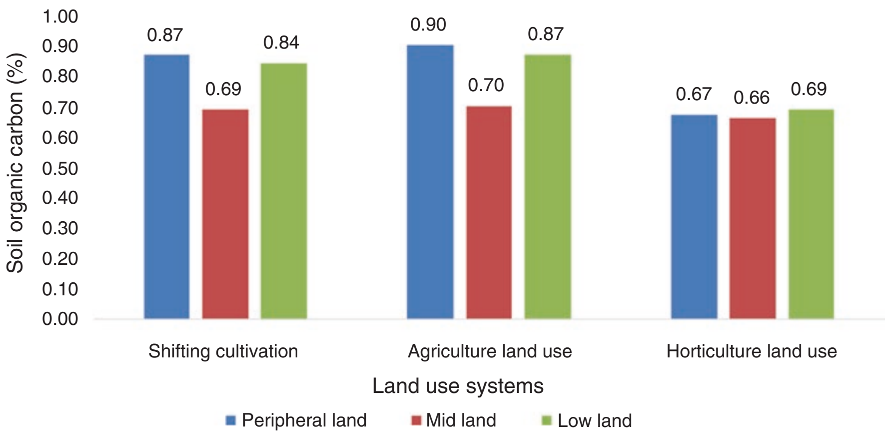

Fig. 8.2 Soil organic carbon content under different land use in Tripura (Bhattacharyya et al. 1998)

lands, the situation is different. Hilly areas of Tripura in the north, central and southern parts have different elevations, mean annual rainfall and different types of vegetation. In the *tilla* lands, agriculture and horticulture are gradually dominating the land use. Many such areas still remain under the category of degraded forest, which are vulnerable to SOC loss. Field information indicates that many such areas have flat slope and are under cultivation. These soils used for bunded paddy arrest SOC loss. It was reported how conservation agriculture should form a part of management technique in semi-arid and arid bioclimates. With the help of a threshold value of SOC stock of 0.03 Pg m ha^{-1}, nearly 156 m ha was reportedly prioritized for conservation agriculture. Like SAT, humid tropic climate requires conservation not only to protect soil erosion but also to prevent SOC loss for preserving soil fertility (Tiwary et al. 2015). Organic carbon in paddy soils of Tripura can be increased at a rate of 427.9 kg ha^{-1} $year^{-1}$ with adoption of reduce tillage (RT) along with improved plant nutrient management (IPNM) comprising 25% N (20 kg N) through green leaves manuring (GLM) + 60 kg N, 9 kg phosphorus (P), 17 kg potassium (K), 2 kg Boron (B) and 5 kg zinc (Zn) ha^{-1} through fertilizer + cellulose decomposition microorganism along with 30% residue retention in aman rice and conventional tillage (CT) + integrated nutrient management (INM) comprising 25% N through FYM and 75% N and remaining P and K (after deducting quantity supplied by FYM) through inorganic fertilizer +30% residue incorporation (RI) under boro rice. This combination of tillage and nutrient management also lowers bulk density (ρ_b), improves soil organic carbon (SOC)/N concentration, pool, accumulation, sequestration, C retention efficiency, soil microbial biomass C and dehydrogenase activities in paddy soils of Tripura (Yadav et al. 2017c). Further, no-till with residue retention may increase carbon efficiency (10.36) and C sustainability index (9.36) values over those under conventional tillage with residue incorporation (Yadav et al. 2018a). Retention of residue under no-till helps to store more moisture in soils and promote better crop growth and development which leads to higher carbon-sequestration than those under CT soils (Yadav et al. 2018b).

8.7.2 Meghalaya (Mid-Altitude)

At mid-altitude Meghalaya, land uses comprising conventional tillage, NT, organic farming (OF), in situ residue retention (IRR) in rice and maize and pine forest (dominant forest), *jhum* (slash and burn agriculture) and improved farming system (FS) involving crop-livestock-fodder on terrace risers were evaluated for SOC stocks. Soil samples were collected from 0–15 and 15–30 cm layers using standard procedures. The results revealed that the SOC concentrations ranged from 16. 4 to 34.7 g kg^{-1} at the surface layer (0–15 cm) and 15.5 to 33.5 g kg^{-1} at the sub-surface layer (15–30 cm). Among all the land uses, SOC stock was recorded maximum under in situ residue retention (IRR) in rice (10 years) in lowland rice followed by rice under organic farming. Pine forest had the lowest SOC stock among all the land uses. Farming system involving crop-livestock (Agro-pastoral) components had higher SOC stock in surface layer at upper slope (US), mid-slope (MS) and lower slope (LS) than that under jhum fields (Das et al. 2011, 2017). The soil available N was higher under rice grown with organic package of practices (250–255 kg ha^{-1} in 0–15 cm), IRR, farming system mid-slope and abandoned jhum fields than other land uses (110–190 kg ha^{-1} in 0–15 cm and 100–140 kg ha^{-1} in 15–30 cm layers). Thus, IRR in lowland rice and adaptation of farming system (FS) approaches are favourable for building soil fertility, especially the SOC stocks (Das et al. 2018).

8.8 Agroforestry and SOC

Agroforestry is an ideal scientific approach for eco-restoration of degraded lands and sustainable management. Numerous studies have described the beneficial effects of agroforestry systems in long-term soil productivity and sustainability, but the magnitude of the beneficial effects may vary with a number of site-specific factors and attributes of associated tree species. Increased nutrient inputs and recycling, reduction in nutrient losses, and improved soil physical properties are all characteristics of agroforestry systems as compared to sole cropping systems under hilly ecosystems. Improved soil aggregate stability, nutrients availability and microbial activity were observed under agroforestry systems in comparison to other land-use systems. In hills, agroforestry systems (AFS) play an important role in sustainability, resource conservation and food security (Bhatt et al. 2006). Multistoried AFS/home gardens are the classic example of agroforestry in the Eastern Himalayan region. Agri-horticulture, agri-silviculture, agri-horti-silvi-pasture, agri-pisciculture and multitier system are some of the important AFS in this part of the Himalayas (Bhatt et al. 2006). MPTs can improve bulk density, maintain higher moisture content and MWD than control (no tree) plots. Tree species such as *Alnus nepalensis* and *P. kesiya* had favourable effects on soil physical properties, particularly on soil BD, moisture content and MWD. A lower bulk density coupled with higher MWD under tree species could be attributed to their larger and deeper root system and root biomass than dominating grasses and crops resulting from accumulation of higher organic carbon, proliferation of rhizosphere and microbial activities, and root exudation below ground which helps to bind soil particles into larger aggregates and thereby loosen the soil and decrease its bulk density. *Alnus nepalensis* and *Michelia oblonga* considerably favoured the accumulation of SOC and available nutrients compared to other tree species under mid-hill condition of Meghalaya. The accumulation of SOC under tree species depends on the quantity as well as quality of chemical composition (lignin/nitrogen ratio, carbon/nitrogen ratio, cellulose, hemi-cellulose, etc.) of tree roots and litter and varies widely as a function of climate and soil type. Multipurpose trees (MPTs) like *M. oblonga* were identified as a better bio-ameliorant for these soils because continuous leaf litter and root exudates improved soil physical behaviour and SOC (Ghosh et al. 2009).

8.9 Prospects of Biochar in C-Sequestration in North East India

It is believed that biochar can store carbon in soil for hundreds to thousands of years and thus the level of greenhouse gases like CO_2 and methane can be reduced significantly. Biochar application for environmental management can be encouraged for soil improvement, waste management, energy production and climate change mitigation. Biochar can be used as a soil amendment to increase plant growth and yield, improve water quality, increase soil moisture retention, reduce emission of greenhouse gases from soil, reduce leaching of nutrients, reduce soil acidity, reduce irrigation and fertilizer requirements, and to reclaim degraded and spoiled land (acidic and alkaline soils).

Any cellulosic biomass can be used as feedstock for biochar production such as paddy straw, rice husk, maize stalk; leaves and cobs, saw dust, wood chips, forestry residues, weeds, etc. In NE India, 37 million tons of agricultural crop residues are produced annually (Bujarbaruah 2004). But a huge biomass is burnt (at least 10 Mg ha^{-1}) in about 0.76 m ha of shifting cultivation areas (at least 7.6 Tg of dry biomass is burnt). Even if a minimum of 10% of this huge biomass (10% of 44.7 mt, i.e. 44.7 Tg) is pyrolyzed by any of the methods listed above, a substantial amount of biochar can be produced. By assuming that only 25% (equal or more in most the pyrolysis processes) is converted to char, about 1.3 Tg of biochar can be produced containing 70% organic carbon. This much biochar may trap 3.50 Tg of CO_2 (Mandal et al. 2013).

8.10 Shifting Cultivation and Soil Carbon

Shifting cultivation has caused the destruction of forest and species habitat, which accounts for the most profound losses in biodiversity. During the recovery phase (abandoned periods), the vegetation evolves towards the original climax condition. If full recovery is achieved before the area is again cultivated, the system can be sustainable. The dynamics of vegetation of abandoned *jhum* field as influenced by changes in time were studied. During the first 5 years, species' diversity remained low and plots were dominated by herbaceous species. Between 5 and 15 years of abandonment, diversity increased rapidly as the vegetation passed into bamboo (*Dendrocalamus hamiltonii*)-dominated forest. Still later, it gradually passed into a mixed broad-leaved forest approaching the climax type, as compared with the species composition of sacred groves in the locality. However, they could not follow the process beyond 20 years.

Soil humic acid extracted from surface soils under shifting cycle was analyzed for its characteristics**.** The ratio of optical densities at 465 and 665 mm (E_4/E_6) of humic acid showed a concomitant rise from 3.88 to 4.66 over the shifting cycle of 3 years. A high ratio of E_4/E_6 reflects a low degree of aromatic condensation and large proportion of aliphatic structures. Hence humic material with high E_4/E_6 ratio may be considered to have low aromatic condensation. After 2nd and 3rd year of shifting cultivation like E_4/E_6 ratio, the CEC of humic acids also underwent an increasing trend from 250 to 375 c mol (p^+) kg^{-1}. Both the reduced viscosity and molecular weight showed an increase followed by a sharp decline from 10.85 to 8.05 ml g^{-1} and 6805 to 4300, respectively (Datta et al. 2012). This indicated smaller molecules of low molecular weight and low viscosity in soils under 3rd year of shifting cycle. Infrared studies showed the predominance of polymeric hydroxyl, carboxylic, carbonyl or quinone groups in humic acids with the rise in shifting cycle.

8.11 Conclusion

SOC concentrations in subtropical hill ecosystems are lower than temperate and alpine ecosystems of north east India mainly due to higher temperature, lower biomass production and inappropriate management practices like poor nutrient supplementations, low addition of organic manure, etc. Soil acidity and low phosphorus availability are two major soil-related constraints which limit agricultural productivity. Adoption of IFS, AFS, INM, residue recycling, perennial forage crops, cover crops, crop intensification with legumes, etc. offers great opportunity for C-sequestration and soil properties improvement in the NER in general and subtropical ecosystems in particular.

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Good Agricultural Practices and Carbon Sequestration

9

A. R. Sharma and U. K. Behera

Abstract

Conservation agriculture (CA) technologies include minimum soil disturbance, permanent soil cover through crop residues or cover crops, and crop rotations for achieving higher productivity. Intensive agriculture and excessive use of external inputs have led to degradation of soil, water, and genetic resources, widespread soil erosion, nutrient mining, depleting water table, eroding biodiversity, high energy requirements, reduction in availability of protective foods, air and groundwater pollution, and stagnating farm incomes. To overcome this, CA is recognized as a potential tool. CA systems demand a total paradigm shift from conventional agriculture with regard to management of crops, soil, water, nutrients, weeds, and farm machinery. Reduction in cost of production, saving in water and nutrients, increased yields, more carbon sequestration, environmental benefits, crop diversification, and resource improvement are few prospects and opportunities lying with CA technologies. Laser land leveling, conservation tillage, direct-seeded rice, *Sesbania* brown manuring, residue management, integrated nutrient management, agroforestry, and use of biochar are important management practices for improving the carbon sequestration. There is need of developing policy frameworks and strategies for promotion of CA in the region. This article reviews the emerging concerns due to continuous adoption of conventional agriculture systems and analyzes the constraints, prospects, policy issues, and research needs for conservation agriculture and carbon sequestration.

Keywords

Carbon sequestration · Conservation agriculture · Management practices

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9.1 Introduction

Warming of the climate system is unequivocal, which is now evident from observations of increases in global average air and ocean temperatures. Eleven years from 1995 to 2006 rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). The 100-year linear trend (1906–2005) of 0.74 [0.56–0.92]°C is larger than the corresponding trend of 0.6 [0.4–0.8]°C (1901–2000), and over the twenty-first century, average temperature of earth surface is likely to go up by an additional of 1.8–4 °C (IPCC 2007). This temperature increase can be attributed to the altered energy balance of the climate system resulting from changes in atmospheric concentrations of the greenhouse gases (GHGs). Among the principal components of radiative forcing of climate change, CO_2 has the highest positive forcing leading to warming of climate (Fig. 9.1). CO_2 has the least global warming potential among the major greenhouse gases, but due to its much higher concentration in the atmosphere, it is the major contributor toward global warming and climate change.

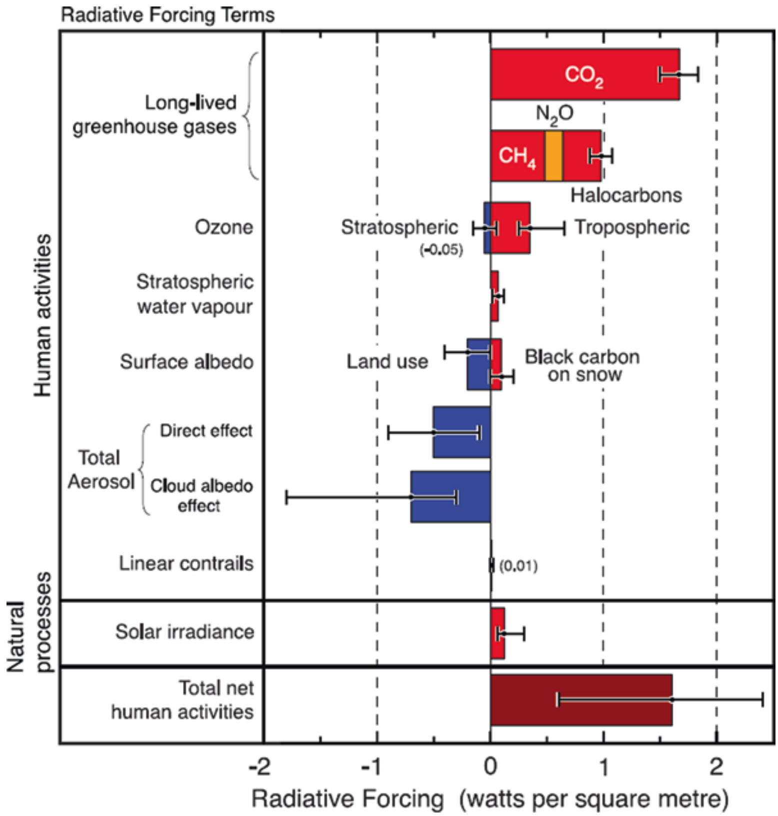


Fig. 9.1 Principal components of radiative forcing of climate change (IPCC 2007)

Carbon sequestration refers to storage of carbon in a stable solid form. It occurs through direct and indirect atmospheric CO_2 fixation processes. Direct soil carbon sequestration process occurs by inorganic chemical reactions that convert CO_2 into soil inorganic carbon compounds such as calcium and magnesium carbonates. Direct plant carbon sequestration occurs as plants photosynthesize atmospheric CO_2 into plant biomass; some of this plant biomass is indirectly sequestered as soil organic carbon (SOC) during decomposition processes. The amount of carbon sequestered at a site reflects the long-term balance between carbon uptake and release mechanisms. Many agronomic, forestry, and conservation practices, including best management practices, lead to a beneficial net gain in carbon fixation in soil. Soil gaining SOC is also generally gaining in other characteristics that enhance plant productivity and environmental quality. Increases in SOC generally improve soil structure, increase soil porosity and water holding capacity, as well as improve biological health for countless life forms present in soil. In general, there is a favorable interaction between carbon sequestration and various recommended land management practices related to soil fertility (e.g., adding mineral fertilizers, organic manures, sludges, and biosolids), tillage, grazing, and forestry.

9.2 Potential of Soil Carbon Sequestration in India

There is large number of options available for carbon sequestration in agro-ecosystems. Agricultural soil is a potential sink for sequestering atmospheric carbon. The carbon sequestration in soil is influenced by cropping systems and management practices. Rice-wheat is a dominant cropping system in the Indo-Gangetic plains which has positive as well as negative impacts on soil carbon sequestration. The implementation of effective land use and management practices, such as the conservation reserve program, forestry incentive program, integrated nutrient management and conservation tillage, and crop diversification, helps in increasing aboveground carbon sequestration and soil organic carbon.

Different processes are available for sequestering the atmospheric carbon. The potentiality of these different processes is varying in terms of the carbon sequestration. Soil carbon, atmosphere, and biotic pool contain 2500 Pg, 650 Pg, and 560 Pg, respectively. Soil erosion-controlling measures improve the soil carbon pool. Decline in soil quality, depleting soil organic carbon (SOC), and degradation of land resources due to erosion are the major impediments for future global food security. The productivity of some lands has declined by 50% due to soil erosion and desertification. In South Asia, annual loss in productivity is estimated at 36 million tons of cereal by water erosion. Eroded lands left unprotected lead to further erosion on-site and have greater off-site impacts. On the other hand, rehabilitation of eroded lands with conservation measures not only reverses the process of soil degradation but also improves the soil quality and converts these lands to potential carbon sinks (Lenka et al. 2012). In India, 146.82 million ha (about 45% of the land area) area is under various forms of land degradation. Degradation is particularly severe in regions with sloping and hilly terrains and those affected by unsustainable land management practices such as shifting cultivation. The sloping and hilly region of eastern India, called Eastern Ghats region, with a geographical area of 19.8 million ha is such an erosion-prone zone, having characteristic link of poor lands with people's poverty. For instance, the share of good quality soil in Orissa is one of the lowest, merely 10.4% of the land area of the state (Kumar 2011). It also happens to be the most backward Indian state with 46.4% of the population below poverty line. Shifting cultivation is prevalent in the hill slopes of the region. However, reduction in restoration or fallow cycle from 15 to 20 years to the current level of 2–3 years due to population pressure resulted in reduced farm output and increased land denudation. Mechanical measures for controlling soil erosion are not affordable by individual farmers because of extreme poverty condition. On the contrary, vegetative measures involving hedgerows and grasses are cost-effective and durable and find people's acceptance in this region as they offer multiple benefits such as for fodder and fuel wood. They are effective in low- to medium-slope ranges of arable lands. The species generally used are vegetative barriers of grass species or shrubs, and their performance for soil and moisture conservation depends upon their hedge-forming ability. Hedgerow intercropping though initially developed to restore the fertility of degraded soils in the tropics has been adopted in other regions not only for soil amelioration but also to provide additional products (e.g., fodder) and services (e.g., erosion control). Contour hedgerows are reported to promote the SOC storage because of a local effect under the hedge and also due to their anti-erosive effect (Walter et al. 2003). They are also effective in maintaining soil fertility and reducing the soil and nutrient losses in sloping lands. As the cultivated lands are scarce and fragmented, systems such as alley cropping are not popular in arable lands of the study region. The most acceptable measures are modification to field bunds through strengthening with vegetative measures with shrubs or grass species. Management practices such as conservation tillage and erosion control measures can improve the SOC stock and net C sink potential of sloping arable lands. Keeping in view the finite C sink capacity of soil (Chung et al. 2010), eroded lands, if put under erosion control measures, can be potential C sinks. Certain soil management practices such as application of manures and fertilizers and irrigation of semiarid and marginal lands for crop production, though increase the SOC status, are not net C sinks for CO_2 emission and do not contribute to the Kyoto Protocol because of the associated carbon costs. Even the advantages of no-till system over conventional tillage for SOC sequestration are questioned in recent studies; SOC buildup may be higher where the land cover is fully changed to pasture or agroforestry. But, subsistence farming, as prevalent in the region, may not permit pasture or agroforestry in agricultural lands used for growing food crops, even if they are eroded. On the other hand, keeping the land use unaltered, eroded lands can be treated with conservation measures to offset the on-site and off-site impacts on soil and environment.

In India different cropping systems are predominant and among them rice-wheat (RW) cropping system occupies 10.5 mha in Indo-Gangetic plain. Now, the productivity and sustainability of the RW system are threatened because of (a) the inefficient use of inputs (fertilizer, water, labor); (b) increasing scarcity of resources, especially water and labor; (c) changing climate; and (d) socioeconomic changes (urbanization, labor migration, preference of nonagricultural work, concerns about farm-related pollution, etc.). Therefore, there is a need for appropriate resource-conserving technologies (RCTs) to overcome these emerging constraints and to enhance system productivity, input use efficiency, and farm profitability on a sustainable basis. Besides this rice-wheat cropping system, several other cropping systems are available which can mitigate the problem arising from rice-wheat cropping system.

9.3 Processes Affecting Soil Organic Carbon Dynamics

- Aggregation: Increase in stable microaggregates due to the formation of organo-mineral complexes which encapsulate C and protect it against microbial activities (Fig. 9.2)
- Humification: To sequester 10,000 kg of C in humus, 833 kg of N, 200 kg of P, and 143 kg of S are needed
- Translocation into the subsoil: Transfer of SOC into the subsoil
- Formation of secondary carbonates
- Burial of SOC-laden sediments: Transport of SOC-enriched sediments to various depressional sites and/or aquatic ecosystems
- Plantation of deep-rooted plants

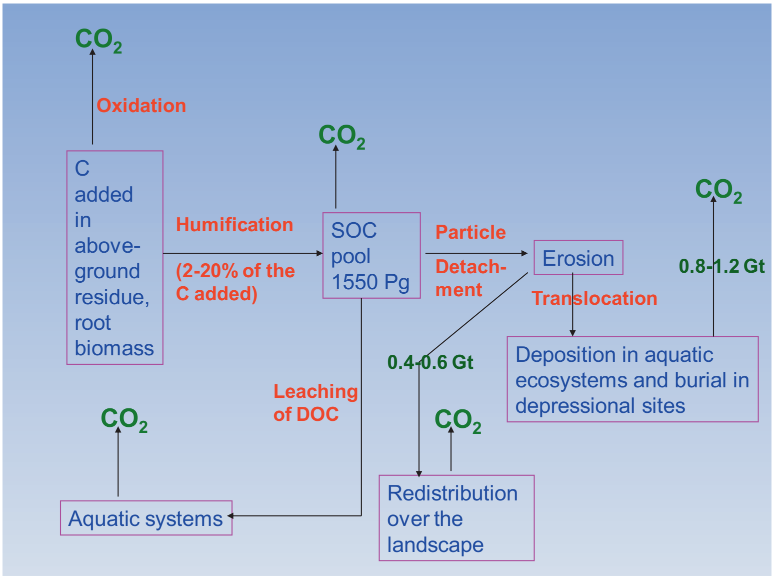


Fig. 9.2 Processes involved in soil organic carbon dynamics

9.4 Management of Soil for Increasing the Carbon Sequestration

There are different strategies for improving carbon sequestration and those are described below.

9.4.1 Laser Land Leveling

Laser land leveling (Fig. 9.3) alters fields having a constant slope of 0–0.2% using laser-equipped drag buckets and gives a smooth land surface (± 2 cm). Large horsepower tractors and soil movers equipped with global positioning systems (GPS) and/or laser-guided instrumentation help to move soil either by cutting or filling to create the desired slope. Laser leveling provides a very accurate, smooth, and graded field, which helps in saving of irrigation water up to 20% and improves the use efficiency of applied N.

9.4.2 Conservation Tillage (Zero/Minimal Tillage)

Conservation tillage (Fig. 9.4) is the collective umbrella term, commonly given to no-tillage, direct-drilling, minimum-tillage, and/or ridge-tillage, to denote that the specific practice has a conservation goal of some nature. Usually, the retention of 30% surface cover by residues characterizes the lower limit of classification for conservation tillage, but other conservation objectives for the practice include conservation of time, fuel, earthworms, soil water, soil structure and nutrients.

9.4.3 Bed Planting (Narrow/Broad Beds)

In bed planting (Fig. 9.5), crops are grown on the raised beds alternated by furrows. Beds are usually made at 0.6–1.0 m wide, and two to three rows of crops are sown on the beds. The furrow-irrigated raised-bed system (FIRBS) of wheat cultivation

Fig. 9.3 Laser land leveler

Fig. 9.4 Zero-tilled sowing

Fig. 9.5 Bed planting

has been shown to result in saving of seed by 25–40%, water by 25–40%, and nutrients by 25%, without affecting the grain yield (Das 2012).

9.4.4 Direct-Seeded Rice

Direct dry seeding of rice (Fig. 9.6) with subsequent aerobic soil conditions reduces overall water demand; saves labor, fuel, and time; and gives similar yield to transplanted rice, if weeds are effectively controlled. The technology does not affect rice quality and can be practiced in different ecologies such as upland, medium, and lowland and deepwater and irrigated areas (Pathak et al. 2012). Soil health is maintained or improved, and fertilizer and water use efficiencies increase. Therefore, it can be a feasible alternative to conventional puddled transplanted rice.

Fig. 9.6 Direct-seeded rice

Fig. 9.7 Brown manuring with *Sesbania*

9.4.5 *Sesbania* Brown Manuring

In brown manuring (Fig. 9.7), rice and *Sesbania* are sown together and allowed to grow for 25–30 days before knocking down *Sesbania* crop with 2,4-D ester salt at a rate of 0.40–0.50 kg ha^{-1}. The technology smothers weed, reduces herbicide use, lowers irrigation application, supplies 15–20 kg N ha^{-1} with a fresh biomass of 10–12 t ha^{-1}, facilitates better emergence of rice where soil crusting occurs, conserves moisture with brown mulch, improves soil C content, and increases farmers' income.

9.4.6 Leaf Color Chart (LCC)

Leaf color chart (LCC) (Fig. 9.8) is an easy-to-use and inexpensive tool for site-specific N management in crops/plants. Use of the LCC would promote timely and efficient use of N fertilizer in rice and wheat to save costly fertilizer and minimize the fertilizer-related pollution of surface and groundwater. It is a promising eco-friendly and inexpensive tool in the hands of the farmers.

Fig. 9.8 Leaf color chart

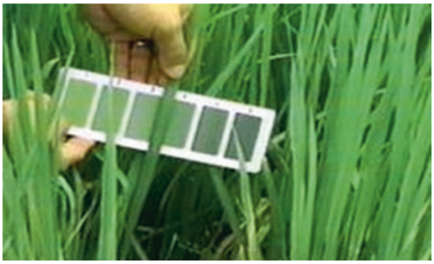


Fig. 9.9 Zero-till wheat with rice residues

9.4.7 Residue Retention for Mulch

Cropland offers a huge potential for sequestering C, especially when crop residues are managed properly. Permanent or semipermanent crop/plant residue cover on soil, which can be a growing crop or dead mulch, has a role to protect soil physically from the sun, rain, and wind and to feed soil biota/microorganisms that take over the tillage function and soil nutrient balancing. Crop residues (Fig. 9.9) significantly influence soil physical, chemical, and biological properties. It helps in water conservation through enhanced water infiltration, and reducing evaporation, and wind and water erosion.

9.4.8 Integrated Nutrient Management

The common recommended management practices leading to improve soil C sequestration under integrated nutrient management include the use of manures, compost, crop residues, and biosolids, mulch farming, conversation tillage, agroforestry, diverse cropping systems, and cover crops (Lal 2004). All these practices have the potential to alter C storage capacity of agricultural soil. The addition of fertilizer on a regular basis leads to an increase in SOC and soil microbial biomass and also alters soil C and N dynamics. Soil organic carbon is reported to increase by the continuous application of different combinations of N, P, and K, whereas it decreased in unfertilized soils. Accordingly, integrated use of FYM and fertilizers either maintained or improved SOC. The beneficial effect of incorporation of crops residues is more as compared to its burning or removal. The use of FYM/GM along with incorporation with crop residues has been found to be even more beneficial (Singh et al. 2007). The incorporation of organic manures and crop residues to soil on long-term basis helps in C sequestration, but the rate of C sequestration can vary with the type and nature of organic manure. The rate of change in SOM in agricultural soils is very slow and can take decades to centuries. The change in SOC fractions like labile carbon, water-soluble carbon, and microbial biomass C can be promptly influenced by changes in C inputs. Labile C is the fraction of total C that declines faster and is restored faster and is sensitive to best management practices.

9.4.9 Agroforestry in Carbon Sequestration

- *Direct role*: Carbon sequestration rates ranging from 1.5 to 3.5 Mg C ha^{-1} $year^{-1}$ in agroforestry systems.
- *Indirect role*: Agroforestry has also some indirect effects on C sequestration since it helps to reduce pressure on natural forests.

9.4.10 Arbuscular Mycorrhizal Fungi in Carbon Sequestration

It increases the surface area of roots and releases some organic acids. Mycorrhiza is responsible for better soil aggregation and improves the carbon sequestration in soil (Fig. 9.10).

9.4.11 Biochar in Carbon Sequestration

Biochar is a fine-grained and porous charcoal-like material produced by pyrolysis of biomass in an oxygen-limited condition. It acts as atmospheric carbon sink. A

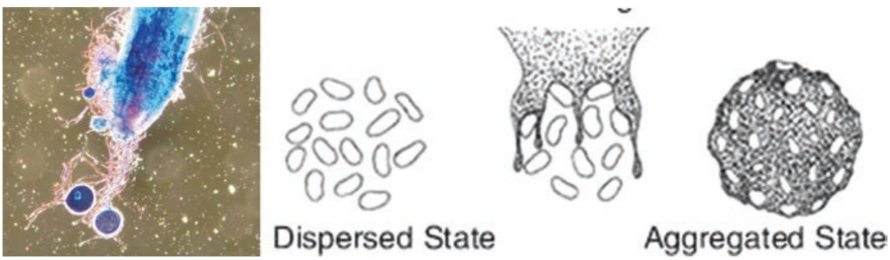
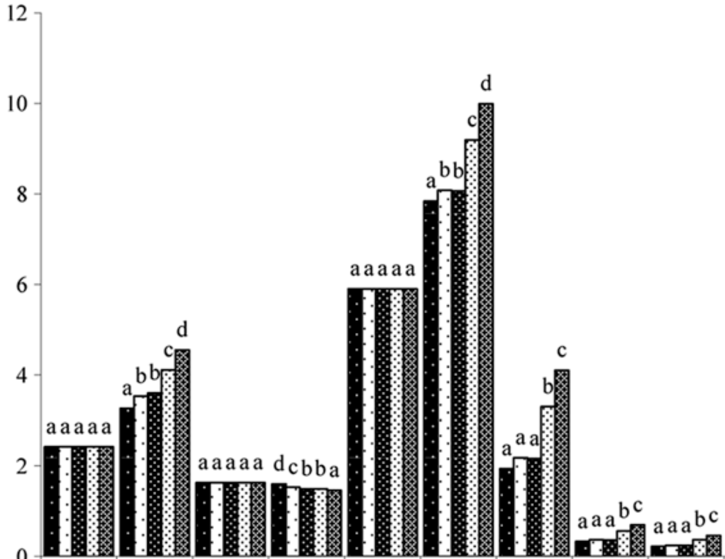


Fig. 9.10 Arbuscular mycorrhiza

significant portion of biochar is found in the organo-mineral fraction of soil suggesting that biochar forms interactions with minerals. Direct spectroscopic evidence for large particles showed biochar to be embedded within the mineral matrix.

The soil organic carbon pools and rate of carbon sequestration (Fig. 9.11) were significantly increased through balanced fertilization (100% NPK) when farmyard manure was applied in conjunction with 100% NPK in rice-wheat cropping system (Brar et al. 2012).

The bulk density of soil decreased with fertilization. This decreased was nonsignificant with imbalanced fertilizer application. However, balance fertilizer application (100% NPK) integrated with organic manure (FYM) proved best among all the treatments which significantly decreased the bulk density of surface soil (0–15 cm) over the imbalanced fertilizer treatments. The decrease in bulk density over the years could be attributed to the addition of root and plant biomass and to the conversion of some micropores into macropores due to cementing action of organic acids and polysaccharides formed during the decomposition of organic residues by higher microbial activities.



	SOC		Db		SOCP		CS	CS/CI	CSR
	1999	2008	1999	2008	1999	2008			
■ Control	2.42	3.26	1.63	1.60	5.90	7.84	1.94	0.33	0.22
□ 100% N	2.42	3.53	1.63	1.53	5.90	8.08	2.18	0.37	0.24
■ 100% NP	2.42	3.60	1.63	1.49	5.90	8.06	2.16	0.37	0.24
⊡ 100% NPK	2.42	4.11	1.63	1.49	5.90	9.19	3.30	0.56	0.37
▩ 100% NPK+FYM	2.42	4.55	1.63	1.46	5.90	9.99	4.10	0.69	0.46

Fig. 9.11 Effect of INM on soil organic carbon pool and sequestration rate

Table 9.1 Impact of tillage on SOC and greenhouse gas emissions in IGP

Region/state	Gross SOC stock (Mg C ha^{-1})		Associated GHGs (Mg C ha^{-1})	
Rice-wheat	Conv. till	No-till	Conv. till	No-till
Bihar	27.25	**33.52**	23.29	**23.33**
Haryana	24.14	**28.25**	32.10	**30.84**
Punjab	26.22	**30.68**	34.67	**33.52**
Uttar Pradesh	26.22	**30.68**	26.52	**25.17**
West Bengal	37.69	**46.35**	25.67	**24.76**
Maize-wheat				
Uttar Pradesh	24.14	**28.25**	8.65	**8.14**
Cotton-wheat				
Haryana	21.39	**25.03**	11.62	**10.87**
Punjab	24.14	**28.25**	13.16	**12.42**

A switch over from conventional to conservation tillage reduces carbon oxidation and thus emissions of CO_2. Grace et al. (2011) reported (Table 9.1) that the C sequestration potential of rice-wheat systems of India on conversion to no tillage is estimated to be 44.1 Mt. C over 20 years. Implementing no-tillage practices in maize-wheat and cotton-wheat production systems would yield an additional 6.6 Mt C. This offset is equivalent to 9.6% of India's annual greenhouse gas emissions. So long-term use of zero tillage improves the carbon sequestration in soil, and the three pillars of conservation agriculture – (1) minimum disturbance of soil, (2) permanent soil cover, and (3) crop rotations – are responsible for carbon sequestration.

Contour hedgerows and grass filter strips are important toward enhancing and sustaining productivity of sloping agricultural lands in medium- to high-rainfall regions. Averaged over 3 years of observation, the efficacy of *Indigofera* + grass filter strip was found superior (Table 9.2) with lowest runoff (8.9%) and soil loss (5.0 Mg ha^{-1}), followed by *Gliricidia* + grass filter strip (10.7% runoff and 6.3 Mg ha^{-1} soil loss). A consistently lower runoff and soil loss under *Indigofera* + grass filter strip was observed as compared to sole *Gliricidia* (Lenka et al. 2012). Higher SOC buildup is possible with complete land cover change with pastures or agroforestry systems due to increased rate of organic matter addition and retention. A SOC buildup rate of 3.5–4.5 Mg ha^{-1} year^{-1} could be possible with *Stylosanthes* and grass cover in degraded hillock sites as reported by Lenka et al. (2012). If lands are degraded, the response to restorative measures may be higher, and thus the C sequestration rate may be higher in the initial years before reaching a plateau, as compared to crop fields cultivated with management practices. For instance, the rate of change in SOC stock observed after 21 years in a rice-lentil cropping system varied from 0.043 to 0.462 Mg ha^{-1} year^{-1} (Srinivasarao et al. 2011), which is relatively lower as compared to the findings of this study. Agroforestry systems have the potential to sequester atmospheric carbon in trees and soil for maintaining sustainable productivity.

Pathak and Aggarwal (2012) reported some potential low carbon agricultural technologies (Table 9.3) for wheat production in the upper IGP. In case of wheat

Table 9.2 SOC sequestration rate potential of hedgerows and grass filter strips

	SOC sequestration rate (Mg ha^{-1} $year^{-1}$)		
Treatments	1 m	2 m	Plot
Indigofera	0.416	0.258	0.21
Indigofera + GFS	1.346	0.642	0.39
Gliricidia	0.942	0.692	0.336
***Gliricidia* + GFS**	**1.418**	**0.818**	**0.412**
Control	–	–	–
Sole GFS	0.318	0.19	0.128
Initial	0.046	0.112	0.088
CD ($P = 0.05$)	0.07	0.12	0.06

Table 9.3 Potential low carbon agricultural technologies for wheat production in upper IGP

Technology	GWP (CO_2 eq. ha^{-1})	Change in GWP over conventional practices (%)	B:C ratio with carbon credit	Area required for 1000 t CO_2 mitigation (ha)
Conventional	1808	–	–	–
Sprinkler	1519	−15.98	1.92	3460.2
Zero tillage	111	−93.86	2.26	589.3
INM	−171	−109.46	1.98	505.3
Organic	−1880	−203.98	2.01	271.2
Nitrification inhibitors	1663	−8.02	2.01	6896.6
SSNM	1696	−6.19	1.91	8928.6

crop, GWP reduction strength of the technologies ranged from 6% to 204% in the upper IGP. The GWP reduction was maximum with organic management and minimum with SSNM in wheat crop. But the B:C ratio of organic management was less than conventional management. Zero tillage and nitrification inhibitor technologies have shown higher values of B:C ratio than the conventional practice in the wheat crop.

9.5 Future Aspects

Detailed study about the interaction mechanisms of different GHGs should be evaluated.

- Long-term impacts of conservation agricultural practices on soil quality still need to be assessed.
- Future research should try to optimize the production of biochar and bio-oil by varying the feed stock quality and pyrolysis temperature to obtain the best possible combination for the purpose of carbon sequestration.

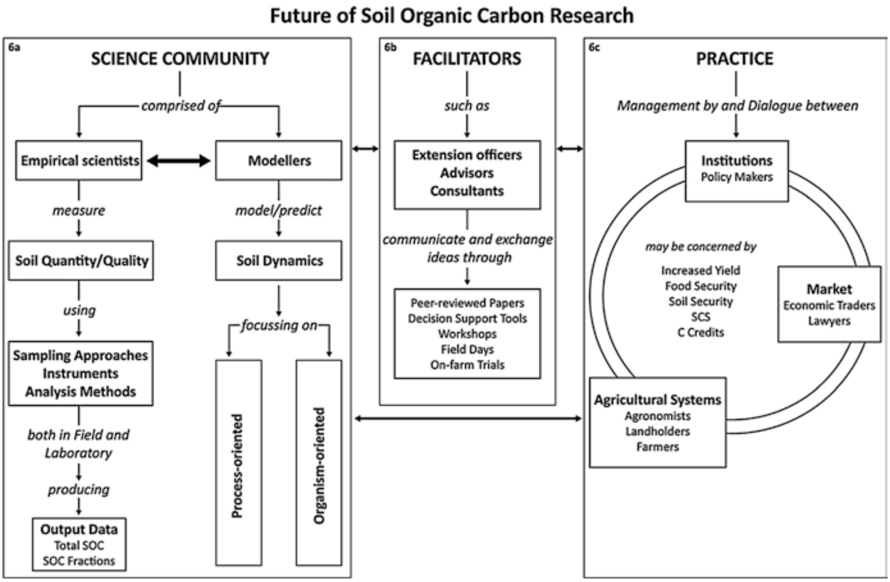


Fig. 9.12 Interdisciplinary approaches in carbon sequestration

- Any single process cannot improve the carbon sequestration in soil. There is need of multidisciplinary approach with scientist, farmers, and policy-makers to come together for mitigating this gravest threat.

Further research (Fig. 9.12) evaluating investment certainty is needed before recommending wide-scale dissemination of new technology for carbon sequestration and climate change mitigation.

9.6 Conclusion

- Soil carbon sequestration is an important cost-effective tool in climate change mitigation program.
- Conservation agriculture, organic farming, agroforestry, and biochar application can easily be adopted, and these practices have a positive impact on soil carbon sequestration and crop productivity.
- Crop diversification and intercropping could be viable options for enhancing carbon sequestration in changing climatic scenario.
- For sequestering the atmospheric carbon and for maintaining sustainability, integrated nutrient management has a pivotal role.
- Successful carbon sequestration in major production system in India requires knowledge, thorough understanding, proper channel to disseminate the technology, financial backup, and government efforts.

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10 Soil Carbon Dynamics in Relation to Soil Surface Management and Cropping System

Anand Prakash Singh, Satish Kumar Singh, Sumit Rai, and Maneesh Kumar

Abstract

A high soil organic matter content is synonymous with high-quality agricultural soils, as it affects many soil processes such as microbial activity, nutrient storage and release, water retention and soil aggregate formation. Due pressure on agricultural intensification with improved and science-based technology imposed a challenge to increase agricultural production without accentuating risks of greenhouse gas (GHG) emissions, hence affecting the terrestrial carbon balance, which has been a research focus for more than a half-century. Agricultural practices including soil surface management, crop rotation, residue and tillage management, fertilization, and monoculture affect soil quality, soil organic matter (SOM), and carbon transformation. Consequently, soil surface management practices and cropping system have a major effect on the distribution of C and N and the rates of organic matter decomposition and N mineralization.

Keywords

Carbon dynamics · Cropping system · Soil organic carbon · Surface management

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10.1 Introduction

The world cropland area is estimated at about 1338 million ha (mha) (FAO 1996), which provides more than 97% of the world's food. While the world population is increasing, its land resources are finite and unequally distributed. During the 1970s, the increase in food production in most developing countries was achieved by bringing new land under agricultural production. Presently, however, reserves of potentially arable prime agricultural land are rapidly dwindling. Potentially arable land is located within fragile or ecologically sensitive ecoregions, for example, tropical rainforest, acid savannahs, steep lands, and the West African Sahel.

Agricultural intensification is also an important factor influencing the soil C dynamics and greenhouse gas (GHG) emissions. Because of the disturbance and exposure of the soil surface due to tillage and soil management practices, cropland soils are prone to numerous degradative processes. Degradation of cropland soils is a serious issue (Oldeman 1994), with drastic adverse impacts on global food security and environment quality. Two important environmental impacts of soil degradation are declining water quality (Lal and Stewart 1994) and feedback to the greenhouse effect (Lal 1995). A report of the Intergovernmental Panel on Climate Change estimated that 20% of the greenhouse effect is related to agricultural activities. Therefore, agricultural intensification with improved and science-based technology is inevitable, especially for countries that presently practice predominantly resource-based or subsistence agriculture. Therefore, producers, scientists, and planners have a challenge to increase agricultural production without accentuating risks of GHG emissions. In this regard, the management of soil resources, in general, and soil organic carbon (SOC), in particular, is extremely important. World soil resources may be the key factors in the creation of an effective carbon sink and mitigation of the greenhouse effect.

Long-term experiments are very valuable for evaluating the influence of soil management practices on SOC stocks, and they allow the estimation of average rates of SOM decomposition and stabilization in different soils under distinct climatic conditions (Bayer et al. 2006). Based on these estimates, future scenarios of soil management and their role in building up SOM and mitigating increased atmospheric CO_2 can be forecasted (Bayer et al. 2000, 2006; Lal 2004). In a long-term experiment, Bayer et al. (2006) estimated the SOM decomposition rate under no-till conditions as being about half (0.019 year^{-1}) that found under conventional tillage (0.040 year^{-1}), but the humification coefficient was not affected by the tillage system (14.8% under no-till and 14.6% under conventional tillage). Based on these results, they estimated a minimal requirement of 8.8 mg ha^{-1} of annual C input by the crops under conventional tillage to maintain the original SOC stock in the soil. This C input requirement is more than twice the 3.1 and 3.56 mg ha^{-1} year^{-1} estimated by Kong et al. (2005) and Majumder et al. (2008) under conventional tillage systems on a Mediterranean soil from the USA and a subtropical soil from India, respectively. This difference in C input to maintain SOC levels highlights the favourable climatic conditions for microbial SOM decomposition under humid and hot subtropical climate in southern Brazil. Only half of that quantity was required in a no-till system (3.9 mg C ha^{-1} $year^{-1}$), however, thereby indicating the importance of the no-till system on the SOM stabilization and the improvement of soil quality in this subtropical region (Vieira et al. 2009).

10.2 SOM Dynamics in Tropical and Temperate Soils

Primary plant production and soil microbial activity are the two main biological processes governing inputs and outputs of SOM. The balance between them determines SOM turnover and is controlled by both biotic and abiotic factors. Climate, parent material, biota, topography, and time are the major controlling factors on the production and decomposition (by microorganisms) of SOM (Jenny 1941). Climate, parent material, and biota (e.g., vegetation) are the main factors that vary the most between tropical and temperate regions. It is generally assumed that organic compounds (Ayanaba and Jenkinson 1990) and SOM (Trumbore 1993) have a faster turnover in tropical than temperate soils due to enhanced decomposition under higher moisture and temperature regimes of the tropics. For example, Trumbore (1993) found a mean residence time (MRT) of C of 470 years in the surface layer (0–22/23 cm), estimated with radiocarbon, versus 990 years for a tropical and temperate soil. Another way to estimate C turnover and MRT relies in the difference in ^{13}C natural abundance between plants (and the SOM-C derived from them) with different photosynthetic pathways (Calvin cycle [C_3 plants] vs. Hatch–Slack cycle [C_4 plants]). A change in vegetation type results in a change to the ^{13}C natural abundance signature of the soil C, which enables one to calculate the proportion of C derived from the original vegetation. The turnover of C derived from the original vegetation is then calculated by using a first-order decay model. The higher turnover rate of tropical soils is primarily due to faster turnover rates of the slow C pool in tropical soils. Feller and Beare (1997) compared the incorporation rates of C derived from new vegetation in particle size classes (sand, silt, and clay) in temperate and tropical surface soils.

10.3 Agricultural Management Practices and Soil Carbon Dynamics

SOC is chosen as the most important indicator of soil quality and agricultural sustainability. Agricultural management including soil surface management, crop rotation, residue and tillage management, fertilization, and monoculture affect soil quality, SOM, and carbon transformation. The results confirm that SOM is not only a source of carbon but also a sink for C sequestration. Cultivation and tillage can reduce soil SOC content and lead to soil deterioration. Tillage practices have a major effect on the distribution of C and N, and organic matter decomposition rates and N mineralization. Proper adoption of crop rotation can increase or maintain the quantity and quality of SOM and improve soil chemical and physical properties. Appropriate application of fertilizers combined with farmyard manure could increase soil nutrients, as well as SOC content. Manure or crop residue alone may not be sufficient to maintain SOC levels. The type of crop influences SOC and soil function in continuous monoculture systems (Liu et al. 2005). SOC can be best preserved by rotation with reduced tillage frequency and also with additions of chemical fertilizers and manure. Knowledge and assessment of changes (positive or negative) in SOC status with time are still needed to evaluate the impact of various management practices.

The SOC content is a function of soil management, and change in management can alter SOC content. The rate of change (sequestration or release per unit time), however, depends on the net SOC content under the new management system. The net SOC content in soil depends on several interacting mechanisms, most of which are set in motion by addition of biomass to the soil. The use of a CT system affects C sequestration in soil through its effect on C dynamics, aggregation and soil structure, and interaction with cropping system. Carbon sequestration in soil depends on two factors:

(i) Turnover time and
(ii) Physical or chemical protection against microorganisms and soil erosion (Carter 1995).

10.3.1 Effect of Aggregation on Soil C Dynamics

A principal mechanism of that has a direct effect on C dynamics in soil is through the formation of stable microaggregates. The higher the SOC is, the more and stable are the aggregates. Microaggregates are developed around decomposing particulate organic matter because of the formation of humic polymers and organo-mineral complexes (Beare et al. 1994a, b). These microaggregates consist of clay particles, clay domains, hydrous oxides of Al and Fe, and organo-mineral complexes. Therefore, a strong correlation exists between aggregation and SOC (Table 10.1; Douglas and Goss 1982; Chaney and Swift 1986; Haynes et al. 1991). However, the degree of correlation depends on climate, soil type, texture, clay mineralogy, and cropping history. In pasture soils with high SOC, a substantial portion of SOC is not involved in aggregation, and the correlation is often low. In soils with low SOC, mechanisms of aggregation are different, and the correlation coefficient of SOC with aggregation is also low. Soils with higher clay content usually require more SOC content for maintaining a desired level of aggregation and aggregate stability than those with low clay content (Douglas and Goss 1982). Differences in clay content also cause differences in soil moisture regime. Aggregate stability often increases with decreasing soil moisture content (Perfect et al. 1990). Similar to the degree of aggregation, aggregate stability is also related to SOC content. Water-stable aggregates usually contain more SOC than those that are unstable (Elliott 1986). Source of crop residue is also a factor in aggregate stability. Skidmore et al. (1986) observed that application of sorghum (*Sorghum bicolor*) residue produced more stable aggregates than that of wheat (*Triticum aestivum*) residue.

Table 10.1 Relationship between aggregation and soil organic carbon (×) content

Regression equation	Correlation coefficient	Reference
% WSA (16% clay) = 2.0.× − 11.5	r = 0.86	Douglas and Goss (1982)
% WSA (39% clay) = 1.33× − 14.0	r = 0.73	
%WSA (49% clay) = 1.54.× − 58.0	r = 0.95	
MWD (mm) = 0.24.× + 0.31	R^2 = 0.86	Haynes et al. (1991)
%WSA > 2 mm =21.5× − 20.3	R^2 = 0.93	Tisdall and Oades (1980)
%WSA > 0.25 mm = 158.9× − 9.5	R^2 = 0.87	Tyagi et al. (1982)
%WSA > 20 pm = 74.3 + 6.3 pnX	R^2 = 0.58	Dalal and Bridge (1995)
Dispersible clay (%) = 2.39–0.42 x	R^2 = 0.53	

x organic carbon (%), *WSA* water-stable aggregation, *MWD* mean weight diameter

10.3.2 Effect of Surface Management on Soil C Dynamics

Tillage is the most important surface management practice that is used to mix and aerate the soil and to incorporate cover crops, crop residue, manure, fertilizers, and pesticides into the rooting zone (Acquaah 2002). Soil tillage management can affect factors controlling soil respiration, including substrate availability, soil temperature, water content, pH, oxidation–reduction potential, kind and number of microorganisms, and the soil ecology (Robinson et al. 1994, Kladivko 2001). Beare et al. (1994b) indicated that tillage improved short-term CO_2 evolution and microbial biomass turnover and accelerated organic C oxidation to CO_2 not only by improving soil aeration but also by increasing contact between soil and crop residues and by exposing aggregate-protected organic matter to microbial activities. Tillage also exposes organic C in both the inter- and intra-aggregate zones and that immobilized in microbial cellular tissues to rapid oxidation (Roscoe and Burman 2003). This is due to the improved availability of O_2 and the exposure of more surfaces for decomposition, thereby stimulating increased microbial activity (Beare et al. 1994b; Jastrow et al. 1996). Conventional tillage significantly reduces biological diversity in surface soil.

No-till (NT) management can increase SOM, both through constant addition of plant residues on the soil surface and through a decrease in its decomposition rate (de Souza Nunes et al. 2011). Positive results in SOM accumulation under NT systems are related to a decrease in soil C emissions to the atmosphere (Bayer et al. 2006), a decrease in soil C lost via surface runoff, and an increase in soil C as a result of crop rotations (Conceição et al. 2013). An important effect to be emphasized is the possibility of recovering lost SOC fractions by adopting high biomass-C inputs (>7 mg ha^{-1}) in cropping systems under NT management (Tivet et al. 2013), but the impact of NT management on SOC is soil and site specific (Christopher et al. 2009; Mishra et al. 2010).

Increased C storage has been usually observed in soils under conservation tillage, particularly with NT (Unger 1991; Zibilske et al. 2002). A widespread adoption of conservation tillage could result in net increases in C sequestration in farmlands, reversing the decline caused by intensive tillage practices used for decades (Campbell et al. 2001). The values of SOC and total N were the highest in the minimum tillage and residue-retained treatment and the lowest in conventional tillage and residue-removed treatment. Tillage reduction from conventional to minimum and zero levels along with residue retention increased the proportion of macroaggregates by 21–42%. Active microbial biomass and C mineralization were higher under NT than under conventional tillage in the top 5 cm of the soil profile (Alvarez and Alvarez 2000). Dao (1998) indicated that cultivation, high temperature, and a semiarid climate accelerated organic carbon loss and weakened soil structure in the Southern Plains, and tillage and residue incorporation enhanced C mineralization and atmospheric fluxes, suggesting that the intensity of tillage should be decreased to reduce C loss. Tillage operations control the soil environment strongly by altering the soil geometry. These effects influence many physical, chemical, and biological characteristics of the soil and thereby the conditions for crop growth. Alvarez and

Alvarez (2000) stated that conservation tillage, particularly no-tillage, induced changes in the distribution of organic pools in the soil profile. SOC gains under no-till were about 250 kg ha^{-1} $year^{-1}$ greater than tilled systems regardless of cropping frequency in Canadian prairies under semiarid conditions (Campbell et al. 2005). Within the surface 7.5 cm, the no-till system possessed significantly more SOC (by 7.28 mg ha^{-1}), particulate organic matter C (by 4.98 mg ha^{-1}), potentially mineralizable N (by 32.4 kg ha^{-1}), and microbial biomass C (by 586 mg ha^{-1}), as well as greater aggregate stability (by 33.4%) and faster infiltration rates (by 55.6 cm h^{-1}) relative to the conventional tillage (Liebig et al. 2004).

After 11 years of different tillage operations in Chinese Mollisols, Liu et al. (2005) reported that integrated tillage, where tillage operation varied with each crop in the rotation (i.e. mouldboard plough for wheat, deep chisel for corn, and rotary plough for soybean), had the highest levels of SOC and N in the upper soil layer in the Chinese Mollisol. Mouldboard ploughing had the lowest level of SOC and N content in the profile, with the largest reduction being in the top two layers. The SOC and N contents at 16–30 cm in the rotary ploughing and conventional tillage were higher than in the depth between 0 and 15 cm, indicating that more root residues were incorporated into this layer. This result was consistent with mixing of organic matter by ploughing but opposite to results with no-tillage practice or conservation tillage (Arshad et al. 1990; Dalal et al. 1991). In general, integrated tillage appeared more effective in maintaining SOC and, maybe, soil productivity. Yang et al. (2003a) indicated that the conversion from conventional tillage to conservation tillage, particularly no-till, at an annual rate of 2% could reverse the loss of SOC in Chinese Mollisols within 20 years. However, this positive effect of conservation tillage on SOC in the black soil area of China was only effective in severely eroded soil or in the farmland with slope, and it was not effective in flat and low-damp farmland. It is thus evident that tillage practices have a major effect on soil properties, distribution of C and N, and organic matter decomposition rate and N mineralization. The adoption of conservation tillage for reversing the decline of SOC in agricultural lands is possible in the black soil area of China, as it has been in many other countries. Continuous monitoring of long-term changes in the SOC and soil quality under conservation tillage in different agroecological zones is essential. There is also a need to obtain more data on long-term effects of different tillage systems on C and N mineralization and immobilization in field situations.

10.3.3 Effect of Crop Rotation on Soil C Dynamics

Crop rotation could have a major impact on soil health due to emerging soil ecological interactions and processes that occur with time. These include enhancing soil structural stability and nutrient use efficiency, increasing crop water use efficiency and SOM levels, providing better weed control, and disrupting insect and disease life cycles (Carter et al. 2002, 2003). Crop rotations also increase yields and enhance N availability when nitrogen-fixing legumes are included (Galantini et al. 2000, Miglierina et al. 2000). They are more effective at reducing long-term yield variability than monoculture systems, and they increase total soil C and N concentrations over time, which may further improve soil productivity (Varvel 2000; Kelley et al. 2003). Carter et al. (2003) observed that losses of SOC during a 11-year period ranged from marginal (4%) for rotations with Italian ryegrass, to significant (16%) under barley rotation, which illustrates the importance of C inputs in maintaining SOM levels. Blair and Crocker (2000) studied the effect of different rotations, including legumes and fallows on soil structural stability, unsaturated hydraulic conductivity, and the concentration of different C fractions in a long-term rotation trial, and found that the inclusion of legume crops in the rotation resulted in an increase in labile carbon concentrations compared with continuous wheat or a long fallow period.

While comparing maize–rice and rice–rice cropping systems, Witt et al. (2000) found that the replacement of dry season rice by maize resulted in reduction of soil C and N due to a 33–41% increase in the estimated amount of mineralized C and N during the dry season. As a result, 11–12% more C sequestration and 5–12% more N accumulation was observed in soils continuously cropped with rice than in the maize–rice rotation, with the greater amounts sequestered in N-fertilized treatments. Their results documented the capacity of continuous, irrigated rice systems to sequester C and during relatively short time periods. Yang and Kay (2001) found that continuous alfalfa had the greatest average SOC concentration (0–40 cm), and rotations had more SOC concentration than continuous corn. Huggins et al. (1998) found that in the treatments containing both crops, the aboveground C returned to the soil from corn was on average 40% higher than the C returned from soybean. Although more aboveground C was returned with corn, SOC did not differ with crop sequence or depth. Smith et al. (2000) developed a dynamic soil quality model to evaluate optimum cropping systems in the northern Great Plains and found that a crop production system with continuous spring wheat and direct planting was the most profitable system and had lower soil erosion and higher soil quality attributes.

From a 9-year crop rotation experiment in the Chinese Mollisol, Liu et al. (2003) found that the SOC in the treatments of the wheat–sweet clover and wheat–soybean with addition of pig manure or wheat straw was significantly higher than the commonly used wheat–soybean rotation (wheat straw removed), particularly in the 0–17 cm horizon. For the overall SOC concentration (means of all three horizons), soil with addition of wheat straw was 22% greater than that of wheat–soybean alone, and similar differences occurred for overall SOC in the wheat–sweet clover rotation and wheat–soybean rotation with addition of pig manure. Liu et al. (2003) also showed that the wheat–sweet clover rotation not only increased the SOC content in all soil depths but also had a decrease in soil bulk density.

The total SOC storage (total of all three horizons) increase was 10.7% for wheat–soybean rotation with manure addition and 14.4% for wheat–soybean rotation with wheat straw addition. The total amount of SOC increase (11,700 kg ha^{-1}) in wheat–soybean rotation with addition of wheat straw would correspond to sequestration of approximately 43 tonnes of CO_2 ha^{-1} from atmosphere. Fang et al. (2005) indicated that improved crop rotation strategies can increase the organic carbon reserve and improve soil structure and quality of the black soils, thereby sequestrating CO_2 from the atmosphere and thus mitigating against the greenhouse effect. Further, the adoption of appropriate crop rotations to increase the quantity and quality of soil organic matter and hence soil chemical and physical will help to ensure the long-term sustainability of agriculture in the world.

10.3.4 Effect of INM on Soil C Dynamics

Integrated use of fertilization sources is one of the most important practices in crop production for its influence on soil nutrient availability. Ishaq et al. (2002) showed that fertilizer application significantly improved soil P and K concentrations, and the concentrations of N, P, K, and SOC were higher in the plough layer than in the subsoil. Nitrogen is the nutrient most limiting to crop production throughout the world and is usually applied to soil in a large quantity. Since the N applied to soil is subject to losses by volatilization, immobilization, denitrification, and leaching, it is necessary to compensate this by adjusting the fertilizer management. Fertilizer use efficiency will also change with changes in tillage management. Malhi et al. (2001) indicated that placing the fertilizer in a band reduced contact with soil microorganisms and reducing immobilization of both ammonium (NH_4^+) and nitrate (NO_3^-). Banding also slowed down the conversion of urea to NH_3 and NH_4^+ to NO_3^-, which reduced N losses by volatilization and leaching. Reducing tillage intensity modified both the crops' N demand due to changes in yield potential and supply of N due to changes in N cycling and losses. The N fertilization effects on SOC were most evident when stover was returned to no-till plots (Clapp et al. 2000). Farmyard manure application and recycling of crop residues with NPK supplementation are efficient ways of fertilizing maize and wheat. With high levels of NPK fertilizer use, significantly higher yields were obtained especially in rotations, where the proportion of maize or wheat was 50% or higher (Berzsenyi et al. 2000).

After 16 years of three fertilization treatments in crop rotation, Liu et al. (2005) reported that the profile average SOC content (0–90 cm) was only 0.9%, 4.1%, and 8.6% higher for manure, chemical fertilizers, and manure plus fertilizers, respectively, than that with no fertilizer application or control in the Chinese Mollisols. However, SOC at the 0–15 cm soil depth was 6.2%, 7.7%, and 9.3% higher with manure, chemical fertilizers, and manure plus fertilizers, respectively, than with no fertilizer application. These results indicated that the annual rate of decline rate of SOC in the 0–15 cm layer without fertilizer was not very high ($<0.58\%$ year^{-1}) when a well-designed crop rotation was used. The results were comparable to data from long-term experiments in Denmark and England that revealed a slow change in SOC levels under temperate conditions in response to changes in different land uses (Christensen and Johnson 1997). Yang et al. (2003b) further indicated that the SOC content could be maintained at a relatively stable level under sufficient chemical fertilizer application without return of manure and crop residue conditions, and SOC content was increased with application of chemical fertilizer and manure combination. This indicates that corn residue and exudates could keep SOC equilibrium under current production level and management practices.

Liu et al. (2005) also reported for the Chinese Mollisols that manure alone did not increase the N content in the soil profile compared to that of no fertilizer application in the crop rotation. However, chemical fertilizers and manure plus fertilizers significantly increased N content, particularly at 0–15 and 16–30 cm soil layers. Francioso et al. (2000) also reported that after 22 years, SOC and N differed significantly for all treatments where the amendments with cattle manure markedly increased the SOC and N contents, while cow slurries and crop residues decreased SOC and N contents. The maximum reduction in SOC and N contents was found in the unamended plots after 22 years. Reeves (1997) also suggested that SOM can be preserved only by 'ley' rotations with reduced tillage frequency. Adequate application of fertilizers combined with farmyard manure could increase soil nutrients and SOC content in the Chinese Mollisols. Manure or crop residue alone could not maintain SOC levels, and SOC can only be preserved by rotation with reduced tillage frequency and additions of chemical fertilizers and manure.

10.4 Conclusion

World soils, large reservoir of reactive carbon, moderate the global C cycle, atmospheric chemistry, radioactive forcing, and ecosystem services; as such, soil C sequestration is very important in limiting global warming to 2 °C. Therefore, soil carbon management will be an increasingly important strategy during the coming decades because of its numerous co-benefits as a natural fix to climate change. Among uncertainties are emissions from soils and permafrost, the CO_2 fertilization effect, weathering of silicate, the fate of eroded carbon, efficiency of natural sinks, permanence of carbon sequestered in soil, and measurements of changes in soil C over short periods. In addition to being a cost-effective option of reducing the net anthropogenic emission of CO_2, restoring the soil carbon pool is also essential to achieving global food security, improving renewable freshwater supply and quality, and enhancing biodiversity. Food insecurity, affecting approximately 1 billion people globally, can be realized through enhancing soil quality by restoring the soil carbon pool to above the critical level of 1.2–1.5% in the root zone. Adoption of proven technologies such as soil surface management and best agricultural management practices can sequester carbon at the rate of 50–500 kg ha^{-1} $year^{-1}$ in grazing lands, 500–1000 kg ha^{-1} $year^{-1}$ in forestlands and 5–10 kg ha^{-1} $year^{-1}$ of pedogenic carbonates in arid lands. Soil C is stabilized through deep placement, interaction with clays, and formation of stable aggregates. Adoption of recommended practices can be promoted by payments for ecosystems services. Researchable priorities include understanding trends of principal drivers, quantifying feedbacks related to climate change, and impacts on ecosystem services.

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Part II

Conservation Agriculture and C Sequestration

11 Conservation Agriculture and C Sequestration in Tropical Regions

Uttam Kumar Mandal, K. L. Sharma, D. Burman, Subhasis Mandal, and B. Maji

Abstract

This chapter discusses the status, problems and prospects of conservation agriculture (CA) in the smallholder farming system in the tropics. The resource conservation technology in the form of no-till wheat after rice in the Indo-Gangetic Plains (IGP) is picking up by alleviating system's constraints through advancing wheat planting, which addresses the issues of terminal heat stresses, helps control of weed (*Phalaris minor*), reduces production costs and saves water and energy. The analysis shows that conservation agriculture (CA) in the broader context of resource conservation technology not only improves soil health but also gives higher net returns per unit of land to the farmers. The major constraints for practising CA in these regions include insufficient amounts of residues due to water shortage and degraded nature of soil resources, competing uses of crop residues, resource-poor smallholder farmers and lack of in-depth research. There is a need for strategic long-term research, particularly in the rainfed regions for exploring the prospects for the adoption of CA before it could be taken to the farmers' doorsteps.

Keywords

Carbon sequestration · Conservation agriculture · Crop rotation · Residue retention · Tillage · Tropical region

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11.1 Introduction

No-till (NT) or reduced-till (RT) farming practiced in combination with crop residue incorporation as well as mulch and growing a cover crop in the rotation cycle, broadly called conservation agriculture (CA), is widely recognized as a viable alternative to conventional cultivation for making agriculture a part of the solution in improving the environments and sustaining use of natural resources. The benefits of conservation agriculture such as erosion control, water conservation, nutrient cycling, time saving, reduction in use of fossil fuels, less wear and tear of machinery, stable and sustainable crop yields and soil carbon sequestration along with an additional income stream for farmers through trading of carbon credits have been documented since the 1960s (Lal 2007a; Lal 2018). Yet, until 2013, CA was practiced in 157 M ha, merely 11% of the global cropland area (FAO 2014), mostly in the USA, Brazil, Canada, Chile, Paraguay, Australia and other developed countries. These regions are characterized by large-scale mechanized mono-cropping of corn, soybeans, wheat and other row crops.

The adoption of NT farming is practically negligible by resource-poor small landholders of Sub-Saharan Africa (SSA), South and Southeast Asia, Central America, the Caribbean and the Pacific Islands. In India, research on conservation tillage practices started in the 1970s. Still the total cultivated area under conservation tillage is less than 1% of the total cultivated area, mainly confined to the rice–wheat system in the Indo-Gangetic Plains (IGP). In India, other than NT, many resource-saving agricultural management practiced under traditional farming systems qualify in the definition of CA. Although major research and development efforts in the Green Revolution era in the country focused on enhancing production and productivity of selected food grains and other crops, the new challenges demand that issues of efficient resource use and resource conservation receive high priority to ensure sustained productivity and meet the emerging needs (Abrol et al. 2005). The CA has assumed importance in view of widespread resource degradation and the need to reduce production costs, increase profitability and make agriculture more competitive. While for developed economies like the USA, saving the surface soils might be the prime driver for adoption of CA, for the developing economies, besides protecting the lands, other additional emerging agrarian concerns such as shortage of water, labour and energy, deteriorating soil health, and climate change are also important (Kumar et al. 2011).

11.2 Conservation Agriculture Worldwide

Soil preparation by tillage has always been an important component of traditional agriculture. A wooden plough, called an ‘ard’ was probably developed in Mesopotamia about BC 4000–6000. Over time, the ard evolved into the well-known ‘Roman plough’ around 1 AD (Fowler 2002). The plough with iron share was widely used in Europe at about the fifth century AD, and the Roman plough evolved into a soil-inverting plough between the eighth and the tenth centuries AD. The major advance before 1000 AD was the development of the heavy plough like coulter designed to cut a thin strip in the turf. Historically, the mouldboard plough was an essential tool for the early pioneers in settling the prairies of central and western USA and Canada. The mouldboard plough has been a symbol of US agriculture since about 1850. It allowed the farmer to create a soil environment in which grain crops could thrive and meet the needs of the increasing population (Lal 2007b).

The use of ploughs expanded rapidly with the introduction of the steam horse in 1910. As new technology evolved, farmers in the USA got equipped with some of the largest equipment in the world. Use of powerful tractors and large machinery along with fertilizers and improved varieties enhanced crop yields by a factor of 3–5 during the early twentieth century. But the euphoria of intensive tillage led to widespread severe soil erosion and environmental degradation, culminating in the Dust Bowl of the 1930s in America's Great Plains region. As early as the late 1940s, attention changed towards the development of systems that required less tillage. Since the 1950s, there had been a gradual transition from the mouldboard plough to various forms of conservation tillage to no-till with minimum soil disturbance throughout the world. Minimum tillage researchers advocated reduced amounts of tillage in the late 1940s and began to use plant growth regulators for post-emergence weed control. The no-till movement got impetus with the invention of 2,4-D after the Second World War and development of paraquat by Imperial Chemical Industries (ICI) in the UK (Hood et al. 1963, 1964). The development of a non-selective contact weed control material that became commercially available in the mid-1960s was a major breakthrough in making conservation tillage work.

By the 1970s, a wide range of herbicides was available, and rapid progress was made to develop machinery to effectively planting in soils, with little or no tillage and with minimal disturbance of residues remaining at the soil surface. By the 1990s, there was a wide range of machinery available specifically developed for conservation tillage. This included planters, disks, sprayers and tillage equipment, especially designed to leave residues at or near the soil surface. The 1985 and 1990 Farm Bills had strong conservation tillage provisions that require any farmer growing annual crops on highly erodible land to have a conservation plan in place by 1990 and fully implemented by 1995 in order to be eligible for commodity price supports. The timing of successful development of conservation tillage technology was ideal for the US farmers. The no-till area increased from 7 Mha in 1990 to 35.6 Mha in 2009, making the USA a pioneer in adopting CA systems (Jat et al. 2012). The spread of CA in the USA has been the result of a combination of public pressure to fight against erosion, a strong tillage and conservation-related research and education back up and public incentives to adopt reduced tillage systems. Other countries where CA practices have been widely adopted for many years include Australia, Argentina, Brazil and Canada. No tills have spread rapidly in the production of corn and soybeans in other parts of the Western hemisphere, covering 31.8 Mha in Brazil, 29 Mha in Argentina and 18 Mha in Canada (Table 11.1) (Source: FAO; http://www.fao.org/ag/ca/6c.html). Australia, with 17.6 Mha under NT, ranks fifth among the leading countries adopting the no-till system. The continuous adoption of NT by farmers in different Brazilian regions has been due to

Table 11.1 Extent of adoption of conservation agriculture worldwide by country in the 2008/09 and 2013 updates (FAO 2014)

Country	CA area 000ha 2008/09 update	CA area 000 ha 2013 update
USA	26,500.00	35,613.00
Brazil	25,502.00	31,811.00
Argentina	19,719.00	29,181.00
Canada	13,481.00	18,313.00
Australia	12,000.00	17,695.00
China	1330.00	6670.00
Russia	–	4500.00
Paraguay	2400.00	3000.00
Kazakhstan	1300.00	2000.00
India	–	1500.00
Uruguay	655.10	1072.00
Spain	650.00	792.00
Bolivia	706.00	706.00
Ukraine	100.00	700.00
Italy	80.00	380.00
South Africa	368.00	368.00
Zimbabwe	15.00	332.00
Venezuela	300.00	300.00
Finland	200.00	200.00
France	200.00	200.00
Zambia	40.00	200.00
Germany	354.00	200.00
Chile	180.00	180.00
New Zealand	162.00	162.00
Mozambique	9.00	152.00
United Kingdom	24.00	150.00
Colombia	102.00	127.00
Malawi	–	65.00
Turkey	–	45.00
Mexico	22.80	41.00
Moldova	–	40.00
Slovakia	10.00	35.00
Kenya	33.10	33.10
Portugal	25.00	32.00
Ghana	–	30.00
Syria	–	30.00
Tanzania	–	25.00
Greece	–	24.00
DPR Korea	–	23.00
Switzerland	9.00	17.00
Iraq	–	15.00
Sudan	10.00	10.00
Tunisia	6.00	8.00

(continued)

Table 11.1 (continued)

Country	CA area 000ha 2008/09 update	CA area 000 ha 2013 update
Madagascar	–	6.00
Hungary	8.00	5.00
Morocco	4.00	4.00
Uzbekistan	–	2.45
Lesotho	0.13	2.00
Azerbaijan	–	1.30
Lebanon	–	1.20
Kyrgyzstan	–	0.70
The Netherlands	–	0.50
Namibia	–	0.34
Belgium	–	0.27
Ireland	0.10	0.20
Total	106,505.23	156,980.96
% difference		47.39

cost reduction through savings on fuel, labour and machinery and soil erosion control (Machado and Silva 2001). In Brazil, CA adoption has increased with time, and the area under NT increased exponentially, and more than 60% cultivated land is under CA. Spread of CA systems is relatively less in Europe as well as in South East Asia including China and Africa. The latest statistics in 2015 on adoption of CA worldwide cover an area of 156.99 Mha (Source: FAO; http://www.fao.org/ag/ca/6c.html).

11.3 Conservation Agriculture Practice in India

In India, research on NT started almost three decades ago during the 1970s. But the adoption of CA did not get the momentum due to technical difficulties such as lack of adequate planting equipment and the difficulty in controlling the weeds chemically. In 1991, a first prototype of the Indian NT seed drill was developed at G.B. Pant University of Agriculture and Technology, Pantnagar (Thakur 2005). In 1992–1993, a collaborative programme for further development and commercialization of NT was initiated with small-scale industries in Punjab. After considerable investment of resources and several design changes, the first NT seed drill was made available for field-testing within 12 months.

In the early 1990s, concerns over the sustainability of the rice–wheat cropping system started emerging, which led to the launch of the rice–wheat consortium (RWC), a Consultative Group for International Agricultural Research (CGIAR) initiative in partnership with the national research system of the countries of the region (Bangladesh, India, Nepal and Pakistan) in 1994 (Erenstein and Laxmi 2008). Over the past 10 years, the RWC developed and promoted a number of resource-conserving technologies to increase farm-level productivity, conserve natural resources and limit negative environmental impacts.

In India, the rapid and widespread adoption of NT started in Haryana State during the late 1990s (Malik et al. 2005). In Haryana, NT helped farmers to address two constraints: (1) the late sowing of wheat due to the prevalence of late-maturing fine-grained rice varieties (e.g. basmati) and long turnaround time and (2) the widespread incidence of the weed *Phalaris minor*. Several organizations played a key and complementary role in spreading the NT technology, including the Haryana Agricultural University, the Directorate of Wheat Research (Indian Council of Agricultural Research [ICAR]) and the State Agricultural Department aided by the various sponsored R&D projects from the RWC, International Maize and Wheat Improvement Center (CIMMYT), ICAR and the Australian Centre for International Agricultural Research (ACIAR). The state government also supported NT in the form of some 25% subsidy on the purchase cost of a new NT drill, which enhanced farmers' access to the machine. NT, as applied to the rice–wheat systems in the IGP, has three distinctive features that distinguish it from related systems elsewhere (Erenstein 2002, 2003). First, NT is typically only applied to the wheat crop in the double-cropped system, with the subsequent rice crop still intensively tilled. Second, NT wheat after rice does not necessarily entail an increased reliance on herbicide, reflecting that paddy rice fields are relatively weed free at harvest time. Third, NT wheat does not necessarily imply the retention of crop residues as mulch.

In 2003–2004, the total estimated wheat area under CA was 8,20,000 ha in the Indian IGP. Most of the adoption was concentrated in Haryana (46%), Punjab (26%) and west Uttar Pradesh (UP) (21%). These areas are all in the north-west IGP and characterized by high agricultural productivity. The CA adoption is yet to pick in the eastern part of UP and Bihar, where agricultural productivity was comparatively lower. In 2004–2005, the total estimated NT + RT area was 1.6 Mha in the Indian IGP (Shoran 2005).

To date, the most widely adopted resource-conserving technology in the IGP of South Asia has been NT wheat after rice, particularly in India. Erenstein and Laxmi (2008) highlighted several benefits of CA after the adoption of NT in the region. NT wheat after rice generates substantial benefits at the farm level (US\$97 ha^{-1}) through the combination of a 'yield effect' (a 5–7% yield increase, particularly due to more timely planting of wheat) and a 'cost savings effect' (US\$52 ha^{-1}, particularly tillage savings). The reduced turnaround time was reported to have allowed wheat planting to be advanced by 7–10 days in Haryana and by 8–25 days in Bihar and 10 days in eastern UP. NT is generally reported to save irrigation water in the range of 20–35% in the wheat crop compared to CT (conventional tillage), reducing water usage by about 10 cm ha^{-1} or approximately 1 M Lha^{-1}. The savings arise because, with NT, it is possible to sow wheat just after the rice harvest making use of residual moisture for wheat germination, potentially saving a pre-sowing irrigation. With NT, more of the residual moisture after rice is productively transpired by the wheat crop instead of being lost to unproductive evaporation. Moreover, irrigation water advances faster in untilled soil than in tilled soil. With the adoption of NT in rice–wheat systems in the IGP, comparatively less weeds were found in the wheat crop. The major weed affecting wheat in the Indian IGP is *Phalaris minor* Retz. (little seed canary grass), which in the mid-1990s showed emerging resistance to isoproturon herbicide after the continuous and widespread use of this herbicide during previous decades (Singh et al. 1999; Franke et al. 2003). By reducing soil movement, NT serves as an effective control measure of *P. minor*. The ability to control herbicide-resistant *P. minor* therefore became a major initial driver for adoption of NT in (North West [NW] IGP), which, in combination with new herbicides, eventually managed to control the *P. minor* problem. In fact, NT also enhanced the earthworm population and predator diversity and density.

Although the spread of conservation tillage technologies is taking place in the irrigated regions of the IGP where the rice–wheat cropping system dominates, CA systems rather conservation tillage have not been tried or promoted in other major agro-eco regions like rainfed semiarid tropics, arid regions, coastal region or the mountain agro-ecosystems. But many resource conservation technologies are available in traditional farming system, which needs to be refined and redesigned under the umbrella of CA. The term CA, which has been defined by the FAO as resource conservation agricultural crop production, may be expanded in the local context for the Indian subcontinent. Conservation of soil and water besides practices that contribute towards improving soil health and its productive capacity must form the major components of CA in rainfed regions. Hence, the practices of in situ moisture conservation such as contour/field bunding, conservation furrows, ridge and furrow, continuous contour trenches, water absorption trenches, percolation tanks, water harvesting through farm ponds, energy-saving during water lifting and re-cycling, check dams, minimum tillage, zero tillage, cover crops/residue application (Fig. 11.1), agro-forestry, vegetative cover for uncultivated lands, introduction of perennial species along with seasonal crops, organic farming, crop rotations and integrated nutrient management (INM) may form the components of CA. Based on the long-term experimental data and review of studies across the arid, semiarid and sub-humid coastal regions undertaken over the past 30 years, different CA management practices were identified by Kumar et al. (2011) and Burman et al. (2013) for different types of rainfalls, soil and production systems (Table 11.2).

11.4 CA and Soil Carbon Sequestration

Dwindling soil organic matter (SOM) and, consequently, declining soil fertility of cultivated lands is a major concern in the tropical soils for lower crop productivity and resource use efficiency. Soil organic carbon (SOC) is the most consistently reported soil attribute from long-term studies and is a keystone soil quality indicator, being inextricably linked to other physical, chemical and biological soil quality indicators, and therefore, it is considered as an indicator of sustainability. Restoring carbon into the soils is important not only for climate change mitigation but also to improve soil quality for agricultural uses. Many long-term studies have shown that continuous cropping results in decline of SOC, although the rate is climate and soil dependent, and can be curbed by the choice of soil management practices (Mandal

Fig. 11.1 Sorghum stover and *Gliricidia* leaves used as mulch under conservation tillage experiment in castor and cowpea crops. (Picture taken from Hayathnagar Research Farm, at Central Research Institute for Dryland Agriculture, Hyderabad)

2011). A common claim by the proponents of CA is that NT with residue mulching can halt this decline and leads to accumulation of SOM. But there is contrasting opinion as to whether it is cover crop and residue retention or NT which contributes to SOM increase.

While CA was not initially conceived as a practice to sequester soil C, it is now considered as a potential technology to mitigate greenhouse gas emissions and has become a focus of carbon research. Several reviews summarize the effects of the different component practices of CA on soil C stocks compared to conventional practices (Palm et al. 2014). Even though most studies report changes in soil C stocks or storage, the increase in soil C stocks does not necessarily represent sequestration or climate mitigation potential, if there is not a net transfer of CO_2 from the atmosphere. In addition, some consider soil C sequestration as that C which is held in the more recalcitrant or protected forms and thus less susceptible to losses from decomposition (Powlson et al. 2011; West and Post 2002). However, most studies just report on the changes in the total C stored and not the changes in the recalcitrant fractions.

Table 11.2 Conservation agriculture practices and their potential benefits under different agro-eco-region (Kumar et al. 2011; Burman et al. 2013)

Rainfall (mm)	Major Soil Types/Order	State	Major Production Systems	Suggested CA Practice	Increment in the Yield of the System (%)
<500	Aridisols	Haryana and Rajasthan	Pearl millet-based	Conservation tillage (and sowing) with ridger seeder	23
				Implement: Ridger seeder	
				INM in pearl millet	14–20
				Bullock-drawn blade hoe for soil mulch creation and weed control	12
500–750	Alfisols	Andhra Pradesh	Sorghum, castor-based	Formation of conservation furrow in castor	30
				INM by conjunctive use of fertilizers + green biomass of N-fixing trees such as *Gliricidia*; N use of compost + fertilizers (50:50%).	15
				Water harvesting and recycling through a farm pond; a 250 m^3 farm pond with lining + sprinkler with a 3 hp pump set	15–25 (increase in cropped area 10–15%)
			Groundnut, castor-based	Application of groundnut shell at 5 t/ha after 10 days of sowing in groundnut	10–15
				Water harvesting and recycling through farm ponds with lining with soil +cement (6:1 ratio), a 250 m^3 farm pond with lining + sprinkler with a 3 hp pump set	20–24 Diversification into vegetables
				Use of *Rhizobium* at 500 g/ha +20-40-40 N, P_2O_5 and K_2O in groundnut	20
	Inceptisols	Rajasthan	Maize-based	Early rabi cropping of chickpea under the Nadi system of water harvesting (conserves soil, higher use efficiency of harvested rainwater)	30–35
				Water harvesting and recycling through farm ponds with lining; a 500 m^3 farm pond with lining + sprinkler with a 3 hp pump set	20–25, Diversification + bringing wasteland into cultivation

(continued)

Table 11.2 (continued)

Rainfall (mm)	Major Soil Types/Order	State	Major Production Systems	Suggested CA Practice	Increment in the Yield of the System (%)
	Vertisols	Gujarat	Groundnut-based	Set row planting of groundnut (conserves soil and saves seed, fertilizer and labour)	15
				Use of enriched compost (6 t ha^{-1})	15–23
				Recharging defunct open wells through filters (retains 67% sediment load and enhances groundwater level), filter and deepening of the defunct well	15–30
		Tamil Nadu	Cotton-based	Compartmental bunding and balanced nutrition in rainfed cotton	20–28
		Maharashtra	Rabi, sorghum-based	Compartmental bunding in rabi sorghum	15–20
				Ridge and furrow for in situ moisture conservation (conserves 45% more moisture). Implement: Tractor-drawn ridge maker	15–30
				Two-bowl ferti-seed drill for efficient sowing of rainfed crops, higher nutrient use efficiency, labour saving	20–25
				50% N through crop residue (sorghum/*Leucaena*) + 50% N through fertilizer to rabi/sorghum	20
		Karnataka	Rabi, sorghum-based	Compartmental bunding	30–40
				Cover cropping with pulse crops (conserves soil and water and improves soil quality)	20–25
				Inter-plot rainwater harvesting	25
	Entisol	Uttar Pradesh	Pearl millet, mustard-based	Ridge planting of pearl millet	20–30
				INM through 50% fertilizer N+ 50% FYM N	20
	Aridisols	Gujarat	Castor, pearl millet-based	Compartmental bunding in pearl millet	20

				Silvipasture system (amla+ *Dichanthium annulatum*), conserves soil and water, improves soil quality, higher carbon sequestration and supplies fodder	15–20 As compared to sole amla
750–1000	Alfisol	Karnataka	Finger millet-based	Rainwater harvesting and recycling through lined farm pond, 250 m^3 farm pond with lining + sprinkler with a 3 hp pump set	15–20 (10–15% more area under vegetables)
	Vertisol	Madhya Pradesh	Soybean-based	Conservation tillage and sowing of soybean with ridger seeder. Implement: ridger seeder	15–18
				Gully control to reduce their length	10
				Water harvesting through ponds. A 1000–4000 m^3 pond without lining mainly for large farmers	20–40, Diversification into flori-horticulture
		Maharashtra	Cotton-based	Rainwater harvesting and recycling through farm ponds. A 500 m^3 farm pond without lining + sprinkler with a 3 hp pump set	20–25 (+15–20% increase in cropped area + aquaculture)
				In situ moisture conservation through top sequence-based cropping. Conserves soil and water, saves energy and reduces tillage	20–25
				In situ incorporation of crop residues through Rotavator at 12–14% moisture in field	5–20
				Application of 5 tonnes of FYM + 40 kg P_2O_5 + microbial culture at 1.5 kg/ha to pigeon pea	25
	Inceptisols	Uttar Pradesh, Bihar	Paddy-based	Power-operated till planting for sowing of crops in rice fallows, reduces tillage, uses residual moisture and saves time	15–19
1000–1400	Inceptisols	Jammu and Kashmir	Maize-based	Rainwater harvesting and recycling through farm pond. A 250 m^3 farm pond with lining + sprinkler with a 3 hp pump set	25 and diversification
		Uttar Pradesh, Bihar	Paddy-based	Ridge and furrow system and diversification of the rice–wheat cropping system into the rice–pigeon pea system. Reduces cost, improves soil health and conserves rainwater. Implement: Bullock-drawn for small farmers	8–12

(continued)

Table 11.2 (continued)

Rainfall (mm)	Major Soil Types/Order	State	Major Production Systems	Suggested CA Practice	Increment in the Yield of the System (%)
	Oxisols	Jharkhand	Paddy-based	Rainwater harvesting and recycling through farm pond, size of 1000–4000 m^3 with lining+ sprinkler with a 3 hp pump set	30–50
	Vertisols	Madhya Pradesh	Paddy, soybean-based	Rainwater harvesting and recycling through a farm pond. A 250–500 m^3 farm pond without lining + sprinkler with a 3 hp pump set	20–25 (higher diversification)
>1400	Inceptisols	West Bengal, Orissa, Andaman-Nicobar Islands	Farm pond	20% area converted to pond for rainwater harvesting, dugout soils used for highland/dikes, medium-sized land, integrated farming fisheries with paddy and vegetable cultivation year-round	Yield benefit 3.8 times than that in farmers' practice
			Deep furrow and high ridge	50% farmland shapes into alternate ridge and furrows, integrated farming fisheries with paddy and vegetable cultivation year-round	Yield benefit 3.0 times than that in farmers' practice
			Shallow furrow and medium ridge	About 75% of the farmland is shaped into medium ridges and furrows with a gap of 3.5 m between two consecutive ridges and furrows, integrated farming fisheries with paddy and vegetable cultivation year-round	Yield benefit 2.9 times than that in farmers' practice
			Paddy cum-fish	Trenches are dug around the periphery of the farmland, and dugout soil is used for making dikes; a small ditch is dug out at the corner of the field, integrated farming fisheries with paddy and vegetable cultivation year-round	Yield benefit 2.7 times than that in farmers' practice
			Direct seeded rice cultivation with INM	Directed seeding of germinated paddy seed under reduced tillage condition during the rabi season	3–5% yield improvement and 10–15% labour saving

11.4.1 Conservation Tillage

Reduced tillage or NT as a CA component may increase soil C compared with conventional tillage (CT), but these increases are often confined to near-surface layers (<10 cm). At deeper depths, soil C in CA may be equal or even lower compared to CT. The potential of CA for storing C depends on antecedent soil C concentration, cropping system, management duration, soil texture, slope and climate (Govaerts et al. 2009; Luo et al. 2010). More data are available from temperate (i.e. the USA) than from tropical regions. Across 100 comparisons, soil C stock in NT was lower in 7 cases, higher in 54 cases and equal in 39 cases than that in CT in the 0- to 30-cm soil depth after 5 years or more of NT implementation (Palm et al. 2014). These studies were primarily reported from the USA and Canada, and some from Brazil, Mexico, Spain, Switzerland, Australia and China. A meta-analysis found increased soil C in the topsoil (0–10 cm) on conversion of CT to NT but no significant difference over the soil profile to 40 cm due to a redistribution of C in the profile (Luo et al. 2010).

The results of a long-term experiment trial conducted in Alfisols of the semiarid Bangalore region of India indicated that among the tillage management practices, the highest carbon stock was recorded with NT + 100% organic N (9.01 Mg ha^{-1}), followed by RT + 100% organic N (8.24 Mg ha^{-1}); RT + 50% organic N + 50% inorganic N (7.37 Mg ha^{-1}) in the finger millet–based cropping system (Sharma 2014). In these studies, when compared with CT (5.81 Mg ha^{-1}), significantly higher carbon stock was observed with NT (7.39 Mg ha^{-1}) and RT (7.17 Mg ha^{-1}), which was 21% and 19% higher, respectively.

In some other experiment conducted on CT, RT and INM treatments with the sorghum–green gram system under rainfed conditions at Hyderabad, organic carbon content increased from 5.7 g kg^{-1} (control) to 7.2 g kg^{-1} (RT + 4 t compost +2 t *Gliricidia* lopping) after 8 years of the experiment, thus exhibiting an increase of 26.3% C. Whereas in CT + 4 t compost +2 t *Gliricidia* lopping (6.5 g kg^{-1}), the increase over control (5.6 g kg^{-1}) was to the tune of 16.1%. The INM treatments significantly increased the organic carbon content over control (Sharma 2014).

11.4.2 Crop Rotations

Crop rotations, though exerting less effect on soil C than tillage (West and Post 2002), can affect soil C by increased biomass production and C inputs from the different crops in the system or through altering pest cycles, diversifying rooting patterns and rooting depth. High residue–producing crops may sequester more C than crops with low residue input. Intensification of cropping systems such as increased number of crops per year, double cropping and addition of cover crops can result in increased soil C storage under NT. West and Post (2002) reported interactions with crop rotations and tillage practice; in general, more C sequestration was found in crop rotations than monocultures on conversion to NT, although there were notable exceptions with corn–soybean rotations with less soil C than monoculture maize.

The differential effects of rotations on soil C are related to the amounts of above- and below ground biomass (residues and roots) produced and retained in the system (West and Post 2002). Mina et al. (2008) reported that lentil (*Lens esculenta*, variety VL-4; October–April) and finger millet (*Eleusine coracana*, variety VL-149; June–September), in rotation per year, increased C and N and enhanced enzymatic activity under zero-tillage systems in Indian sandy clay loam soils.

11.4.3 Residue Retention

Retention of crop residues is an essential component of CA for increasing and/or maintaining soil C. Factors that increase crop yields will increase the quantity of residue available and potentially soil C storage. Fertility management may be the single most important factor to increase residue production and ultimately increase soil C storage, whether the system is NT or CT (Giller et al. 2009). This will be important for increasing C inputs and soil C in low input–low productivity systems found in much of Sub-Saharan Africa and parts of South Asia (Paul et al. 2013). Hazell and Wood (2008) did a rough comparison using average regional yields and a harvest index of 50% for maize; farms in the USA generate 10 Mg ha^{-1} of maize residue, while farms in South Asia and sub-Saharan Africa generate 3 and 1–2 Mg ha^{-1} of maize residue, respectively. A study in Kenya by Paul et al. (2013) illustrated the point that limited quantities of residue input had little or no effects on increasing soil C. They found no differences in soil C concentration between CT and RT when both tillage systems received 4 Mg ha^{-1} residue for 6 years. A similar lack of response to 4 Mg ha^{-1} of residue after 4 years of application was also seen in a subtropical area of Nepal (Ghimire et al. 2012).

Based on the results of a long-term experiment conducted in the cotton-based system in Vertisols at Akola, India, organic C in soils varied from 5.72 g kg^{-1} (control) to 7.32 g kg^{-1} in a treatment with 25 kg P_2O_5 ha^{-1}+ 50 kg N ha^{-1} through *Leucaena,* followed by 25 kg N (fertilizer) + 25 kg P_2O_5 ha^{-1} + 25 kg N ha^{-1} through FYM (7.24 g kg^{-1}), thus registering an increase of about 28% and 26.6% in soil organic C over control over a period of 19 years (Sharma 2011). Similarly, residue application and graded N levels for 7 years exhibited a significant increase in organic carbon content in rainfed Alfisol in case of castor–sorghum rotation irrespective of the tillage levels (Sharma et al. 2005). Continuous surface application of sorghum stover at 6 t ha^{-1} with minimum tillage for 5 years under the sorghum–cowpea system in Alfisol significantly increased soil organic carbon content from 4.36 g kg^{-1} (control) to 6.79 g kg^{-1}, thus registering an increase of 55.8% (Sharma 2014).

Soil C storage is affected more by quantity rather than by the type or quality of organic inputs. The quality of the residues is primarily determined by the C:N ratio and can be modified by the amount of lignin and polyphenolics present in the material. Materials with a high C:N ratio, characteristic of cereal crop residues, reduce the available N in the soil due to N immobilization and could result in lower crop production, whereas residues with high N contents and low C:N ratios, as is the case with many legume residues and legume cover crops, increase soil N availability and also possibly crop production (Powlson et al. 2011; Palm et al. 2001). The amount of crop residue retained after harvest, either on the soil surface or incorporated, is a key component to CA performance. Unlike most temperate zone agricultural systems and other large-scale farming systems, where NT or RT results in higher production and retention of crop residues, residues produced in many small-scale farms in Sub-Saharan Africa, parts of Latin America and South Asia are not only low but also have many competing uses (Erenstein 2002). The fate of residues is decided by many factors including human and livestock population density, production potential of an area and fodder markets. The majority of small farmers are mixed-crop and livestock farmers, and they use most crop residues as fodder for livestock. In some areas, crop residues are simply burnt to clear agricultural fields, while, in other areas, residues are removed from fields by termites.

11.4.4 Tillage, Crop Rotation and Residue Retention Interactions

Soil C stocks are affected by tillage, rotations and residue management separately. It is important to recognize that these CA components interact. The types of crops, cropping intensity and duration of the cropping systems determine input quantity, and thus, the ability of CA to store more C than CT. Intensification of cropping systems with higher above and below ground biomass (i.e. deep-rooted plant species) inputs may enhance CA systems for storing soil C relative to CT. Moreover, CA practices like NT may not store more soil C than CT if limited amounts of residues are left. While it is clear that an increasing amount of residues is essential for increasing soil C storage, interaction of residues with soil texture and soil microclimate (moisture and temperature) will ultimately determine rates of residue decomposition and soil C turnover and storage (Palm et al. 2014). These multiple and complex interactions that ultimately determine soil C storage make it difficult to identify clear patterns and trends needed for developing practical guidelines. Several simulation studies (Leite et al. 2009; Apezteguía et al. 2009) have confirmed relatively small gains in soil under NT due to enhanced sequestration in the soil organic matter pool. Farage et al. (2007), while using CENTURY and RothC for estimating soil C changes with tillage practices, found a small increase in soil C with conversion to NT on sandy soils of West Africa. These modelling exercises can be used to look for these types of threshold effects and interactions among the CA practices in determining the primary factors affecting soil C storage in different environments.

In India, measurement of the amount of C sequestered under different management practices is mainly done using long-term experiments located in different agro-ecological zones of the country. In northeast India, conservation tillage in terrace upland, valley upland and low land ensured double cropping and improved livelihood. An experiment (2006–2009) on conservation tillage and residue management showed that NT in rice-based system restored SOC, increased biological activity to 46.7%, saved water and produced 49% higher yields than CT (Ghosh et al. 2010). A study conducted on permanent beds with residue retention increased crop yield in maize by 11–17% and in wheat by 12–15% over conventional practices in western Uttar Pradesh (Naresh et al. 2012; Nayak et al. 2012). CA along with integrated nutrient management (INM) plays a significant role in C sequestration.

A 20-year meta-analysis of an NT system in IGP showed that the associated GHGs emitted in NT systems were 3% less than those under CT with the rice–wheat system, and conversion to NT C sequestration potential was estimated to be 44.1 Tg C (Tg is million ton). Further, implementation of NT in maize–wheat and cotton–wheat systems would sequester an additional 6.6Tg C (Grace et al. 2012).

11.5 Conservation Agriculture and Climate Change Mitigation and Adaptation

CA has the potential to improve adaptation to climate change mainly due to enhanced water balance in CA-managed fields and to climate change mitigation through possible C sequestration and reduced emission of CO_2 to the atmosphere (Jat et al. 2012). NT is also seen as an important soil management practice in the context of global climate change, as it may increase C sequestration in soil due to improved crop residue management (Batjes and Sombroek 1997; Lal 1997). The CO_2 emission from the conventionally managed soils is due to ploughing, mixing crop residues and other biomass into the soil surface and burning of biomass (FAO 2001). Conversely, practices such as reducing tillage intensity, decreasing or eliminating the fallow period, using a winter cover crop, retention of crop residues on soil surface, changing from mono-cropping to rotation, altering soil inputs to increase primary production (fertilizers, pesticides, irrigation, etc.) and less use of fossil fuels, all could contribute to greater organic C storage in the soil (West and Post 2002; Jat et al. 2012). All these practices result in increasing SOC to reach new SOM equilibrium.

Farmers practising the rice–wheat system in the IGP tend to burn the crop residue after crop harvest, which is a significant source of air pollution; however, CA can help to avoid such environmental pollution, as it retains the crop residues on soil surface. Reduced fuel consumption in farming for tillage, water pumping, reduced residue burning and reduced loss of nutrients especially N under CA practices lead to reduction in emission of greenhouse gases (GHGs). Further, minimal soil disturbance results in less exposure of SOM to oxidation and hence lower CO_2 emission to the atmosphere compared to tilled soils. Due to avoidance of tillage operations under CA, it saves considerable amount of diesel and thus reduced CO_2 emission, one of the gases responsible for global warming. According to a survey of farmers adopting zero tillage (ZT) in Haryana (India) and Punjab (Pakistan) during 2003–2004 by Erenstain and Laxmi (Erenstein and Laxmi 2008), farmers were able to save 35 L diesel for land preparation, or 98 kg C ha^{-1}. One-litre diesel contains 0.74 kg C and emits 2.67 kg CO_2 (Environmental Protection Agency 2009).

No-tillage mainly brings about two modifications: (i) minimal soil disturbance and (ii) addition of plant residue in soil. These two factors cause changes in soil properties and processes physically as well as biologically. Under the absence of soil disturbance, moisture retention improves, aggregates are stabilized, organic matter is protected and microbial communities are less disturbed. Absence of tillage, however, increases soil compactness, which may in the long term offer problems in farming practices, and hence tilling after certain gaps may be needed (Soane et al. 2012). Increased resistance to gaseous diffusivity under no-tillage causes low mobility of gases along soil profile, thus affecting gaseous transport (Beare et al. 2009). Under reducing conditions as is common in flooded rice fields, residue incorporation tends to make soil more anaerobic, since organic compounds usually serve as electron donors (Mosier et al. 2004). All these factors interact in complex ways, thus influencing GHG emissions, transport and consumption.

Lifeng et al. (2008) reported that CO_2 flux was 135% and 70% more from soil in the ploughed field for residue cover and no cover plots, respectively, compared to no-till field. Hutsch (1998) suggested that a reduction in tillage intensity could help minimize the adverse effects of cultivation on soil CH_4 uptake. But according to Omonode et al. (2007), anaerobic conditions are frequent under ZT, and consequently, there will be an emission of CH_4. CA applied to rice could be a way to reduce CH_4 emissions, since it would eliminate the puddling and encourage more percolation of water through the soil profile and help aerate the soil.

Emissions of N_2O increase with applications of N fertilizers by increasing N availability in the soil (Davidson 2009). The quantity and quality of residues or cover crops of CA systems can also affect N_2O emissions. Legume residues can result in higher N_2O–N losses than those from non-legume, low-N residues (Yao et al. 2009). The N_2O emissions from legume N-rich residues compared to N mineral fertilizers, however, are lower per unit N added (Baggs et al. 2000). On the other hand, low-quality cereal crop residues (C:N ratio is generally greater than 25) combined with surface application of residues in CA systems could result in immobilization of N and ultimately decreased N_2O production compared to conventional systems. Though legume residues may lead to higher N_2O emissions than cereal residues, the quantity of legume residues returned to soil is substantially less. The net result of CA in N_2O emissions will depend on the crop rotation practices and the types and amounts of crop residue in CA systems compared to the conventional one. Snyder et al. (2009) mentioned that there was no clear response on the effects of NT or RT compared to CT on N_2O emissions. With NT, residues are returned to the soil resulting in surface mulches, which may lower evaporation rates and hence increase soil moisture and increase labile organic C (Galbally et al. 2005) and consequently increase N_2O emissions compared to CT. Increased bulk density with CA compared to CT may also increase emissions. On the other hand, lower soil temperatures and better soil structure under NT may reduce the incidence of soil saturation and reduce emissions of N_2O. Agricultural soils contribute to CH_4 emissions as a result of methanogenic processes in waterlogged conditions that are usually associated with rice production. Methane has a lifetime of 12 years and a global warming potential 25 times that of CO_2 over a 100-year time horizon. Rice production under flooded condition contributes 15% of total global CH_4 emissions (IPCC 2001). The magnitude of CH_4 emissions is primarily a function of water management, with the addition of both mineral and organic fertilizers having a significant influence.

The effect of tillage practices on the rate of CH_4 consumption, in general, depends on the changes in gas diffusion characteristics in soil (Gregorich et al. 2006; Hutsch 1998). Reduction in CH_4 consumption and a potential net CH_4 emission could be expected with RT or NT due to increased bulk density and water filled pore space (WFPS). Yet no significant tillage effect on CH_4 oxidation rates has been detected (Jacinthe and Lal 2005; Smith et al. 2012). Residue retention provides a source of readily available C, which enhances CH_4 emissions from rice fields, which are generally under anaerobic conditions. Crop residues may affect CH_4 oxidation in upland soils and emission patterns in flooded soils differently depending on their C/N ratio; residues with a high C/N ratio have less effect on oxidation, while residues with a narrow C/N ratio inhibit oxidation (Hiitsch 2011). Reduced tillage or NT is currently being promoted in the Indo-Gangetic Plains (IGP) in the rice–wheat system. With this system, direct-drill seeded rice does not require continuous soil submergence and thereby could either reduce or eliminate CH_4 emissions from lowland rice when it is grown as an aerobic crop (Pathak 2009). The overall impact of RT in this environment, however, appears to be relatively minor. Grace et al. (2012) estimated an average of 29.3 Mg ha^{-1} of GHGs emitted over 20 years in conventional rice–wheat systems across the IGP; this was decreased by only 3% with the widespread implementation of CA. Studies examining the impact of different CA practices on all relevant GHGs, including soil C sequestration, and the resulting net global warming potential are rare, yet such studies are crucial for developing comprehensive management options for climate change mitigation in different environments. One of the few comprehensive studies over multiple years (Dendooven et al. 2012a, b) found no differences in either N_2O or CH_4 emissions between CA and CT in a long-term dryland cropping trial in Central Mexico. CA was found to have a significantly lower global warming potential than CT due to the changes in soil C alone. Management strategies that can be aligned with NT to keep soil in the oxidative state and promote aerobic organic matter decomposition are potential mitigation strategies for reducing CH_4 emissions. Reducing the duration of flooding is also being promoted as a practical solution to reduce CH_4 emissions in CA rice production systems generally, but these may offset partially by an increase in N_2O emissions (Ortiz-Monasterio et al. 2010).

Pandey et al. (2012) assessed the impacts of four tillage practices in cultivation of rice–wheat system on fluxes of GHGs (CH_4, N_2O and CO_2) and yield of rice at Varanasi in IGP, India. The tillage practices were tilling of soil before sowing of both the crops (RCT-WCT), tillage before sowing of rice but no tillage before sowing of wheat (RCT-WNT), tillage before sowing of wheat but no tillage before sowing of rice (RNT-WCT) and no tillage before sowing of both rice and wheat (RNT-WNT). Reduction in tillage frequency resulted in significant reductions in CH_4 and N_2O fluxes, but increased CO_2 while permutations of tillage and no-tillage influenced grain yield.

11.6 Strategies in Scaling-Up Conservation Agriculture

There is a need to create awareness among the communities about the importance of conservation of land/soil resources and organic matter in soil. Traditional practices such as burning of residues, clean cultivation, intensive tillage and pulverization of soil up to the finest tilth need to be discouraged. A large-scale electronic media support is a must to convey these aspects to the farming communities.

At least the non-edible (for animals) agricultural residues must not be burnt and should be used for mulching. Agroforestry systems with special emphasis on silvi-pasture systems need to be introduced. For the adoption of conservation tillage, it is essential that a complete package of practices (Table 11.3) may be identified for each agro-ecological region.

Conservation farming also has the objective to minimize the inputs originating from non-renewable energy sources, for example, fertilizers and pesticides. Hence, research focus is required on enhancing fertilizer use efficiency and reduction in the use of pesticides. This aspect can be strengthened by following INM and integrated pest management approaches.

To make CA a success, there is need of the availability of suitable equipment that can place seed and fertilizers at optimum depth through surface-applied residues in zero-tilled fields. Therefore, there is need to develop equipment that are cheaper and lighter and can be powered by smaller tractors or even by bullocks. To cater this need, there is a need to have close interactions between farmers, technicians, machine builders, local private entrepreneurs, craftsmen, scientists, engineers and so on. For example, multi-crop, zero-till ferti-seed drills fitted with inverted-T openers, disk planters, punch planters, trash movers or roto-disk openers have been developed for seeding into loose residues for zero-till-sown wheat in the rice–wheat system of IGP (Jat et al. 2012).

Severe weed infestation particularly during initial years of adoption is one major hindrance to motivate the farmers to adopt CA as not tilling the soil commonly results in increased weed pressure. Weed management in CA requires more herbicide application, which, in many cases, is beyond the capacity of poor farmers of the region. Moreover, sometimes continuous rainfall may not allow the application of herbicides or reduce the efficiency of applied herbicides. At the same time, tremendous increase in herbicide use, when CA is followed at large scale, may lead to serious repercussions on health of local people and the ecosystem. Export of herbicide residues in water streams will make their water unfit for human and animal consumption besides having adverse impacts on marine life. Ploughing remains the single most cost-effective weed control method; even if the marginal return is high for these extra investments, most smallholders may not be able to undertake them due to limited resources and labour constraints. Therefore, there is a need to develop integrated weed management techniques to keep the yield loss due to weeds to minimum. Herbicides may be used in some systems and hand-hoes in others, and farmers who have animal-drawn ploughs can fit simple and inexpensive tines or

Table 11.3 Conditions to be met for adoption of conservation agriculture practices (Kumar et al. 2011)

CA practices/ interventions	Policy and institutional needs	Technology needs
Rainwater harvesting/ farm ponds/well recharging	Initial investment has to come from the government by converging different schemes like MGNREGS/ RKVY/NFSM/watershed programmes, and so on.	Low-cost and easy-to-handle water-lifting devices and micro-irrigation systems matching the needs of different categories of farmers need to be developed
	Operationalization of farm ponds needs to be done as a customized package for water harvesting and utilization (including inlet and outlet pitching and lining of the pond, water lifting, micro-irrigation system etc.)	Farmers must be properly trained to handle and maintain micro-irrigation systems
Integrated nutrient management (conjunctive use of organic and inorganic fertilizers, residue management, mulching through biomass)	Arrangements in place for capacity-building Policy favouring promotion of organic supply of nutrients in terms of crop residue management and higher biomass production for mulching, particularly in fragile soil environments Convergence with RKVY, NHM, etc., may be useful Making biomass shredder available on subsidy to encourage mulching through agricultural residues (non-edible for animals). Rotavator may be used for incorporation of residues in the soil	Location-specific on-farm demonstrations on a large scale Develop and provide power-operated machine to shred the non-edible (as fodder) agricultural residues like cotton stalk to use them for mulching
In situ moisture conservation	Identification of appropriate in situ moisture conservation practices (ISMCP) on agro-climatic zone basis and further narrowing down to district/sub-district level Need to be implemented as an area approach by converging with relevant programmes like MGNREGS/ RKVY/watershed programme covering all categories of farmers cultivating marginal/fragile lands/ soils Need to improve access to needed implements like ridge and furrow maker for wider scale adoption of ISMCPs through custom-hiring services promoted by self-help groups and/or subsidy	Large-scale on-farm demonstrations Launching awareness campaign Appropriate implements (bullock-drawn/tractor-drawn) need to be identified/ modified/developed

(continued)

Table 11.3 (continued)

CA practices/ interventions	Policy and institutional needs	Technology needs
Alternate land use systems (ALUS) – Silvi-agri, horti-agri and agro-forestry systems	Capacity-building of the stakeholders Single-window delivery system of support for promoting ALUS starting from land preparation to the stage when ALUs begin to give economic benefits. Convergence among MGNREGS, NHM and watershed programme may help in this	Delineate suitable areas for promoting ALUS considering local resources, traditional skills, market opportunities, fodder supply, carbon credits and value-addition options

sub-soiling machine. The use of herbicides should be considered only as one of the options in an integrated approach of weeding and cover crop management.

There are many reports on reduced yield under CA particularly during the conversion phase, which are mainly due to high weed infestation, poor crop stand due to low germination, nutrient immobilization, higher insect-pest and disease attack, water-logging in poorly drained soils, lack of skills in adopters during initial years and so on. The absence of tillage in itself can result in adverse effects including higher run-off and lower infiltration, leading to lower yields. The negative effects of NT occur especially on the clay-poor, structurally weak soils of the arid areas, which are widespread throughout sub-Saharan Africa and Asia. On such soils, the beneficial effects of mulching may not always be sufficient to offset the negative effects of NT, resulting in lower yields during the first few years under no-till compared to ploughing even if a mulch of crop residues is applied. Initially, CA practices, especially zero/reduced tillage may result in reduced yields over conventional tillage but catch up with the latter over time. Hence, initial incentives are important to motivate the farmers to follow conservation tillage.

Hobbs and Govaerts (2010), however, noted that probably the most important factor in the adoption of CA is overcoming the bias or mindset about tillage. It is argued that convincing the farmers that successful cultivation is possible even with RT or without tillage is a major hurdle in promoting CA on a large scale in the tropical region. In many cases, it may be difficult to convince the farmers of potential benefits of CA beyond its potential to reduce production costs, mainly by tillage reductions. It is, therefore, necessary to educate farmers on the links between excessive tillage and residue removal with soil sustainability problems, and how these problems can be alleviated through adoption of CA.

The remarkable growth of NT in Latin America, particularly in southern Brazil, so far can be attributed to close collaboration between governmental institutions (research centres and extension service) and farmer associations, agrichemical companies, seed companies and agricultural machinery companies (Busscher 1996). Instead of using a top-down approach where the extension agent places CA demonstrations in farmer fields and expects the farmer to adopt, a more participatory system is required where the farmers are enabled through provision of equipment and training to experiment with the technology and find out for themselves whether it works and what fine-tuning was needed to make it successful on their land.

11.7 Conclusion

CA has been reported by numerous workers as sustainable and eco-friendly crop production technique in the fragile eco-systems of the tropical region. But concerns have been raised about slight yield decline mainly during the initial years of adoption of CA. However, in the long term, CA has been found to render several benefits including soil conservation with improved soil health, higher rainwater-use efficiency, climate change mitigation and adaptation, improved biodiversity, resilience to climate shocks, higher economic returns and more leisure time to farmers. It is essential to undertake medium to long-term studies on CA under given set of agro-climatic and socio-economic conditions to better guide the farmers for successful adoption. The use of decision support systems such as DSSAT and APSIM may be successfully employed after proper calibration and validation to predict the long-term effects of CA on yield and soil quality, which will save time and resources to undertake the long-term studies in the field. Higher carbon sequestration through CA practices may also give additional benefits in terms of carbon emission reduction, if made tradable in future. For promotion of CA practices across diverse agro-ecologies, appropriate technology, policy and institutional support would be a prerequisite. Strengthening delivery system at the village level is important for the adoption of any innovation. Convergence of various schemes, namely, Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS), National Horticulture Mission (NHM), Rashtriya Krishi Vikas Yojana (RKVY), National Food Security Mission (NFSM), National Mission for Sustainable Agriculture (NMSA), watershed programme and so on at the local level involving all major stakeholders would surely contribute towards promotion of CA in the regions.

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12

Soil Organic Carbon Dynamics and Carbon Sequestration Under Conservation Tillage in Tropical Vertisols

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Abstract

Soils, especially managed agricultural soils, have the potential to sequester carbon (C) and contribute to the mitigation of GHGs emissions. Increasing the amount of organic matter addition to soils may not only mitigate GHG emissions, but also benefit agricultural productivity through improvements in soil health and environmental quality. One potential method for increasing the amount of C held in agricultural soil is through conversion of conventional tillage practices to conservation tillage practices that reduce tillage and retain crop residues. Vertisols in India occupy 8.1% of the total geographical area of the country and are generally low in organic carbon content, but these soils have great potential to increase the soil organic carbon (SOC) level. Improvement in SOC content in these soils through traditional/conventional soil management practices is very difficult, as it has already attained the equilibrium level. One of the most attainable pathways to improve and sequester SOC content in this soil is through either regular addition of organic manures such as farmyard manure, compost or crop residues or by switching traditional tillage practices to no-tillage or other forms of conservation tillage. Several long- and short-term field studies on Vertisols reported that management strategies, such as no-tillage (NT) and reduced tillage (RT) with residue retention, played a significant role in increasing SOC concentration and favouring aggregate stability. Adoption of conservation tillage practices resulted in an improvement of surface soil aggregation and an increase in the proportion of macroaggregates compared to conventional tillage. Conservation tillage increases the percentage of carbon-rich macroaggregates in the soil particularly in the surface layers, resulting in sequestration of more car-

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bon into soil stabilized through physical protection. More aggregate-C in large and small macroaggregates favoured better aggregation under conservation tillage than that under conventional tillage, which suggested that macroaggregates are sensitive to changes in the soil microbial community associated with short-term conservation management practices. Conservation tillage also resulted in stratification of SOC and available nutrient levels in soil. Conservation tillage in tropical Vertisols could be a useful technology to partially mitigate the deleterious effect of climate change through sequestration of carbon into the soil and reduction of greenhouse gas emission from agricultural activities to atmosphere. It also improves soil health, its resilience to extraneous stresses and the sustainability of agricultural production system.

Keywords
Carbon sequestration · Conservation tillage · Soil aggregate · Tropical Vertisols

12.1 Introduction

The quantity of carbon stored in the soil on a global context is second only to that in the ocean and represents the largest store of terrestrial organic carbon, at more than four times the biotic carbon pool. Approximately 2500 Gt of organic carbon is stored in the top 3 m of soil, with 60% or 1500 Gt of organic carbon stored in the first meter of soil and about 615 Gt stored in the top 20 cm (Guo and Gifford 2002; Jobbagy and Jackson 2000). Any significant change in the soil organic carbon storage present mainly in the form of soil organic matter in the future will have profound consequences on the terrestrial ecosystem. Management of soil organic matter (SOM) in arable lands thus has become increasingly important in many areas of the world in order to combat land degradation (Lal 2006), increase food security (Swaminathan 2000), reduce C emissions and/or mitigate climate change (Lal 2004; Barbara et al. 2012). SOM is considered as the key in developing drought-resistant soils, through water conservation, evaporation and erosion control, and better rainwater infiltration into soil and in ensuring sustainable food production through improved crop productivity, fertilizer-use efficiency, reduced pesticide use and crop ecological intensification (Bot and Benites 2005). The dynamics of SOM are influenced by agricultural management practices such as tillage, mulching, removal of crop residues and application of organic and mineral fertilizers. SOM is a continuum of substances in all stages of decay. Among them, humus is a relatively stable component formed by humic substances, consisting of humic acids, fulvic acids, hymatomelanic acids and humins. Humic and fulvic substances enhance plant growth directly through physiological and nutritional effects but also improve soil health and quality through amelioration of soil's physical, biological and chemical properties.

Soil can function as either a source of, or a sink for, atmospheric C, and may have an important role in sequestering C from the atmosphere; thus, it can help to restrain build-up of greenhouse gases and aid in mitigating global climate change. Conservation and enhancement of soil organic matter is important for plant nutrition, soil structure, soil compactibility and water-holding capacity. One potential method for increasing the amount of C held in agricultural soil is through conversion of conventional tillage practices to conservation tillage practices that reduce tillage and retain crop residues. Conservation tillage practices reduces the tillage-induced breakdown of soil aggregates resulting in slowdown of the organic matter decomposition relative to the conventional cultivation system and also adds organic matter as residues to the surface soil. Besides this, through reduction of surface soil losses through runoff, conservation tillage decreases loss of soil carbon and plant nutrients with the sediments particularly in sloping terrain.

12.2 Importance of Conservation Tillage

Improvement and sustenance of the SOM status of the arable soil is one of the most crucial challenges facing today's intensive agricultural production system. Thus, conservation tillage (CT) has been recommended as an alternative strategy to invert the soil degradation spiral in many parts of the world partly due to loss of soil organic carbon from the top soil (Derpsch and Friedrich 2009). The conservation tillage systems affect not only the amount of SOM but also its characteristics (Ding et al. 2002). SOM quality is affected by no-tillage either in terms of particulate organic matter or in terms of its composition of humic acids, fulvic acids and humin (McCallister and Chien 2000). These humic substances are specifically involved in improving soil structural stability and plant growth.

The bare and pulverized topsoil under conventional cultivation made them vulnerable to accelerated soil loss through runoff and also to soil loss by wind in arid and semiarid regions. Besides soil and accompanied nutrient losses, conventional tillage operation breaks soil aggregates and exposes soil organic carbon locked inside the aggregates to accelerated microbial degradation resulting in net loss of organic carbon from the arable ecosystem. Burning of surface residue commonly practised in a large geographical location of the country, repeated tillage operations particularly inversion tillage operations with disc harrows, sowing of crop along the slopes, keeping the soil bare in the rainy season as commonly followed under traditional agricultural causes substantial loss of plant nutrients and organic carbon from the topsoil. Resource conservation technologies and conservation tillage promote less disturbances of the surface soil through tillage operations and keep the soil surface covered with anchored crop residues or cover crop during the heavy rainfall period to reduce the negative impact of agriculture on the natural ecosystem. Conservation tillage also offers a sustainable residue management options for a large part of the country where residues are burnt, which causes air pollution through shoot particles and releases considerable amount of carbon dioxide to the atmosphere.

12.3 Need for Conservation Tillage in Vertisols of Central India

Poor SOM content due to lack of crop residues and excessive tillage degrades soil health. This effect is pronounced further under uncertain rainfall, limited water resources, poor nutrient inputs, soil specific constraints like low water infiltration, high incidence of inundation, accelerated runoff and soil erosion in Vertisols of central India (Hati et al. 2006). Vertisols in India occupy a total area of 26.8 m ha, constituting 8.1% of the total geographical area of the country, of which about 60% of the area comes under central India (Bhattacharyya et al. 2009). Improvement in SOC content in these soils through traditional/conventional soil management practices is very difficult, as it has already attained the equilibrium level due to high temperature and decomposition rate of SOC (Jha et al. 2012). The only way to improve and sequester SOC content is either through regular addition of organic manures such as farmyard manure, compost or crop residues (Manna et al. 2005; Hati et al. 2007) or switching traditional tillage practices to no-tillage or other forms of conservation tillage (Lal and Kimble 1997). Stewart et al. (2008) reported that the C sequestration capacity of a soil is determined mainly by the protection of C in the aggregates.

A long-term experiment was conducted with the soybean–wheat cropping system at an experimental farm of the Indian Institute of Soil Science, Bhopal, to assess the effect of different tillage management practices at different nitrogen application levels on soil properties, crop productivity and soil health. In the experiment, three wheat residue management treatments (Fig. 12.1), namely, mould board tillage system (MB), reduced tillage (RT) and no-tillage (NT), were compared against the conventional tillage (CT) system. In the mould board tillage system, wheat residues were incorporated into the soil by mould-board plough during the summer season and allowed to decompose during the summer and before sowing of soybean after the onset of monsoon, the field was ploughed twice by a sweep cultivator for the preparation of a clean seed bed, while in winter season wheat was sown after one pass of rotavator tillage operation. In the reduced tillage system, wheat residues were kept on the surface and soybean was sown after one pass of sweep cultivator. One pass by sweep tillage was included to partially incorporate the wheat residue, for mixing of surface broadcasted fertilizer and controlling weeds and to ease the sowing operation. In conventional tillage treatment, wheat residues were removed

Fig. 12.1 (**a**) Residue removed. (**b**) Residue incorporation. (**c**) Residue retention

during harvest, soil was ploughed once during the summer season as practised in traditional cultivation system and then two passes of sweep cultivator were allowed before sowing of soybean in the rainy season. Both soybean and wheat were grown with three nitrogen levels, namely 50%, 100% and 150% of the recommended dose of nitrogen under each of the four tillage treatments. The experiment was conducted for ten cropping cycles. The results from the experiment showed that the crop growth and productivity of soybean and wheat under no- and reduced-tillage treatments were on par with the conventional tillage system.

12.4 Impact of Conservation Tillage and Soil Organic Carbon Dynamics

Tillage plays a key role in the manipulation of nutrient storage and release from SOM. A global analysis of 67 long-term experiments indicated that, on average, a change from conventional tillage to no-till (NT) can sequester 57–14 g C m^{-2} $year^{-1}$ (excluding NT in wheat fallow systems), with peak sequestration rates being reached within 5–10 years after conversion (West and Post 2002). By contrast, Six et al. (2002b, c) found a general increase in soil C contents of 325–113 kg C m^{-2} $year^{-1}$ under NT compared with CT for both tropical and temperate systems. They also reported that, on an average, C turnover was 1.5 times slower in NT than in CT. The amount of SOM loss due to tillage is dependent on the clay content of the soil. In general, greater SOM loss is observed in coarse-textured than fine-textured soils, primarily due to lack of physical protection of organic matter in sandy soils (Hassink 1995). In fine-textured soils, clay- and silt-sized particles with high surface activity may chemically stabilize SOM and form the building blocks for aggregates, thereby inducing physical protection of SOM by occlusion in aggregates, especially microaggregates (Six et al. 2000). Soil disturbance through tillage is a major cause of reduction in the number and stability of soil aggregates and subsequently organic matter depletion (Six et al. 2000).

The experimental result in Vertisols of central India showed that, after ten crop cycles, the organic carbon content of the soil up to 30 cm depth was higher in conservation tillage treatments compared to the conventional tillage treatment. At 0–5 cm depth, the SOC content recorded was the highest in NT, followed by RT, MB and CT, whereas at 5–15 cm depth, SOC content in NT, RT and MB showed no significant difference, but it was significantly more than that in CT (Fig. 12.2). At 15–30 cm depth, the difference in SOC content was not conspicuous. Conservation tillage, particularly no-tillage, leads to a concentration of SOC in the top layer of the soil (0–5 cm) and alters its distribution within the soil profile because plant residues tend to accumulate on the surface soil (McCarty et al. 1998). Increase in SOC in the surface soil is attributed to a combination of reduced litter decomposition and less soil disturbance under NT. Besides this, organic matter below the surface, including the previous crop's roots, is left undisturbed and thus is not subject to accelerated decay in conservation tillage treatments. This combination of adding organic residues to the soil surface, while not disturbing the existing organic matter stocks

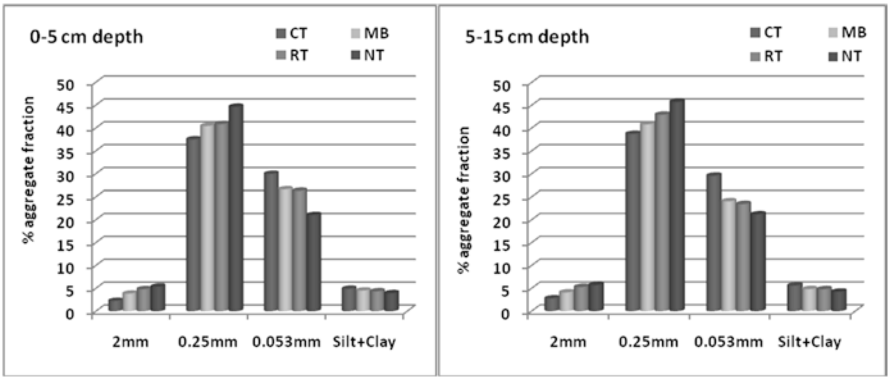

Fig. 12.2 Percent distribution of aggregate size fractions as influenced by conservation tillage

below the surface, could be the probable reason for the increase in organic carbon in the top layers of the soil. Similarly, Paustian et al. (1997) compiled data on NT and CT systems from several long-term field studies and found in most cases an increase in carbon content under NT. The increase in organic matter was largest near the surface but increased slightly below 15 cm soil depth in the conservation tillage system. This attribute is referred as stratification of soil organic carbon in the profile (Franzluebbers 2002).

In this study, a higher stratification ratio was registered under NT (2.11) and RT (1.77) compared to CT (1.53). This indicates better soil quality and soil ecosystem functioning under no-tillage and reduced tillage than that in conventional tillage and MB tillage, as surface organic matter is essential to erosion control, water infiltration and conservation of nutrients. Similar findings were also reported by Franzluebbers (2002). The total carbon stock up to 30 cm depth was also higher in three residue retention treatments than in conventional tillage treatment (Table 12.1). This reasserts that, in Vertisols, the organic carbon stock can be improved through adoption of the conservation tillage system (Hati et al. 2015a).

Another study conducted to evaluate the long-term effect of three wheat residue management practices (residue burning, incorporation and surface retention) in combination with three supplementary nutrient inputs (SNI) – control, fertilizer and farmyard manure (FYM) – on stratification of SOC and phosphorus in the soybean–wheat system in Vertisol showed that wheat residue either incorporated or retained on the soil surface increased the availability of P and SOC content as compared to the common practice of residue burning. Residue retention or incorporation increased stratification of P and soil organic carbon over the residue burning. Irrespective of the nutrient treatments, the stratification ratio of SOC and P was greater under wheat residue incorporation or retention than under residue burning (Kushwah et al. 2016).

Besides this, the results of a short-term experiment conducted on a Vertisol with two tillage treatments, namely no-tillage (NT) and conventional tillage (CT), and five nutrient management practices indicated that soil organic carbon (SOC)

Table 12.1 Effect of tillage systems on soil organic carbon (SOC) content, stratification ratio (0–5 cm)/(15–30 cm) and SOC stock of the top 30 cm soil (Hati et al. 2015a)

Treatment	SOC content (g kg^{-1})				
Tillage system	0–5 cm	5–15 cm	15–30 cm	Stratification ratio	SOC stock (0–30 cm) (mg ha^{-1})
NT	10.4a	6.3b	5.0a	2.11a	24.96
RT	9.1b	6.6b	5.1a	1.77b	24.85
MB	8.3c	7.4a	5.4a	1.54b	26.08
CT	7.8d	5.9c	5.1a	1.53b	23.26

Different letters within a column indicate significant difference between values at $P < 0.05$

Table 12.2 Effect of short-term tillage treatment on soil organic carbon (SOC) concentration and SOC stock of the top 30 cm soil in a Vertisol (Hati et al. 2015b)

	SOC concentration (g kg^{-1})			Total SOC stock (0–30 cm depth) on soil
Treatment	0–5 cm	5–15 cm	15–30 cm	equivalent mass (mg ha^{-1})
Tillage system				
CT	9.8	7.6	5.7	28.18
NT	11.9	8.9	5.5	30.79
LSD (P = 0.05)	1.6	1.1	NS	1.82

concentration of the top 15 cm soil depth and SOC stock of the top 30 cm soil increased significantly under NT compared to that under CT (Table 12.2). Soil organic C stock of the top 30 cm soil was 9.2% higher under NT compared to that under CT practice. The proportion of macroaggregates (>250 μm) was also increased by 6.1% and 2.7%, respectively under NT compared to CT system in 0–5 and 5–15 cm soil layers. The study showed that the short-term no-tillage system could improve soil aggregation and SOC concentration of Vertisols in 0–15 cm soil layer while maintaining the yield level similar to that in the conventional tillage system in the soybean–wheat cropping system. Another experiment of conservation agriculture conducted in Vertisols reported that the SOC was higher in surface layer (0–15 cm) than in the subsurface (15–30 cm) under both tillage systems (Fig. 12.3). Conservation agricultural practices significantly improved SOC (5–6%) compared to conventional cultivation at 0–15 cm depth after completion of three crop cycles. Similarly, soil microbial biomass carbon (SMBC) significantly increased (6–12%) under reduced tillage (RT) compared to that in conventional tillage (CT) system after completion three crop cycles (Fig. 12.4).

12.5 Soil Aggregate Size Distribution and Sequestration of Organic Carbon in Aggregate Fractions

Stability of macroaggregates depends on the formation of bonding materials from soil organic matter. These consist of transient bonding agents comprised of microbial and plant-derived polysaccharides and temporary bonding agents derived from

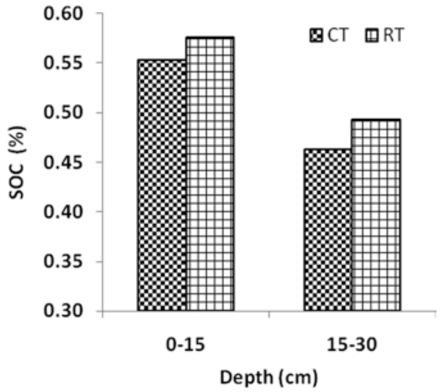

Fig. 12.3 Soil organic carbon after completion of third crop cycle

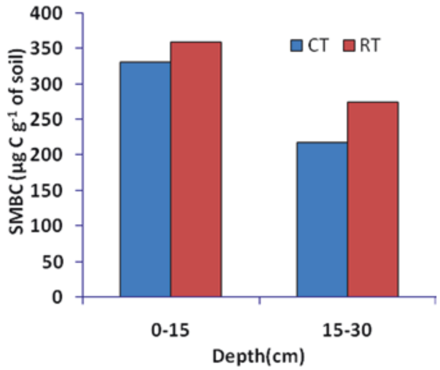

Fig. 12.4 Soil microbial biomass carbon under different tillage systems

roots and fungal hyphae, especially mycorrhizal hyphae (Tisdall and Oades 1982). The retention of crop residues in conservation tillage systems not only protected the soil surface from raindrop impact, but also provided organic materials as a precursor for aggregate formation. A study conducted at Indiana, USA (Griffith et al. 1992), showed that after 5 years of continuous corn cultivation, aggregation in the top 5 cm was increased by 120% for no-till and 35% for ridge-till systems compared to mouldboard ploughing. Removal of residues from the surface and exposing the surface soil through tillage for accelerated decomposition might be responsible for the reduction in aggregate stability under conventional tillage treatment. Physical fractionation of soil for aggregate-size fractions (i.e. wet sieving) has been an effective method for evaluating soil aggregation and degradation induced by management practices, studying the forms and cycling of SOC and providing important information about C sequestration mechanisms (Six et al. 2002a). Data collected from the long-term tillage experiment at IISS, Bhopal, showed that, at 0–5 and 5–15 cm soil depths presence of large macroaggregates (> 2000 μm) in both no-tillage and reduced-tillage systems was significantly higher than that in the conventional tillage system (Fig. 12.2). Similarly, the size fractions of small macroaggregates (2000–250 μm) were also higher in conservation tillage treatments than in conventional tillage treatment. However, the opposite trend was found in microaggregates (250–53 μm) and silt and clay size fractions (<53 μm). This showed that higher percentage of microaggregates were coalesced together in the presence of organic residues and microbial polysaccharides to form macroaggregates under the conservation tillage environment as suggested in the hierarchical model of aggregate formation by Tisdall and Oades (1982). Besides this, macroaggregates are less stable than microaggregates, and therefore, they are more susceptible to the disruption forces of repeated tillage operations in the conventional tillage system (Chen et al. 2009).

The organic carbon content in different aggregate size fractions decreased at lower size fractions under all types of tillage treatments. Larger aggregates generally store more amount of organic carbon in the form of particulate organic matter (POM), a semi-decomposed organic constituent. Stable macroaggregates physically protect a considerable proportion of organic matter from microbial decomposition within it through compartmentalization, making them inaccessible to microbes for decomposition. The organic carbon content was significantly higher in macroaggregates from no and reduced tillage than in the conventional tillage treatment (Fig. 12.5). At lower size fractions also, organic carbon content in conservation tillage was higher than that in the conventional tillage treatment. Organic carbon content in all the size fractions was lower at lower depths, namely 5–15 and 15–30 cm. Addition of organic residues and less disturbance of soil helped in enriching the organic carbon content of the aggregates from conservation tillage (Hati et al. 2013). No tillage here increased the amount of C-rich macro-aggregates and decreased the amount of C-depleted microaggregates. The highest percentages of organic carbon in Vertisols were found in small macroaggregate size fractions. Conservation tillage practices thus helped in sequestration of more carbon in macroaggregate size fractions in Vertisols. Aggregates help in sequestering carbon through compartmentalization, thus restricting the access of microbes to the organic matter inside the aggregates and also creating a relatively less aerobic environment within the aggregates.

Similarly, from 4-year long conservation tillage on a different cropping system experiment on a Vertisol of central India, Somasundaram et al. (2018) reported that

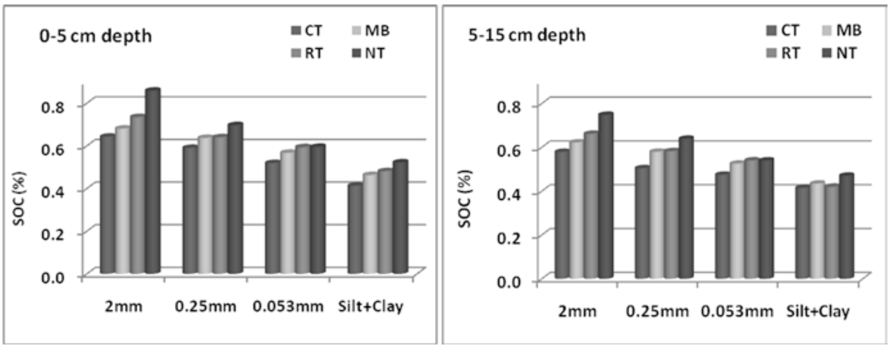

Fig. 12.5 Tillage influence on organic carbon content in different aggregate size fractions

conservation agriculture management had a positive effect on soil aggregation, aggregate stability and soil organic carbon content. Tillage practices also showed a significant positive effect on aggregate-associated C in large macroaggregates at 0–5 and 5–15 cm depths. More aggregate-C in large and small macroaggregates favoured better aggregation under NT and RT than under CT, which suggested that macroaggregates are sensitive to changes in the soil microbial community associated with short-term conservation management practices.

12.6 Conclusion

From the long-term study with the soybean–wheat cropping system on Vertisols, it was observed that management strategies such as NT and N application rate played a significant role in favouring SOC concentration and aggregate stability. Practices of conservation tillage resulted in an improvement of surface soil aggregation and an increase in the proportion of macroaggregates compared to conventional tillage. Conservation tillage increases the percentage of carbon-rich macroaggregates in the soil particularly in the surface layers, resulting in sequestration of more carbon into soil stabilized through physical protection. The effect of reduced tillage was in between NT and CT with respect to SOC concentration and aggregate distribution. The greatest enhancement of SOC in soil could be achieved through higher N dose coupled with NT. Thus, it may be concluded that NT with residue addition coupled with optimal dose of N is the most desirable management strategy for improving soil aggregation, enhancing SOC sequestration in Vertisols. Conservation tillage could also come out as a useful technology to partially mitigate the deleterious effect of climate change on humanity through sequestration of carbon into the soil and reduction of greenhouse gases emission from agricultural activities to atmosphere. It also improves soil health and its resilience to extraneous stresses. In India, through adoption of conservation agriculture, the long-term sustainability of agricultural productivity could be attained, and energy and nutrient use efficiency could be improved. However, for acceptability of this system to larger stakeholders, suitable implements, cropping systems and cover crops are to be assessed and also a crop-specific sustainable weed management package is to be developed for different agro-ecoregions.

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Effect of Tillage on Soil Carbon Sequestration

13

K. K. Bandyopadhyay

Abstract

Climate change, because of anthropogenic interventions, can pose a serious threat to the agriculture in coming years. Sequestration of the atmospheric CO_2 in soil can serve as one of the potential strategies in mitigation of global warming and improvement in soil health. Soil aggregates enhance C sequestration by physically protecting it from the microbial oxidation. Adoption of recommended management practices (RMPs) on agricultural soils can enhance carbon sequestration and reduce the rate of enrichment of atmospheric CO_2 and have positive impacts on soil health, food security and water and environment quality. The global potential of SOC sequestration through these practices is 0.9 ± 0.3 pg C/year, which may offset one-fourth to one-third of atmospheric CO_2 increase annually estimated at 3.3 pg C/year. Conservation agriculture involving minimum soil disturbance, residue retention and crop diversification is one of the important RMPs that can improve carbon sequestration. However, there are several constraints for soil carbon sequestration in the tropics and subtropics, which must be taken into consideration in designing carbon sequestration strategies. Site-specific and cost-effective technologies should be developed and disseminated among the farming community for improving carbon sequestration and enhancing input use efficiency for sustainable agricultural production under the changing climatic scenarios.

Keywords

Carbon sequestration · Climate change · Conservation tillage · Management practices · Soil aggregation

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13.1 Introduction

Climate change is one of the most serious challenges of the present century. Elevated concentration of greenhouse gases (GHGs) in the atmosphere is the major cause behind global warming and climate change. The atmospheric concentration of CO_2 has increased from 280 ppmv in 1750 to 410 ppmv in 2016 and is currently increasing at a rate of 1.5 ppmv or 3.3 pg C/year (IPCC 2001). Similarly, the atmospheric concentration of CH_4 has increased from 700 to 1745 ppbv and that of N_2O has increased from 270 to 314 ppbv during the same period. Since the industrial revolution, the global emissions of C are estimated as 270 ± 30 pg due to fossil fuel combustion and 136 ± 55 pg due to land use change and soil cultivation. Emissions due to land use change include those by deforestation, biomass burning, conversion of natural to agricultural system, drainage of wetlands and soil cultivation. Agriculture contributes to about 28% of the total GHG emissions, and out of this, 59% through enteric fermentation in ruminants, 23% due to rice cultivation, 12% due to emission from soil due to land use change, 8% due to manure application and rest 1% due to crop residue decomposition.

Carbon sequestration is defined as the process of transfer and secure storage of atmospheric CO_2 into other long-lived global pools including oceanic, pedologic, biotic and geological strata to reduce the net rate of increase in the atmospheric CO_2. Carbon sequestration can be a natural or anthropogenic-driven process. To mitigate climate change, CO_2 emissions can be reduced by adopting three strategies (Schrag 2007): (i) reducing the global energy use, (ii) developing low- or no-carbon fuel, and (iii) sequestering CO_2 from point sources or atmosphere through natural and engineering techniques.

Most of the cultivated soils have lost half to two-thirds of their original SOC pool with a cumulative loss of 30–40 mg C/ha. The depletion of soil C is accentuated by soil degradation caused by indiscriminate tillage operations and mismanagement of soil. Indiscriminate tillage operations lead to disruption of soil aggregates, and hence carbon locked inside those aggregates is exposed to microbial and enzymatic activity resulting in loss of this carbon to the atmosphere in the form of CO_2. Adoption of recommended management practices (RMPs) on agricultural soils can enhance carbon sequestration and reduce the rate of enrichment of atmospheric CO_2 and have positive impacts on food security, water quality and environment. The objective of an anthropogenic-driven process is to balance global C budget such that future economic growth is based on a 'C-neutral' strategy of no net gain in atmospheric C pool. A considerable part of the depleted SOC pool can be restored through adoption of RMPs like conversion of marginal lands into restorative land uses, adoption of conservation agriculture involving minimum soil tillage, cover crops, crop residue mulch and crop diversification, nutrient recycling, use of compost and efficient use of inputs in agriculture, that is, nutrient, water and energy. However, any such intervention with RMPs leads to increase in carbon in the surface soil, and it is very difficult to assess change in carbon content in the subsoil. The surface soil carbon is subjected to various atmospheric, anthropogenic and microbial forces and hence subjected to losses. Accordingly, any intervention that can increase carbon storage in the subsoil will help in carbon sequestration for a longer period. The natural rate of soil C sequestration through adoption of recommended management practices ranges from 50 to 1000 kg C/ha/year. The cumulative C sequestration potential is 30–60 pg over 25–50 years. The global potential SOC sequestration through these practices is 0.9 ± 0.3 pg C/year, which may offset one-fourth to one-third of the annual increase in atmospheric CO_2 estimated at 3.3 pg C/year. Besides mitigation of climate change, carbon sequestration helps in build-up of soil fertility, improves soil quality, improves agronomic productivity, protects soil from compaction and nurtures soil biodiversity.

13.2 Global Carbon Pools

There are five main global C pools, of which the largest is the oceanic pool estimated at 38000 pg and is increasing at a rate of 2.3 pg C/year (Fig. 13.1). The geological C pool comprising fossil fuel is estimated at 4130 pg and is the second largest pool, of which 85% is coal, 5.5% is oil and 3.3% is gas. Presently, coal and oil each account for 40% of global CO_2 emissions (Schrag 2007). Thus, the geological pool is depleting through fossil fuel combustion at the rate of 7.0 pg/year. The third largest pool is pedologic pool estimated at 2500 pg up to 1.0 m depth. It consists of two components: soil organic carbon (SOC) pool estimated at 1550 pg and soil inorganic pool (SIC) estimated at 950 pg (Batjes 1996). The SOC pool consists of highly active humus and relatively inert charcoal C. It comprises a mixture of (i) plant and animal residues at different stages of decomposition; (ii) microbially synthesized substances and/or chemically formed substances from the breakdown

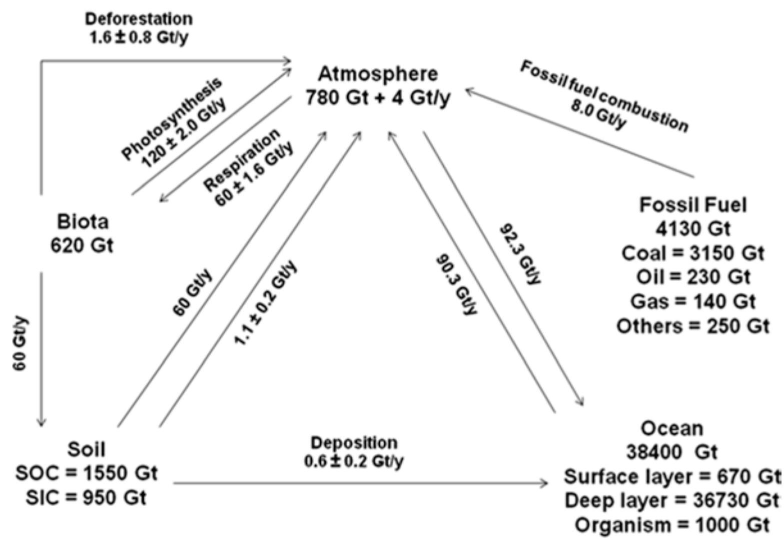

Fig. 13.1 Pools and fluxes of soil carbon (Schrag 2007)

products and (iii) the bodies of live microorganisms and small animals and their decomposing products (Schnitzer 1991). The SIC pool includes elemental C and carbonates of minerals such as calcite, dolomite and gypsum and comprises primary and secondary carbonates. The fourth largest pool is the atmosphere comprising 760 pg of CO_2–C and increasing at the rate of 3.5 pg/year or 0.46%. The smallest among the global pools is the biota pool estimated at 560 pg. The pedologic pool and the biotic pool together is called the terrestrial C pool estimated approximately 2860 pg C. The terrestrial and atmospheric pools strongly interact with one another. The annual rate of photosynthesis is 120 pg C, which is called gross primary productivity (GPP), whereas the respiration is 60 pg C/year. So the net primary productivity (NPP) is 60 pg C/year. The terrestrial C pool is depleted by conversion from natural to managed ecosystem, extractive farming practices based on low external inputs and soil-degrading land use. Among all the pools, C sequestration in the terrestrial pool is most economic and has no negative impact or threat rather has positive impact in the ecosystem and hence is a “win–win” practice (Lal 2011). The terrestrial sink is presently increasing at a rate of 2–4 pg C/year, and its capacity may increase to approximately 5 pg C/year by 2050.

13.3 Importance of Carbon Sequestration

Carbon sequestration builds soil physical and chemical fertility, improves soil quality and hence improves input use efficiency and agronomic productivity (Fig. 13.2). It increases organic matter in soil; improves soil aggregation, which in turn improves

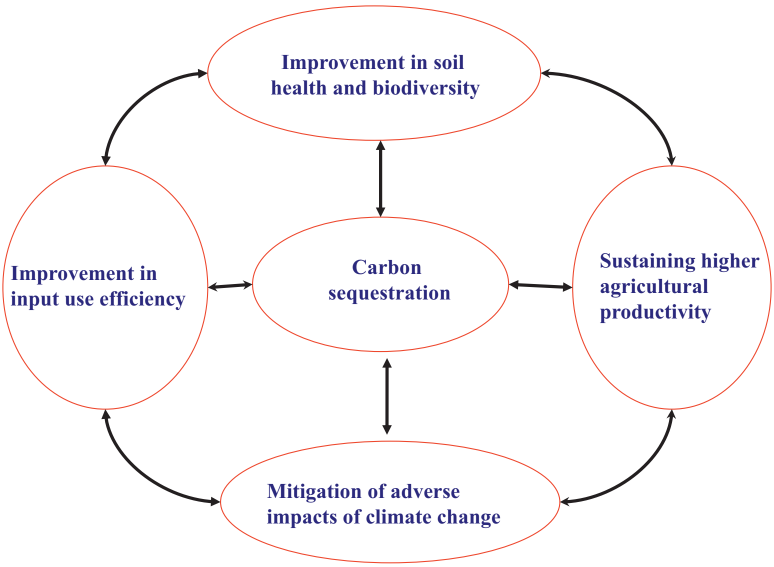

Fig. 13.2 Potential benefits of soil carbon sequestration

soil aeration; improves infiltration; soil water storage; reduces soil erosion; and generally improves surface and groundwater quality. It is also helpful in the protection of streams, lakes and rivers from sedimentation; runoff from agricultural fields; and enhanced wildlife habitat. Besides these, it has major roles in mitigating GHG emissions and tackling the effects of climate change.

13.4 Principle Behind the Process of Carbon Sequestration

In terrestrial ecosystem, through the process of photosynthesis, plants assimilate 120 Gt C/year and return 60 Gt C/year to the atmosphere through respiration. The carbon that remains in plant tissues is either consumed by animals or added to the soil as litter when plants die and decompose. The primary way by which carbon is stored in the soil is as soil organic matter (SOM). SOM is a complex mixture of carbon compounds, consisting of decomposing plant and animal tissues, nematodes, microbes (protozoa, fungi and bacteria), and carbon associated with soil minerals. Carbon can remain stored in soils for millennia or be quickly released back into the atmosphere. Factors such as climatic conditions, natural vegetation, soil texture and drainage all affect the amount and length of time carbon is stored.

Soil aggregates enhance C sequestration by physically protecting it from the microbial activity (Gregorich et al. 1997). Current state-of-the-knowledge based on the existing models leads to the concept that C sequestration is a function of the architectural system of soil aggregate packing. The SOC turnover decreases from macro- to microaggregates, thereby implying that there is a greater physical protection of SOC in microaggregates, which could be translated into greater SOC sequestration. The SOC is first enmeshed in macroaggregates and then emerges as a dynamic nucleus for the formation of microaggregates. The SOC is essential for the formation of macroaggregates because it is a primary source of energy for the microorganisms responsible for binding soil particles (Six et al. 1999). Macroaggregates promote higher storage of SOC than microaggregates (Puget et al. 1995); however, this storage is transient (Sainju et al. 2003). Microaggregates, in contrast, promote long-term SOC sequestration, implying that C sequestration would decrease with increasing aggregate size.

The position of SOC in the aggregates and its chemical nature affects the rate of its decomposition (Elliott et al. 1996; Christensen 1996; Besnard et al. 1996), and hence, GHG emissions differ in the micro- and macroaggregates. Organic matter of recent plant origin is believed to be preferentially recovered in sand-size fraction (particulate organic matter), whereas more microbially processed material can be found in the silt- and clay-size fraction (mineral-associated organic matter) (Chesire and Mundie 1981). Camberdella and Elliott (1992, 1993) and Campbell et al. (1995) suggested that the labile organic pool within macroaggregates of grassland soils is either particulate organic matter or relatively low-density, mineral-associated organic matter, probably of microbial origin. On the other hand, the microaggregates are more resistant to microbial decomposition than macroaggregates (Elliott 1986). It was observed that the C and N mineralization rate was greater in the macroaggregates than in the microaggregates, and mineralization was enhanced when the macroaggregates were crushed to the size of microaggregates (Elliott 1986). Similar observations were also made by Aoyama et al. (1999), who reported that the amount of mineralized C in intact aggregates increased with the increase in the aggregate size irrespective of the agronomic treatments. However, there were no consistent trends for the N mineralization in relation to aggregate size. Nonetheless, crushing the aggregates enhanced the mineralization of C by 14–35% and that of N by 17–103% (Aoyama et al. 1999). Thus, the SOM associated with the macroaggregates was more labile and less processed than that associated with the microaggregates. Manna et al. (2005) reported that the C and N mineralization rate was greater in the macroaggregates than in the microaggregates and was correlated significantly with the POM-C and POM-N, respectively, in a long-term fertilizer experiment. Bandyopadhyay and Lal (2014) also reported that emissions of CO_2 and N_2O were higher from macroaggregates than from microaggregates. It was reported that the particulate organic matter is more sensitive to changes in management practices than the total organic matter (Camberdella and Elliott 1992; Franzlubbers and Arshad 1992; Chan 1997; Bowman et al. 1999; Needelman et al. 1999). Therefore, particulate organic matter has been recognized as a sensitive index of soil quality (Franzlubbers and Arshad 1992; Wander et al. 1994; Chan 1997; Wilson et al. 2001). Particulate organic matter had significant correlation with macroaggregate stability and mineralizable nitrogen (Chan 1997). Wilson et al. (2001) also reported strong correlation between particulate organic matter and N mineralization under different farming systems with varying rotations, forms of tillage and cover crops.

The SOC sequestration in the soil is governed by the degree of physical, chemical, biochemical and physicochemical stabilization of SOM inside the aggregates (Fig. 13.3). Aggregates protect SOM physically by forming physical barriers between microbes and enzymes and their substrates and controlling food web interactions and, consequently, microbial turnover. Chemical stabilization involves chemical or physicochemical binding between SOM and soil minerals (i.e. clay and silt particles, clay type). Biochemical stabilization includes stabilization of SOM due to its own chemical composition (e.g. recalcitrant compounds such as lignin and polyphenols) and through chemical complexing processes (condensation reactions). Physicochemical interactive mechanisms define the maximum SOC sequestration capacity in a soil (Six et al. 2002). The encrustation of SOM in the centre of microaggregates is the fundamental pathway to SOC sequestration (Tisdall and Oades 1982; Golchin et al. 1994). This process of encrustation prevents organic matter from physical and chemical decomposition by microbial processes while sequestering SOC. The protected SOC pool stabilizes microaggregates, while microaggregates protect the SOC from microbial processes.

The SOM comprises a large and heterogeneous pool of C-enriched compounds. So the residence times of SOC in the organic pools range from a few minutes to hundreds of years. Residence times of relatively labile organic matter can be about 7 years in both silt and clay particles, whereas residence times for stable organics can reach 400 years in silt and up to 1000 years in clay (Buyanovsky et al. 1994).

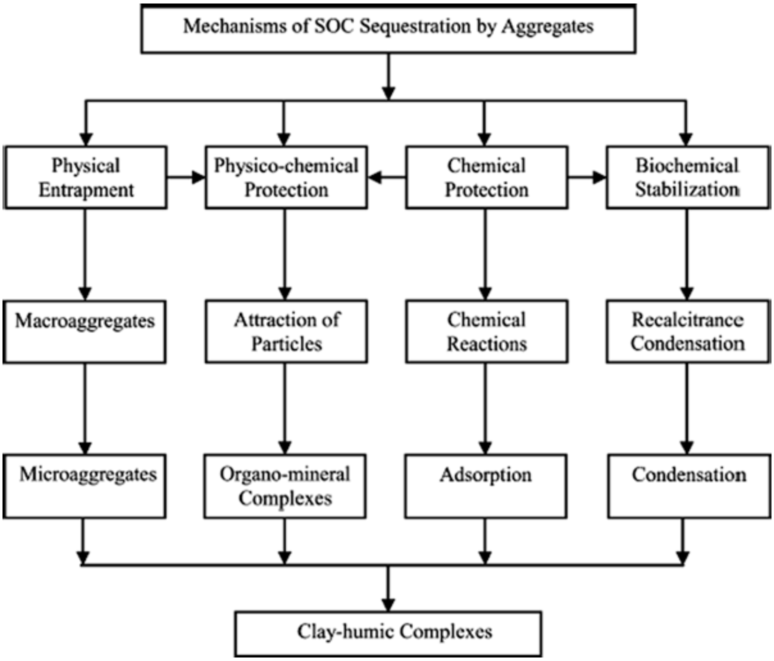

Fig. 13.3 Pathways of soil organic carbon (SOC) sequestration by aggregates (Lal 2004a)

Residence times of SOC in macro- and microaggregates may differ because of (i) differences in physiochemical attraction between mineral and organic particles and (ii) location of the organic-binding agents within the aggregates (Emerson 1959). The SOC residence time depends on the geochemical composition (Greenland, 1965), bonding agents (Tisdall and Oades 1982) and size (Camberdella and Elliot 1993; Six et al. 2000) of aggregates. Residence time of C increases with decreasing aggregate size. Losses of SOC from macroaggregates are faster and larger than those from microaggregates due to the differences in physical and chemical protection.

The SOC protection is proportional to the specific external surface area of the clay particles, and to the monolayer interfaces between clay and sand particles. Emerson (1959) found that organic matter unavailable to microbial processes is confined between the clay crystals. The stabilizing power of clay is high; hence, clay soils contain more SOC than sandy soils (Wild, 1988). Montmorillonitic clays store and protect SOC more than illitic and kaolinitic clays because montmorillonites possess greater surface area, more interlayer spaces, and higher swell and shrink potential than illites and kaolinites. Montmorillonites protect SOC by preventing the microbes from accessing the C-rich organic substrates, controlling microbial population and preserving the microbial metabolites (Wild 1988). Bhattacharyya et al. (2009) reported that short-term conservation tillage and continuous leguminous cropping under rainfed conditions improved SOC and total soil nitrogen (TSN) storage in the soil surface due to better soil aggregation in the Indian Himalayas.

13.5 Management Options for Enhancing C Sequestration

The technological options for sequestration of atmospheric CO_2 into one of the other global C pools can be broadly grouped into two categories: abiotic and biotic sequestration.

Abiotic Sequestration It is based on physical and chemical reactions and engineering techniques without intervention of living organisms (e.g. plant and microbes). The abiotic strategy of C sequestration in oceanic and geological structures has received considerable attention (Freund and Ormerod 1997) because, theoretically, abiotic sequestration has a larger sink capacity than biotic sequestration. It includes (i) oceanic injection, (ii) geological injections and (iii) scrubbing and mineral carbonation.

Biotic Sequestration It is based on management intervention of higher plants and microorganisms in removing CO_2 from the atmosphere and also the anthropogenic interventions to reduce emissions or offset emission. Increasing use efficiency of inputs (e.g. water, nutrient and energy) also contributes to increasing terrestrial C sequestration. The biotic sequestration includes C sequestration in oceans, forest ecosystem, wetlands and soil carbon sequestration.

The strategy to enhance soil carbon sequestration involves increase of SOC density in soil, improves depth distribution of SOC and stabilizes SOC by encapsulating it within stable microaggregates so that C is protected from microbial processes or as recalcitrant C as humus with long turn over time. For increasing SOC sequestration, the management options include (i) conservation tillage, (ii) cover crops, (iii) efficient nutrient management, (iv) efficient water management, (v) restoring degraded soils, (vi) practising crop diversification and efficient cropping system, (vii) minimizing soil and water erosion, (viii) efficient pasture management, (ix) afforestation and efficient forest management and (x) efficient management of urban soils.

13.6 Effect of Tillage on Soil Carbon Pools

Tillage is the practice of physical manipulation of soil by digging, stirring or overturning, which makes the soil suitable for crop production. Soil tillage is one of the important factors affecting soil physical properties and crop yield. Tillage practices change the physical, chemical and biological environment of soil. These, in turn, influence crop growth and yield and thereby the input use efficiency of crops. Tillage either loosens or compacts the soil and changes its volume and mass relationship, changes clod-size distribution, increases surface roughness and soil porosity and kills weeds. These changes affect soil–water regime, resistance to erosion, mechanical impedance, soil aggregation, aeration status, soil temperature and hence many biogeochemical cycles. Tillage practices influence soil carbon storage mainly through its effect on soil aggregation turnover. Excessive conventional tillage operation leads to the breakdown of macroaggregates, and hence, carbon locked inside them is exposed to microbial and enzymatic action and lost to the atmosphere as CO_2, which ultimately causes global worming leading to climate change. However, conservation tillage practices involving minimum soil disturbance and residue retention leads to protection of soil aggregates, and hence, the carbon locked inside it is sequestered for longer period. Second, improvement in crop growth due to conservation tillage practices adds more root and shoot biomass to soil, which also contributes towards carbon sequestration.

13.6.1 Conservation Tillage and Carbon Sequestration

Conservation tillage practice includes minimum soil disturbance and retention of residues either on soil surface or anchored to soil surface. This concept has been modified to encompass crop diversification, and the modified management practice is called conservation agriculture (Table 13.1), which includes minimum soil disturbance, retention of residues and crop diversification. Several studies compare soil organic carbon (SOC) in conventional and conservation tillage systems. Tillage generally disrupts aggregation and exposes particulate organic matters (POM), which decompose quickly by microbial action. Reduced C sequestration in conventional tillage (CT) compared to no-tillage (NT) is due to differences in aggregates and aggregate-associated carbon. A study revealed that concentration of fine iPOM (intra-aggregate POM) was less in CT than in NT macroaggregates. On a whole soil

Table 13.1 Comparison between traditional methods and recommended management practices (Lal 2011)

Sl. no.	Traditional methods	Recommended management practices
1.	Biomass burning and residue removal	Residue return as surface mulch
2.	Conventional tillage and clean cultivation	Conservation tillage, no till and mulch farming
3.	Bare/idle fallow during off-season	Growing cover crops during off-season
4.	Continuous monoculture	Crop rotations with high density
5.	Low-input subsistence farming and soil fertility mining	Judicious use of off-farm inputs
6.	Intensive use of chemical fertilizers	Integrated nutrient management with compost, bio-solids and nutrient cycling, precision farming
7.	Intensive cropping	Integrated trees and livestock with crop production
8.	Surface flood irrigation	Drip, furrow or sub irrigation
9.	Indiscriminate use of pesticides	Integrated pest management
10.	Cultivating marginal soils	Conservation reserve programme, restoration of degraded soils through land use change

basis, fine iPOM C was 51% less in CT than in NT and accounted for 21% total carbon difference between NT and CT. The concentration of free light fraction (LF) was not affected by tillage but was on average 45% less in CT than in native vegetation (Six et al. 1999). The results suggest that switching from CT to zero-till would clearly reduce on-farm emissions (Maraseni et al. 2010). Vanden Bygaart et al. (2003) found that reduced tillage increased the amount of carbon sequestered by an average of 320–150 kg C/ha in 35 studies of western Canada and that bringing the fallow land under cultivation enhanced soil carbon storage by 150–60 kg C/ha based on 19 Studies. West and Marland (2002) reported that carbon emission from conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) were, respectively, 72.02, 45.27 and 23.26 kg C/ha in case of corn cultivation and 67.45, 40.70 and 23.26 kg C/ha for soybean cultivation based on annual fossil fuel consumption and CO_2 emission from agricultural machinery. Thus, there was 67.70% and 65.41% reduction in CO_2 emission due to no-tillage as compared to conventional tillage for corn and soybean cultivation, respectively. Mosier et al. (2006) reported that based on soil C sequestration, only NT soils were net sinks for GWP and economic viability, and hence, environmental conservation can be achieved by minimizing tillage and utilizing appropriate levels of fertilizer. Ghosh et al. (2010) reported that double no-till practice in the rice-based system was cost-effective, restored soil organic carbon (70.75%), favoured biological activity (46.7%), conserved water and produced yield (49%) higher than that in conventional tillage. Das et al. (2013) reported that zero tillage with bed planting (ZT-B) and zero tillage with flat planting (ZT-F) had nearly 28% and 26% higher total SOC stock than the conventional tillage with flat and bed planting (CT-B) (~5.5 mg ha^{-1}), respectively, in the 0–5 cm soil layer. Plots under ZT-B and ZT-F contained higher total SOC stocks in the 0–5 and 5–15 cm soil layers than CT-B plots under the cotton–wheat system in a sandy loam soil of the Indo-Gangetic Plain region. Hati et al. (2015) reported that due to the retention of crop residues and minimum disturbance of the surface soil, the organic carbon content and physical properties like aggregation and saturated hydraulic conductivity of the soil under no-tillage and reduced tillage were improved compared to the conventional tillage system. The no-tillage system accumulated a higher amount of organic carbon near the surface soil layer under the soybean–wheat system in a Vertisol.

Paustian et al. (1997) reported that the SOC content in no-till (NT) was significantly higher than that in the conventional tillage (CT) due to reduced litter decomposition and less soil disturbance in NT. The reduced rate of litter decomposition may be due to the micro-climate less conducive to microbial activity in the surface layer and less soil to residue contact. The disturbance-related soil organic matter (SOM) losses in CT versus NT may be attributed to reduced aggregation in CT when compared with NT and increased decomposition due to aggregate disruption in CT (Beare et al., 1994). Six et al. (1999) reported that a faster turnover rate of macroaggregates in CT than in NT leads to a slower rate of microaggregate formation within macroaggregates and less stabilization of new SOM in free microaggregates under CT. Lal et al. (1999) reported that NT can have a positive effect on SOM storage, and therefore, it can contribute to mitigation of CO_2 emissions from agricultural soils. Abid and Lal (2008), Madari et al. (2005), Mando et al. (2005) and Li et al. (2007) reported significant increase in the SOC concentration under NT compared with the CT system. However, Bandyopadhyay and Lal (2015) reported that although there was increase in the concentration of total C and N in NT compared to that in CT by 12.7% and 15.1%, respectively, the effect was not statistically significant. Similar trends were reported by Salinas-Gracia et al. (1997), Franzlubers and Arshad (1997) and Jarecki et al. (2005). Rasmussen and Collins (1991) hypothesized the importance of temperature-limiting changes in SOC due to tillage management, that is, lower temperatures are not conducive to drastic changes in SOC concentration.

In a survey of 29 farms in the Piedmont and Coastal Plain regions of the southeastern USA, it was observed that on an average soil organic C sequestration under pasture was higher than that by conventional tillage under croplands by 0.53 mg C/ha/yr at a depth of 0–5 cm ($p < 0.01$), 0.17 mg C/ha/yr at a depth of 5–12.5 cm ($p < 0.01$) and 0.05 mg C/ha/yr at a depth of 12.5–20 cm ($p > 0.05$) with a total of 0.74 mg C/ha/yr to a cumulative depth of 0–20 cm (Causarano et al. 2006). So the impact of conservation tillage on carbon sequestration is mostly visible in the surface layer. Therefore, stratification ratio of soil organic carbon is more in case of conservation tillage than conventional tillage treatments. High stratification ratios of soil C and N pools could be good indicators of dynamic soil quality, independent of soil type and climatic regime, because ratios >2 would be uncommon under degraded conditions (Franzlubbers 2002).

13.6.2 Impact of Tillage and Crop Residue Management on Carbon Sequestration

The impact of conservation tillage and crop residue combination has shown a remarkable potential for C sequestration as compared to conservation tillage alone. Conservation agriculture, based on the use of crop residue mulch and no-till farming, can sequester more SOC through conserving water, reducing soil erosion, improving soil structure, enhancing SOC concentration and reducing the rate of enrichment of atmospheric CO_2 (Lal 2004a). Doraiswamy et al. (2007) found that ridge tillage in combination with fertilizer and crop residue is very effective in SOC sequestration through erosion control. Ghimire et al. (2008) reported that SOC sequestration could be increased with minimum tillage and surface application of crop residue and SOC sequestration was highest in the top 0–5 cm soil depth irrespective of the tillage and crop residue management practices. They observed that soil (0–50 cm depth) retained 8.24 kg C/m^3 under no-tillage practice, which was significantly higher than 7.86 kg C/m^3 from conventional tillage treatment (Table 13.2). Crop residue treatment in no-tillage soils sequestered significantly higher SOC than any other treatments in soil depth of top 15 cm. Crop residue served as a source of carbon for these soils, especially in the upper soil depths. No-tillage practice minimizes exposure of SOC from oxidation, ensuring higher SOC sequestration in surface soils of no-tillage with crop residue application.

Table 13.2 Soil organic carbon content as affected by interaction of tillage × crop residue management in different soil depths (Ghimire et al. 2008)

	Soil organic carbon (kg/cm^2)				
	Conventional tillage		No tillage		
Soil depth (cm)	Mo	M1	Mo	M1	LSD
0–5	11.01	12.12	12.73	14.23	1.72
5–10	8.53	10.83	10.08	10.94	1.72
10–15	7.13	9.26	10.11	8.06	1.72
15–30	4.63	5.73	5.80	4.82	1.72
30–50	4.43	4.90	4.69	3.99	1.72
0–50	7.15	8.57	7.81	8.68	0.77

Mo: No crop residue M1: Crop residue at 4 ton/ha for each crop in the rotation

Suman et al. (2009) reported that changes in residue management and incorporation of organic manures may help in carbon sequestration by restoring soil organic carbon (SOC).

13.6.3 Impact of Tillage and Crop Rotations on Carbon Sequestration

Crop rotations in combination with conservation tillage sequestered more soil carbon compared to monocropping as reported by many researchers conducting several field experiments under different climatic conditions (Meyer-Aurich et al. 2006; Yang and Kay 2001; Sainju et al. 2006). Meyer-Aurich et al. (2006) conducted an experiment with two levels of tillage and eight different corn-based crop rotations and found that continuous alfalfa rotation had the highest sequestration rates at 513 kg C/ha/year. The continuous corn and the rotations involving cereals had carbon levels between the highs noted for rotations with alfalfa and the lows for rotations with soybeans. The integration of legumes into corn-based cropping systems provides multiple benefits, including higher yields, cost savings, carbon sequestration and the mitigation of GHGs. Carbon storage of soils in the corn–corn–alfalfa–alfalfa rotation was significantly higher than in the corn–corn–soybean–soybean rotation. Rotations, which included cereals and red clover, had soil carbon levels between those observed for continuous alfalfa and a corn–corn–soybean–soybean rotation. Crop rotation is very effective in carbon sequestration than continuous cultivation of a single crop year to year. Mandal et al. (2007) reported that rice–mustard–sesame (1.91 mg C ha^{-1} year^{-1}) registered a significantly higher rate of carbon sequestration than that of the rice–fallow–rice (0.28 mg C ha^{-1} year^{-1}) and rice–wheat–fallow (0.27 mg C ha^{-1} year^{-1}) systems. Inclusion of crops that leaves behind enhanced crop residues and/or root carbon facilitates higher SOC sequestration. They observed that besides quantity, the quality of residue also decides the rate of SOC sequestration. The residues with a wider C:N ratio (rice and wheat) facilitate higher SOC sequestration than residues with a narrower C:N ratio (jute, berseem, etc.). Bhattacharyya et al. (2012) reported that adoption of continuous NT is the best management option for improvement of soil C under a rainfed lentil [*Lens esculentus* (L.)]–finger millet [*Eleusine coracana* (L.) Gaertn.] cropping system in the Indian Himalayas, as the management practice has the potential to improve productivity and soil aggregation with greater accumulation of POM-C and SOC stabilization apart from other known benefits like weed control, less cultivation cost and higher profits.

Cropping and pasture systems were compared for soil organic C enrichment in Georgia, and it was observed that soil organic C was greater near the soil surface under pasture than under conservation-tilled cropland, which was in turn greater than that under conventional-tilled cropland. In several field experiments, crop rotation including legume crops was found to be more beneficial for carbon sequestration. Even under conventional tillage, crop rotations increase the rate of carbon sequestration than that of monocropping, and with conservation tillage in combination with crop rotation, the rate is much higher than the former (Gaisera et al. 2009). Franzlubbers (2010) reported greater soil organic C accumulation under pastures than under annual crops due to longer growing periods, more extensive root system and less soil disturbance.

13.7 Constraints in Soil Carbon Sequestration

Despite the benefits of carbon sequestration, there are several constraints for soil carbon sequestration as given below that must be taken into account when designing any carbon sequestration strategies (Lal 2011).

- In the tropics and subtropics, the climate is harsh and the resource-poor farmers cannot afford the off-farm inputs.
- There are biophysical constraints on agricultural production.
- SOC sequestration requires input of crop residues/biosolids and fertilizers/manures to enhance biomass production. However, there are alternate competing demands of these inputs.
- Hidden carbon costs are involved with the agricultural inputs.
- The rate of C mineralization is high than its rate of humification in the tropics.
- There is finite sink capacity of the SOC pool.

13.8 Conclusion

All the above discussions indicate that tillage practices can influence carbon sequestration in soil and thereby CO_2 concentration in atmosphere. Indiscriminate tillage practices lead to disruption of soil aggregates and hence loss of carbon locked inside it to the atmosphere in the form of CO_2, which gives a positive feedback to global warming and climate change. Recommended management practices like conservation tillage, crop rotation, residue management and integrated nutrient management can help in improving soil carbon sequestration. Conservation agriculture practices involving minimum tillage, residue retention and crop diversification have a great potential for soil carbon sequestration. Efficient use of agricultural inputs leads to reduced greenhouse gas emissions and results in carbon sequestration. Sequestration of carbon in soil can improve soil health, and improvement in soil health will help in improving input use efficiency in agriculture, and hence, it is a win–win situation. Site-specific technologies should be developed and disseminated for improving carbon sequestration and enhancing input use efficiency.

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Part III

Soil Physical and Biological Factors Regulating SOC Storage

Functional Behaviour of Soil Physical Parameters for Regulating Organic C Pools

14

P. K. Bandyopadhyay

Abstract

Soil organic carbon (SOC) is one of the critical components of the global carbon cycle, and the study of SOC accumulation, protection and stabilization is important in evaluation and maintenance of soil fertility and environmental quality. A number of physical parameters regulate the content and fate of reactive components of SOC pools. Physical mechanisms include encapsulation of SOC through organo-mineral complexes where finer particles with high surface activity determine the structural integrity. Soil bulk density and pore geometry are responsible for C protection and decomposition. Agricultural management practices with tillage and residue management control labile and non-labile SOC pools and their array within different aggregate size fractions. Soil moisture and temperature play a key role in influencing soil microbial properties and SOC decomposition.

Keywords

Aggregate stability · Labile carbon · Organo-mineral complex · Temperature sensitivity · Water retention

14.1 Introduction

Maintaining or enhancing soil organic carbon (SOC) is important for improving soil quality and mitigating carbon dioxide (CO_2) emissions. Understanding the factors and processes that affect the stocks of carbon in the soil is of paramount importance. Tillage and residue management have been identified as major land management factors controlling SOC dynamics in agricultural soils (Mehra et al. 2018). For

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understanding and modelling of SOC, much of the work is done on the study of relative decomposition rates for various SOC pools and their controlling physico-chemical factors. Several studies identified that among the soil physical factors, texture, soil friability, moisture retention, temperature, compaction, etc., had an impact on SOC pools and could act as rate modifiers (Saggar et al. 1996; Watts and Dexter 1998; Thomsen et al. 1999; Schjonning et al. 1999; Balesdent et al. 2000; Wang et al. 2013). Some important physical parameters that affect SOC pools are briefly discussed here to develop a model for projection of changes in terrestrial C sequestration in the future.

14.2 Soil Texture and Surface Area

Soil organic matter (SOM) content as well as different SOC pools are influenced by several factors such as clay content and its mineralogy, soil structure, bulk density, pore geometry, soil moisture, temperature and soil management techniques (Lugato and Berti 2008; Lucas and Weil 2012). Soil texture provides an insight into the properties of soils influencing the hydrological processes and the capacity of soils to store organic C. According to Six et al. (2002), soil texture protects SOM by physical, chemical and biological mechanisms from being decomposed. It is suggested that chemical stabilization of organic molecules takes place through mineral–organic matter bonds from the start (Gonzalez and Laird 2003) and formation of organo-mineral complexes can store SOC for millennia.

The SOC is a highly reactive component, and is the basis of numerous pedogenic processes. Because of the high surface area and charge density, it reacts with clay and minerals to form organo-mineral complexes. The mean residence time (MRT) or the rate of SOC turnover depends on the degree of protection within the soil matrix (Dungait et al. 2012). Physical mechanisms include encapsulation within stable microaggregates (Six et al. 2000, 2002), formation of organo-mineral complexes and transfer deep into the subsoil away from the zone of natural and anthropogenic perturbations. In numerous studies, it is suggested that SOC storage depends on soil texture (Bosatta and Agren 1997; Hassink 1997). Different soil textural classes are important variables in SOC accumulation ratio and C sequestration (McLauchlan 2006). The potential of soils to sequester C is intimately associated with the content and nature of their clay fraction. Sandy soils, which tend to be well aerated and have little adsorptive capacity, generally retain little organic matter. Clayey soils, on the other hand, form strong physicochemical bonds between the active surfaces of the clay particles and the organic macromolecules of humus, which thus become resistant to further decay. According to some evidence, clay concentration affects SOC accumulation in different ratios. It was found that maximum to medium SOC increased with increasing clay content in soil (Nichols 1984; Burke et al. 1989). However, this relationship could not be generalized as SOC was sometimes much more strongly related to other factors such as extractable aluminium, allophone content or physical surface area, which can pull out more SOC than clay (Percival et al. 2000; Krull et al. 2003). The relationship between clay concentration and SOC content was expressed to be strong (at a sufficient level) according to SOM models such as Century (Parton et al. 1987) and RothC (Jenkinson 1990). It was found that, if other factors were fixed, as clay concentration increased, SOC accumulated faster (Jenkinson 1990). As the clay constituents increase, they combine with SOC to form tight water-resistant stable aggregates, the interiors of which restrict aeration and further resist the decay of occluded organic matter. For these reasons, soil texture plays a direct and an indirect role in chemical and physical protection mechanisms (Plante et al. 2006).

Clay content has a different effect on the accumulation of different SOC pools (Franzluebbers et al. 1996). It was found that the SMBC-to-SOC ratio increased with increasing clay content; however, the mineralizable C-to-SOC ratio was not affected by the clay content. According to Sorenhen (1981) and Hassink (1994), clay content affects the turnover of active carbon pools and stabilization efficiency of slow carbon pools, although some workers (Gregorich et al. 1991; Wang et al. 2003a; Muller and Hoper 2004) found no significant effect of soil texture on the rate of decomposition of SOC. On the other hand, Franzluebbers et al. (1999a, b) and Wang et al. (2003a, b) observed a negative correlation between clay content and the rate of SOC decomposition, while others (Nichols 1984; Burke et al. 1989; Schjonning et al. 1999; Kölbl and Kögel-Knabner 2004; Arrouays et al. 2006; Plante et al. 2006) found a strong positive relationship between clay and SOC. Soil textural effects on SOC decomposition could be confounded by clay mineralogy, chemistry of SOM, microbial composition, inhibiting or toxic factors such as extreme pH or heavy metals and other soil properties that are related to the clay content of soils tested. Such confounding effects are more difficult to find out when only a small number of soils are used (Wang et al. 2003a, b). Numerous studies have described that the clay (or clay + silt) content is a relatively important determinant of SOC levels in soils and appears to apply to both cultivated soils and soils under natural vegetation (Parton et al. 1993; Feller and Beare 1997; Bandyopadhyay et al. 2010). Therefore, the formation of passive organic C pools with low turnover rates can be facilitated by clay-rich soils, as clay particles can physically and chemically protect SOC in organo-mineral complexes (Von Lutzow et al. 2006). Increasing concentrations of C levels in soils may occur in clay-rich soils, as C can be captured within the small pores of clay particles (Feller and Beare 1997). Clay also helps to protect SOC from breakdown by binding strongly and creating a physical barrier to protect microbial access. In most cases, clay soils in the same soil conditions under the same land uses will tend to retain more C than sandy soil. It has been suggested that fine particles with high surface activity of clay may physically and chemically protect SOM from decomposition (Tisdall and Oades 1982; Hassink et al. 1993a, b).

14.3 Soil Structure and Aggregation

Soil structure is the key feature of soils that mediates the coupling between biogeochemical and hydrological processes. Aggregation of soil particles can occur in different patterns, resulting in different soil structures. Aggregation is important for increasing stability against erosion, maintaining porosity and soil water movement, and improving fertility and C sequestration in the soil. The interrelationship between SOC and soil structure has been extensively studied, and excellent reviews can be found in Tisdall and Oades (1982), Oades (1984) and Carter and Stewart (1996). While early models of soil aggregation proposed a direct relationship between the specific surface area of clay minerals and SOC storage in soil aggregates (Emerson 1959), most contemporary concepts are based on the model suggested by Oades (1984). C accumulation is facilitated through the formation of a soil macroaggregated structure, and it is expected that the age of recovery has an influence on the distribution of soil aggregates and SOC. Whenever soil aggregates are disrupted by mechanical tillage, soil structure is prone to deteriorate, and SOM tends to decompose more rapidly.

It is well established that addition of SOM can not only reduce bulk density and increase water-holding capacity (WHC) but also effectively increase soil aggregate stability. Angers and Carter (1996) noted that the amount of water-stable aggregates (WSA) was often associated with SOC content, and particularly, labile C was often positively related to macroaggregate stability. Kay and Angers (1999) reported that a minimum of 2% SOC was necessary to maintain structural stability and observed that when SOC content was between 1.2% and 1.5%, stability declined rapidly. Therefore, a threshold of 3.0–3.5% SOC needs to be attained to achieve increases in aggregate stability (Boix-Fayos et al. 2001).

In aggregate hierarchy model, three principal organic-binding agents are involved in the aggregate formation and stabilization: transient, temporary and persistent organic matter (Tisdall and Oades 1982; Oades and Waters 1991). Transient organic-binding agents are rapidly decomposed by microorganisms and are thought to be composed mostly of glucose-like components (mono- and polysaccharides), lasting effectively only for a period of a few weeks, after which their effect diminishes. Temporary organic-binding agents consist of roots and hyphae and may persist for months and years. Persistent organic-binding agents are composed of degraded humic materials mixed with amorphous forms of Fe, Al and Al-silicates. Tisdall and Oades (1982) proposed that the 'fresh' or 'active' part of SOM (consisting of mono- and polysaccharides, exudates from roots and fungal hyphae) is largely responsible for stabilization of aggregates. The key aspect of aggregate formation by polysaccharides is due to the presence of functional groups, which, upon deprotonation, become negatively charged and interact with positively charged oxides, producing stable organic–inorganic microstructures (Oades et al. 1989). However, they found that variation of strength and time for the formation of aggregates was due to the variability of organic matter. Hence, the concept of aggregate hierarchy suggests that organic matter controls aggregate stability and degradation of large (relatively unstable) aggregates creates smaller, more stable aggregates.

Large aggregates (>2000 μm) are hypothesized to be held together by a fine network of roots and hyphae in soils with high SOC content (>2%), while 20–250 μm aggregates consist of 2–20 μm-sized particles, bonded together by various organic and inorganic cements. Water-stable aggregates of 2–20 μm size, in turn, consist of

<2 μm-sized particles, which are an association of living and dead bacterial cells and clay particles. It is evident that the labile C fraction, consisting mainly of carbohydrates, is a key driver in aggregate formation. Generally, microaggregates are relatively stable and bound by persistent polysaccharide-based glues produced by roots and microbes and by calcium bridges. On the other hand, microaggregates are bound into macroaggregates by a network of roots and hyphae. The SOM stored in macroaggregates can become physically protected from decomposition by isolating organic matter resources from the activity of soil fauna (Beare et al. 1994a; Elliott 1986). Stabilization of macroaggregates occurs mainly by binding by fungal hyphae and roots. Particulate organic matter, on the other hand, serves as a substrate for microbial activity, resulting in the production of microbial bonding materials for microaggregates and for the encrustation of plant fragments by mineral particles. Several authors found that aggregate stability and SOM contents of stable macroaggregates were higher in native grassland or reduced tillage than in conventionally tilled and cultivated systems (Elliott 1986; Cambardella and Elliott 1994; Beare et al. 1994a, b; Jastrow et al. 1996; Six et al. 1998). Others reported higher MRT of SOM for less-tilled soils (Balesdent et al. 1990; Six et al. 1998; Collins et al. 2000; Dalal et al. 2007; Metay et al. 2007), which were attributed to better physical protection of soil aggregates in the absence of conventional tillage (CT) practices.

14.3.1 Soil Bulk Density and Pore Geometry

Relationships among SOM and bulk density (BD) are frequently used to estimate soil C pools (Post et al. 1982). BD values are necessary to convert laboratory measurements of soil nutrient concentrations from a mass basis to a volume or area basis. In theory, BD is simple to estimate (oven-dry weight/total volume), but in practice, methods to measure BD are labour-intensive and time-consuming. This is especially true in low-density and root-filled organic horizons and in stony mineral horizons of forest soils. Fortunately, BD is closely related to SOM, which can be easily determined by loss-on-ignition (LOI) (Pêriê and Ouimet 2008). BD tends to decrease as SOM concentration increases (Curtis and Post 1964; Bandyopadhyay et al. 2011). Federer et al. (1993) proposed a theoretical expression based on the organic density concept to relate BD and SOM. Organic density is the organic mass per unit soil volume. In wet conditions, pore space in soils retains enough moisture to allow microorganisms' development (McGill and Myers 1987), whereas under dry conditions, pore space can be reduced (Van Veen and Kuikman 1990; Verberne et al. 1990). In soils richest in fine fractions, soil pore size is reduced and makes difficult for bacteria to access the organic substrate (Van Veen and Kuikman 1990). Pore size and pore geometry of soil are important properties affecting soil hydraulic properties. Pore geometry is a function of SOC content in soils (Brady and Weil 2008). Mondal (2017) when experimented on silt loam soils with incorporation/retention of different amounts of residues for 9 years observed that by sequestrating 1% SOC, the flow rate will increase to 2 cm min^{-1} (Fig. 14.1).

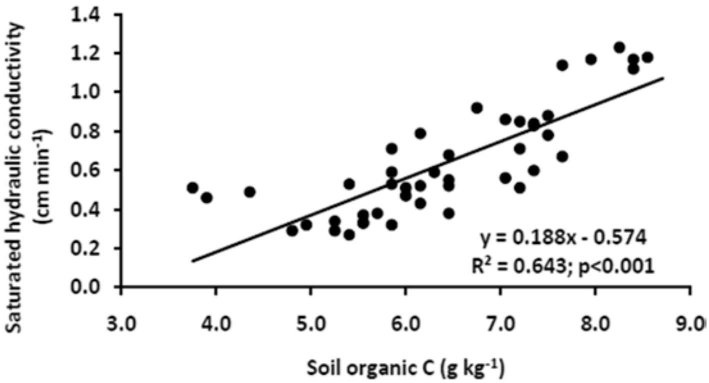

Fig. 14.1 Soil hydraulic conductivity is a function of soil organic carbon (Mondal 2017)

14.4 Soil Tillage Management

Tillage is one of the most important agricultural practices for soil management and has been traditionally carried out to mechanically prepare soils for seeding and minimizing effects of weeds. It has been associated with many negative impacts on soil quality, most notably a reduction in SOC content. Frequent tillage is responsible for microbial decomposition of SOM, since aeration caused by cultivation stimulated decomposition and the subsequent mineralization of both labile and also later stable forms of SOM (Prasad et al. 2016), resulting in an overall decrease of SOM quantity. No-tillage (NT) provides minimum soil disturbance and thus is considered a significant component of conservation agriculture (CA). Higher N_2O emissions can occur with reduced or NT, due to moisture and denser soil conditions, which may eventually offset positive effects on SOC balances (Krull et al. 2003; McLauchlan 2006). Adoption of NT and increased C inputs can rebuild depleted SOC stocks in intensive tilled soils (Fabrizzi et al. 2009). The particulate organic C (POC) is a labile SOC pool containing partially decomposed organic residues, while the macroaggregated organic C (MAOC) consists of more stable and humified organic matter (Cambardella and Elliott 1992). Moreover, both POC and MAOC stocks are higher in the NT than in the CT at soil surface (0–5 cm).

Franzluebbers and Arshad (1996) showed that SOC was greater in macroaggregates of coarse-textured soils but lower in microaggregates under ZT than under CT, while clay-rich soils did not show a significant difference between aggregate classes in soils managed for 4–16 years under CT and zero-tillage (ZT) in cold semiarid climates. This suggests that the potential of ZT to increase SOC was found to be greatest for coarse-textured soils. Furthermore, the labile fractions were found to be sensitive to soil management practices, and the lowest levels of these parameters were observed under CT, therefore increasing the proportion of the more recalcitrant C fractions (Zhao et al. 2012). Several studies have shown that compared with CT and ZT, minimum tillage (MT) can significantly improve SOM content. In a study on silt loam soils, it has been found (Chowdhury, 2018) that the frequency of

Table 14.1 Distribution of aggregate-associated total organic carbon among different size classes under different cropping systems (Chowdhury, 2018)

Cropping system	Aggregate-associated soil organic carbon (g/kg)				
	Aggregate-size class (mm)				
	>2.0	0.25–2.0	0.05–0.25	<0.05	Mean
R–W (28 years)*	11.64^{bA}	10.49^{bB}	10.15^{bB}	7.98^{bC}	10.06^{b}
R–L (9 years)	11.57^{bA}	11.23^{bA}	10.19^{bB}	8.29^{bC}	10.32^{b}
GN–GN (9 years)	8.55^{cA}	8.32^{cA}	8.20^{cA}	7.98^{bB}	8.26^{c}
Permanent fallow	14.10^{aD}	16.06^{aC}	18.13^{aB}	19.33^{aA}	16.91^{a}
Mean	11.47^{B}	11.52^{B}	11.67^{A}	10.89^{C}	

R–W = rice–wheat; R–L = rice–lentil; GN–GN = groundnut–groundnut; * = the year of cultivation; Different small letters within columns and different capital letters within rows are significantly different at $p = 0.05$ according to Duncan Multiple Range Test (DMRT) for separation of means

tillage/cultivation decreased the allocation of SOC in particles of different aggregate size classes compared to a permanent fallow plot (Table 14.1). No-tillage lentil cultivation followed by rice (R–L) maintained a good amount of SOC in different size classes; however, exhaustive tillage under groundnut–groundnut (GN–GN) depleted the array and allocation of SOC within the same period of cultivation. Results further revealed that in order to increase the aggregate stability by 1%, a minimum of 1.86% SOC needed to be sequestrated in these soils.

14.5 Soil Moisture

Soil moisture is known as one of the key factors influencing decomposition of SOC pools under different temperatures and ecological conditions (Brady and Weil 2008; Hassan et al. 2013). Water-holding capacity (WHC) is influenced by the SOM level in soil. Soils with a high level of SOM will hold more plant-available water than lower SOM soils. The potential deterioration of both temperature and soil water regimes can diminish the capacity of the soil to accumulate SOM (Buschiazzo et al. 2004). Results revealed that the moisture regimes possess a strong influence on the temperature sensitivity of decomposition of both labile and recalcitrant organic C pools. Under optimum moisture regime, the rate of decomposition of both labile and recalcitrant organic C pools enhanced with the increase in temperature. However, under submerged and dry moisture regimes, the rate of decomposition of both labile and recalcitrant organic C pools is declined, for all temperatures. Jensen et al. (2003) revealed that the change in water content strongly affected the microbial community activity and decomposition of the organic matter in soil ecosystems with variable temperatures. The structure and compositions of clay minerals regulate the water content. Small pores result in an increase of WHC and of the humidity needed for bacterial growth, which eventually increased the SOC and/or SOM content and the reverse is true for larger pores (Hassink et al. 1993a).

The effect of SOC on the WHC of soil is generally assumed to be positive, but the types of C responsible for this effect and synergistic behaviour with other soil properties is not well understood. De Jong (1983) and Haynes and Naidu (1998) found an increase in water content with increasing SOC content. An increase of 1% SOM can add 1.5% additional moisture by volume at field moisture capacity (Wolf and Snyder 2003). Emerson and McGarry (2003) showed that per gram of additional C at −10 kPa suction, a 50% increase in water content was achieved suggesting organo-mineral complex formation, which would result in pore geometry and a change in water retention at −10 kPa. Moreover, the effect of SOC on soil water retention (SWR) tended to be greater in coarse-textured than in fine-textured soils. In fact, SWR in heavy clay soils decreased with increasing SOC content. There is a strong relationship among clay content, SOC content and WHC, and it is likely that these factors influence each other synergistically. Low initial SOC content resulted in decreased effects on WHC compared with higher initial SOC contents, suggesting that a lower threshold value exists for SOC content. Prolonged submergence with double or triple rice crops, on the one hand, may retard oxidation and also confer recalcitrance character to SOC (Olk et al. 2002; Mandal et al. 2008) that ultimately helps in its stabilization in soils. On the other hand, it may also accentuate SOC loss from soil through CH_4 emission, an important greenhouse gas (Neue 1985). Understanding the relative influence of these two opposing processes on SOC budget in rice ecology is thus essential for evaluating the long-term impact of intensive rice cultivation on global warming as well as soil quality.

Mulching is a technique widely used to prevent loss of soil moisture that may affect SOM through decomposition and soil moisture preservation (Youkhana and Idol 2009). The materials used in organic mulches contain a high percentage of organic matter, which can be incorporated in soil and improve soil properties including the size and activity of the soil microbial community (Huang et al. 2008; Chaparro et al. 2012). Inorganic and synthetic mulches do not have high organic matter content, but they may improve soil properties through soil water preservation, which accelerates SOM decomposition. Forest mulch significantly increases SOM (Bai et al. 2014) and soils with higher SOM have a better water retention capacity as reported by different researchers (Wang et al. 2002; Huang et al. 2008). The effect of rate of mulch addition on SOC levels and aggregation was investigated by Saroa and Lal (2003) and reported that a higher mulch rate increased SOC and per cent water-stable aggregates.

A positive correlation between SOC and altitude is also reported (Sims and Nielsen 1986). Altitude influences SOC by controlling soil water balance, soil erosion and geologic deposition processes. Many authors found that the topography factor also affects accumulation of SOC. Soils at the slope toe have higher C because such area generally remains wet and contains a higher clay content.

14.6 Soil Temperature

The SOM increases with precipitation and decreases with temperature (Burke et al. 1989; Ganuza and Almendros 2003), and normally it is greater in areas of higher rainfall but lower in climatic condition of higher temperature. The rate of decomposition of SOM doubles for every 8 °C or 9 °C increases in mean annual temperature (MAT). For instance, the increase in soil temperature may cause a decrease in soil moisture (Kirschbaum 1995; Davidson et al. 1998). Different C pools may respond differently to temperature changes, which questions the assumption of uniform temperature sensitivities used in some soil C dynamic models. In high latitude regions, for example, increasing temperatures may induce soil CO_2 emission dramatically due to the potential thawing of permafrost soils (Dioumaeva et al. 2002); in wetland areas, higher temperatures may promote evaporation, exposing the thick organic matter to the air and therefore boosting the soil respiration (Waddington et al. 1998). The rate of SOC decomposition in the subtropical zone is faster than that in the temperate zone. Results suggest that a higher capacity of long-term C sequestration as SOC could be achieved in temperate than in subtropical crop lands or forests. In temperate and tropical soils, the stronger mineral–organic matter associations may counteract the increased potential of soil respiration induced by higher temperature.

The response of resistant SOM to temperature change is crucial for predicting climate change impacts on C cycling in terrestrial ecosystems. However, the response of the decomposition of different SOC fractions to temperature is still under debate. The temperature sensitivity of different SOC fractions is an element of uncertainty, and thus, it is a highly debated topic with regard to global climate change. The opinion that the decomposition of labile C is more sensitive to temperature change than the resistant C is mainly reported in earlier studies (Trumbore et al. 1996; Liski et al. 1999). Some studies suggest that the decomposition of the soil labile C fraction is sensitive to temperature variation, whereas resistant components are insensitive (Giardina and Ryan 2000; Fang et al. 2005; Conen et al. 2006). Conversely, some studies suggest the similar response of labile and resistant SOM pools to temperature changes (Fang et al. 2005). Several other studies confirmed that resistant C fractions are more sensitive to temperature change than labile C fractions (Knorr et al. 2005; Vanhala et al. 2007; Conant et al. 2008; Plante et al. 2010). Search of new data on temperature sensitivity of soil C pools will greatly advance our knowledge regarding the prediction of soil C response (Zhou et al. 2013).

The SOC decomposition could be described by chemical reaction kinetics equation, so that the temperature effect on the SOC decomposition is usually quantified by the temperature coefficient of the decomposition reaction rate. The temperature coefficient, used to characterize the temperature sensitivity, is commonly referred to as Q_{10} value, presenting the respiration rate differs for a temperature interval of 10 °C. The observed Q_{10} values for soil respiration fluctuates worldwide between 1.0 and 3.5, with an average value of around 2.5, both in the field (including plant root respiration) and in laboratory incubation with or without root respiration (Lenton and Huntingford 2003). In a study, Tang et al. (2017) found that labile C component and recalcitrant C component from various ecosystems respond similarly to temperature change, suggesting that temperature sensitivity may not be related to SOC quality. From an incubation experiment with Ultisol, Hassan et al. (2015) observed that SOC tended to decrease with the increase in temperature (from 5 to 35 °C), and maximum SOC was observed at 5 °C and minimum at 45 °C. Conversely, the highest increase (6.48-fold) in the recalcitrant organic C pool was noticed at 45 °C, and the impact of other temperatures was in the order 35 > 25 > 15 > 5 °C. The maximum increase in the labile organic C pool, that is, water-soluble organic C (3.52-fold), microbial biomass C (2.31-fold), readily mineralizable C (6.16-fold), permanganate-oxidized organic C (2.81-fold) and reducing sugar C (3.97-fold), was observed at 35 °C, whereas the effect at other temperatures was in the order 25 > 45 > 15 > 5 °C. According to Tian et al. (2016), MAT is a good predictor of SOC values, especially the size of active pools but not the SOC stability. However, other factors such as vegetation type may modify SOC and pool compositions.

14.7 Conclusion

Soil texture provides an insight into the storage and protection of SOC through formation of organo-mineral complexes. Different soil textural classes provide variable SOC accumulation ratio and C sequestration. Reactive surface areas of allophane pull out a huge amount of C, comparable to that in clay minerals. The linear relationship between clay and SOC content depends on the type of soil, climatic conditions and mean annual temperature. The amount of WSA is often associated with SOC content and labile C in particular. Particulate organic matter helps to bring microbial bonding with mineral particles. Native grassland or reduced tillage provides stable macroaggregates and SOC contents compared to conventionally tilled and cultivated systems. Adoption of conservation agriculture through manipulating tillage and residue incorporation rebuilds depleted SOC stocks in intensive tilled soils. Soil moisture possesses a strong influence on SOC content as well as temperature sensitivity of both labile and recalcitrant organic C pools. Prolonged submergence confers characters of recalcitrance to SOC that are sensitive to temperature changes than the labile C fractions.

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Role of Microorganisms in Regulating Carbon Cycle in Tropical and Subtropical Soils

15

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Abstract

The tropics and subtropics of the world are the most densely populated regions of the world. A majority of its population thrives on agriculture for sustaining its livelihood and nutritional requirement. With the increase in the global population and many new technological breakthroughs in agriculture, the food production has increased many folds from these regions. These regions are now being called the food bowl of the world. Albeit of these facts, intensive agro-practices have led to increased burden on our natural resources, in particular to our soils. It is now very well established that soil organic carbon content is getting depleted at a faster rate than the rate at which they are being replenished. Naturally, the biogeochemical cycling of the organic matter efficiently and harmoniously is being orchestrated by the soil microbial flora. Studying the responses of soil microbial flora with respect to various cues of the environmental and anthropogenic activities is helping the soil ecologist and microbiologist in monitoring and controlling any disturbances in the soil carbon cycling. Many of the high precision modelling techniques involving amalgamation of high-throughput spectrometric and next-generation genomic tools have helped over time in closely monitoring and generating high-precision modelling of the soil organic carbon cycling of the region.

Keywords

Carbon cycle · Methanogenesis · Microbial biomass carbon · Microorganisms · Tropical soil

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15.1 Introduction

Tropical region (23.5°N–23.5°S) is characterized by high temperature, plenty of rainfall, more evaporation and evergreen forests. Subtropical regions are the climatic regions typically found adjacent to the tropics, usually between 23.5° and 40° of latitude in both hemispheres, although such climates may occur at greater latitudes, or within the tropics themselves. Most sub-tropical climate falls into two basic types: (i) humid subtropical, where rainfall is often concentrated in the warmest months and (ii) dry summer, where seasonal rainfall is concentrated in the cooler months. There is a wide diversity of soils in tropical and subtropical regions. Different types of soils in the tropical and subtropical regions are arid and semiarid soils, halomorphic soils, alluvial soil, ferrallitic soil, ferruginous soil and tropical podzol (Buringh and Buringh 1979). Soil organic matter in general and soil organic carbon in particular is an important factor of productivity of soils in tropical or subtropical climatic regions. The role of microorganisms in soil organic carbon cycling is a well-established fact. In this chapter, we deal with the role of microorganisms in regulating carbon cycle in tropical and subtropical soils.

15.2 Composition of Soil Organic Carbon

Soil organic carbon is a part of global carbon cycle that involves transformation and cycling of carbon among soil, vegetation, ocean and atmosphere. An estimated amount of 1500 pg of carbon is stored in soil, which is higher than the cumulative amount of carbon stored in atmosphere (760 pg) and vegetation (560 pg) (Ji et al. 2015). In most of the tropics and subtropics, soil organic matter and hence organic carbon comes from plant residues. In addition to plant residues, organic carbon also comes from fixation of carbon dioxide by autotrophic microorganisms, both phototrophs and chemoautotrophs. Decayed organic materials are incorporated into soil, leading to organic carbon incorporation in soil by soil organisms and transformation by microbial community. Transformations by microbial community result in webbing of different biogeochemical cycles, involving dead and decayed organic matter and products of microbial activities. This soil organic matter transformations can be labile, or it may be persistent for years to millennia (Paul 2014). A major portion of plant organic matter incorporated into soil is carbon polymers such as cellulose, hemicelluloses, pectin and starch and hydrocarbons like lignin. Easily mineralizable cytoplasmic constituents such as sugars, amino compounds and organic acids comprise only 10% of the plant litter. Cellulose is the most abundant plant polysaccharide incorporated in any soil and is decomposed by a set of enzymes comprising endoglucanases, exoglucanases and β-glucosidases. Lignin is the second most abundant polymer entering soil at tropical and subtropical conditions. It is more complex than cellulose and is generally decomposed by fungi in soil. The degradation enzymes involved are laccase, lignin peroxidase, manganese oxidase and polyphenol oxidase. Starch is a plant polymer stored in plastids and is composed of two glucose polymers, amylase and amylopectin. Two kinds of amylases are involved in starch degradation, namely α-amylase, which catalyses the cleavage of starch molecules resulting in the release of small glucans called dextrins along with glucose and maltose, and β-amylase, which cleaves maltose residues from the non-reducing end of the starch. Hemicelluloses and pectin are polymers of five-carbon sugars and their degradation is similar to cellulose degradation (Paul 2014).

15.3 Microbial Processes and Carbon Cycle in Tropical and Subtropical Soils

In any terrestrial system (tropical/subtropical/or temperate), the balance between photosynthesis and respiration drives the carbon cycle. Phototrophic and chemoautotrophic microorganisms fix atmospheric carbon in soil through the synthesis of organic material from carbon dioxide. A variety of different processes accounting for respiration by both autotrophic and heterotrophic microorganisms resulted in release of fixed carbon into atmosphere (Gougoulias et al. 2014). Major microbial processes pertaining to carbon cycle occurring in soil are decomposition, CO_2 fixation through autotrophic microorganisms, methanogenesis and methane oxidation.

15.3.1 Decomposition

The soil system receives plant organic carbon from two major sources: (i) shoot remains and its leachates, (ii) root remains, root exudates and root-borne organic substances released into soil during plant growth (Kuzyakov and Domanski 2000; Gougoulias et al. 2014). Both exudates and leachates can be rapidly decomposed by soil microorganisms and respired to atmosphere, while the structural polymers such as cellulose, hemicellulose and lignin that are the constituents of plant tissues in the litter require a plethora of enzymes for their depolymerization and decomposition. As the amount of carbon in any environment is the difference between carbon fixed by autotrophs and carbon loss by decomposition, accurate prediction on carbon cycle requires knowledge of factors affecting decomposition (Cleveland et al. 2006). Like in any other ecosystem, in tropical and subtropical soils, fungi and bacteria are the key decomposers of large amounts of substrates entering soil. Lignin degradation is catalysed by a set of ligninolytic enzymes like lignin peroxidase (LiP), manganese peroxidase (MnP), versatile peroxidase (VP) and dye-decolorizing peroxidase (DyP). Fungi are more important in case of lignin degradation in soil than bacteria (Datta et al. 2017). Decomposition of cellulose in organic matter entering soil is catalysed by the cellulase enzyme complex, which includes β-1,4 endoglucanase (an endocellulase breaking apart cellulose from inside) β-1,4 exoglucanase (breaks apart cellulose by acting at the ends, releasing cellobiose and oligomers) and β-1,4 glucosidase (releases glucose molecules from oligomers and cellobiose) (Coyne and Coyne 1999; Killham and Prosser 2014). It has been reported that decomposition of tropical litters added to soil is partially dependent on extracellular enzymes, especially cellobiohydrolase and polyphenol oxidase (Allison and

Vitousek 2004). Decomposition rates in tropical and subtropical soils are faster than those in temperate regions due to higher soil temperature and humidity (Ross 1993). Labile carbon inputs from litter, leachates and exudates can accelerate decomposition of older soil organic matter, which is described as positive priming effect (Kuzyakov 2010). This kind of positive priming can occur in temperate soils as well as in tropical and subtropical ecosystem (Bird et al. 2011; Nottingham et al. 2012; Qiao et al. 2014). The extent of priming is generally dependant on microbial community composition and nutrient availability in soil. Consistent with the findings from temperate soils, in tropical soils also, Gram-negative bacteria were found to play a potential role in the breakdown of labile substances and Gram-positive bacteria, and fungi were found responsible for mineralization of more complex substrates (Whitaker et al. 2014).

15.3.2 CO_2 Fixation

Terrestrial soil acts as either a source or a sink of carbon and an estimated amount of 1500 pg of carbon is stored in soil organic matter (Ji et al. 2015). Among many other sinks like immobilization and carbon fixation, autotrophic fixation of carbon is one of the important processes in soil carbon cycle, as it reduces global warming threat by 50% (Lacis et al. 2010). Assimilation of CO_2 by autotrophs fixes a net of seven million grams of carbon annually (Berg 2011). Carbon dioxide fixation in tropical and subtropical soil occurs by photoautotrophy and chemoautotrophy. Autotrophic bacteria and blue–green algae (cyanobacteria) capable of fixing atmospheric carbon are widespread in tropical and subtropical soils. The Calvin–Benson–Bassham (CBB) cycle is the most widely distributed pathway for carbon dioxide fixation in terrestrial ecosystem (Yuan et al. 2012). The enzyme responsible for carbon fixation by autotrophic microorganisms is ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco). It has four forms varying in substrate specificity, catalytic nature and structure. Of the four forms, form I Rubisco coded by the *cbbL* gene is the predominant one in soil found in algae, cyanobacteria, photoautotrophic and chemoautotrophic proteobacteria (Wu et al. 2014). Form II is present in some phototrophic and chemoautotrophic bacteria (Shively et al. 2001). Chemoautotrophic bacteria, which use reduced inorganic compounds as the source of energy for CO_2 fixation, fall under two categories: (i) bacteria that oxidize sulphide, sulphur, nitrite, ammonium and reduced metals and ii) bacteria that oxidize hydrogen and carbon monoxide (Tolli and King 2005). Tropical and subtropical soils are characterized by very limited organic matter, and in such environments, phototrophs fix atmospheric CO_2, thereby driving ecosystem development (Macrae et al. 2013). A study on carbon dioxide fixation in upland and paddy soils of tropical ecosystem in China has shown that microbial CO_2 fixation is exclusively phototrophic rather than chemotrophic (Ge et al. 2013).

15.3.3 Methanogenesis

Methane is the second most important greenhouse gas after carbon dioxide, and rice fields are the major source of methane generation in tropical and subtropical conditions. Rice fields account for over 15–20% of total anthropogenic methane generation worldwide (Fazli et al. 2013). A group of obligate anaerobes, methanogens are responsible for methane production. Environments with low redox potential are the active sites of methanogens, which offer conducive conditions for methanogenesis (Pazinato et al. 2010). Methanogens are placed in seven orders, namely *Methanococcales*, *Methanobacteriales*, *Methanosarcinales*, *Methanomicrobiales*, *Methanopyrales*, *Methanocellales* and *Methanomassilicoccales* of the phylum *Euryarchaeota*. There are three biochemical pathways of methanogenesis: hydrogenotrophic methanogenesis, where methane is formed from CO_2 and H_2 is found in all orders but *Methanomassiliicoccales*, acetoclastic methanogenesis (formation of methane from acetic acid) is found only in *Methanosarcinales*, whereas methylotrophic methanogenesis (formation of methane from methylated compounds) is found in the orders of *Methanomassiliicoccales* > *Methanobacteriales* > *Methanosarcina les*. In flooded paddy soils of tropics, acetoclastic methanogenesis is responsible for 70% of methane production as compared to hydrogenotrophic methane generation (Conrad 2007). But in another study, hydrogenotrophic methanogens were found to be predominant in paddy soil (Ma and Lu 2011). Factors controlling methane production in tropical and subtropical soils are redox potential, temperature, CO_2 concentration, water table and water availability, soil pH, salinity, organic matter content in soil and type of vegetation (Dalal et al. 2008). Among these many factors, temperature and moisture have special influence on methane production and methane oxidation. A study by Das and Adhya (2012) has shown that elevated carbon dioxide levels and increased temperature resulted in increased methane production in both alluvial and lateritic soils of tropical origin. The increased methane production was mainly attributed to surge in methanogenic archaeal population, which in turn was positively correlated with low redox potential and high readily available mineralizable carbon (Das and Adhya 2012).

15.3.4 Methane Oxidation

Chemical and photochemical oxidations of methane in atmosphere and stratosphere have negative influence on global warming (Saarnio et al. 2009), whereas biological oxidation of methane plays an important role on methane balance globally. Biological oxidation of methane is catalysed by a specific group of microorganisms called methanotrophs, and the process of biological oxidation of methane is called methanotrophy. Traditionally, only aerobic bacteria are known for methane oxidation; however, in 1976, a study suggested anaerobic oxidation of methane with sulphate as an electron acceptor (Reeburgh 1976). Methanotrophs are mostly found in paddy fields, wetlands, sediments of ponds, lakes, marine sediments and various other freshwater and marine water bodies (Semrau et al. 2010). These environments are characterized by the presence of oxic–anoxic interface, wherein anoxic conditions favour methane production and oxic conditions favour methane oxidation (Wendlandt et al. 2010). Two types of kinetics patterns have been proposed for methane oxidation: low-affinity and high-affinity methane oxidation. Low-affinity methanotrophy has Km value in the range of μM range, whereas the Km value for high-affinity methanotrophy is the range of nM concentration (Das and Adhya 2012). Methanotrophic bacteria are a class of methylotrophs with the capacity to oxidize single-carbon compounds more reduced than formic acid. Methanotrophic bacteria, which oxidize methane, have been characterized into two groups: Type I methanotrophs belonging to the phylum Gammaproteobacteria and are characterized by low-affinity methanotrophy and Type II methanotrophs belonging to alphaproteobacteria exhibiting high-affinity methanotrophy. Type II methanotrophs are the ones that colonize nutrient-poor environment, whereas in nutrient-rich environment, type I methanotrophs are found abundant (Ho et al. 2013). The process of methanotrophy is affected by a number of factors in tropical and subtropical soils, namely, concentration of carbon dioxide, pH, temperature, N source (both type and quantity), soil water content, aeration and soil texture. Although the mechanism is not well understood, it is an established fact that increased CO_2 concentration reduces the activity of methanotrophs (Dubbs and Whalen 2010). Activities of methanotrophs are found to be peak at pH closer to 7, but methanotrophy is reported in a wide range of pH between 3.5 and 9.5. Since ammonium ions and methane are of similar structure and size, higher ammonium concentration inhibits methane oxidation through competition for methane monooxygenase. Sandy soil is characterized by increased aeration, and hence, a higher rate of methane oxidation was observed in sandy soil than in clayey soil. In environments with higher methane concentration, there is a pronounced effect of temperature on methanotrophy (Serrano-Silva et al. 2014). It was found that in a typical tropical soil, higher concentration of carbon dioxide and increased temperature lead to increased relative abundance of type II methanotrophs and decreased relative abundance of type I methanotrophs (Liu et al. 2016).

15.4 Methodologies to Study Carbon Cycle

The intricate networks of the microbial communities residing in soil support cycling and recycling of the soil carbon pool; further, various anthropogenic interventions are also influencing the soils and its organic matter. The cycling of the carbon in the soil is accomplished in multistep stages, resulting in the formation of different types of soil organic carbon fractions, which finally contribute towards the soil organic pool of the soil (Fig. 15.1). In-depth studies of various soil organic carbon fractions are highly essential to study the carbon cycling. Improvement in the technological interventions for studying soil carbon and its cycling is opening new realms and dimensions in this area more efficiently and effectively.

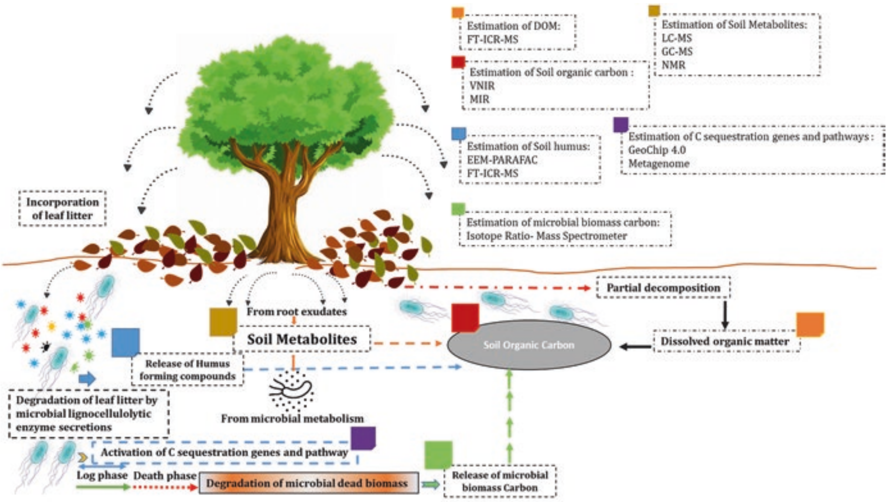

Fig. 15.1 Schematic description of methods to study various components of soil organic carbon

15.4.1 Estimation of Soil Metabolites and Dissolved Organic Matter

The soil organic matter is also contributed by incorporation of metabolites from microbes as well as from the root exudates (Schmidt et al. 2011). The analysis of soil metabolites is helping in establishing the metabolic footprints of the extracellular metabolites found in the soil (Johnston et al. 2004). Defining the metabolic footprints of the soil is helping in establishing the ecological relevance of the compounds in shaping the microbial community structures (Swenson et al. 2015). The advancement in the spectrophotometric and chromatographic techniques and the metabolomics databases helps us in digging up more information on the targeted and untargeted exometabolomics of soil (Swenson et al. 2018). Many new metabolites are being discovered from water-extractable organic carbon using LC/Q-TOF Scan MS/MS and GC/MS. The array of the soil metabolites from the soil biocrust and subsoil has been discovered using the LC–GC–MS; many novel amino acids, amino acid derivatives, mono- and di-carboxylic acids, nucleotides, osmolytes, sugars, sugar acids and sugar alcohols (Swenson et al. 2015, 2018; Johns et al. 2017). The metabolite composition of soil reflects the microbial community-level physiological profiles and thus has been utilized for the design of defined medium for culturing of soil bacteria (Jenkins et al. 2017). The above-mentioned techniques are invasive techniques and involve separation of compounds in the biological material, whereas nuclear magnetic resonance (NMR) spectroscopy is a non-invasive technique to discover soil metabolome. Recently, non-targeted biochemical composition of the agricultural soils has been monitored using the NMR-based metabolomics. The studies were conducted to look into the biochemical dynamics of the soils under anaerobic soil disinfestation studies. NMR was sensitive enough to detect shifts in the organic acid production profiles between the no-treated and anaerobic soil-disinfested soils (Johns et al. 2017). This study advocates NMR as a high-resolution rapid accurate method for deciphering soil metabolome.

The partial decomposition of the plant residues, soil organic matter and water-soluble material secreted by microorganism contributes towards the formation of dissolved organic material (DOM) (Zhou et al. 2015). It acts as the reservoir of labile nitrogen, phosphorous and many non-complex and complex organic acids and cyclic compounds (Yamashita et al. 2010). Presence of the complex cyclic compounds increases its recalcitrance to degrade, and hence, they act as a major pool of slow-degrading soil organic matter (Montaño et al. 2007). Looking into the immense ecological significance possessed by the dissolved organic matter, several attempts have been made to chemically characterize its composition. Several spectroscopic techniques such as NMR, FTIR and excitation–emission matrix combined with parallel factor analysis have been used to decipher the nature of the DOM, but these methods were only efficient enough to resolve the functional groups present in the dissolved organic matter (Howe et al. 2002; Yamashita et al. 2011; Michalzik et al. 2017). Therefore, dependencies on these methods to elucidate the structural and chemical composition of DOM are questionable. The Fourier transform ion cyclotron resonance mass spectrometer (FTICR-MS) offers a greater resolution and efficiency in terms of resolving the structures of complex organic matter. Principally, it measures the mass-to-charge ratio of the ions moving in the strong magnetic field of cyclotron, and the frequencies are converted to Fourier transform spectra (Nicolardi et al. 2015), which enables it to easily determine the molecular formula of the chemicals. Chemodiversity of the paddy fields of China was deciphered using FTICR-MS, and it was found that more than 11,000 different groups of organic compounds are found distributed across the paddy fields, revealing a high molecular diversity of the compound (Li et al. 2018). Further, the Cho1 indexes calculated for the chemical diversity revealed that the use of FTICR-MS was able to resolve more than 95% of the chemo-diversity associated with the paddy fields (Li et al. 2018).

15.4.2 Estimation of Soil Humus

About 50–80% of the soil organic matter comprises humic material or humus. The soil humus is formed as a result of biogeochemical degradation of the organic matter. Based on the earlier studies involving chemical extraction methods, which employ selectively humic acid under the influence of alkalies (Inbar et al. 1990), it was advocated that humic substances comprise the non-polar hydrophobic organic acids humic and fulvic acids. Advancements in various spectrometric techniques have enabled the researchers to throw more light on the chemical and structural complexities of the soil humus. Among the various techniques, use of fluorescence excitation–emission matrix-parallel factor analysis (EEM-PARAFAC) along with FT-ICR MS has been utilized for discovering the chemical composition of the humic substances (Derrien et al. 2017, 2018; Brogi et al. 2018). In the previous section, working of FT-ICR-MS has been discussed, and in this section, the principle of EEM-PRAFAC is explained. The fluorescence excitation–emission matrix measures the total luminescence spectrum of the sample and couples it with the powerful parallel factor analysis tool to deduce the chemical composition of the samples under study.

15.4.3 Estimation of Microbial Biomass Carbon

The living component of the soil comprises the microbial biomass, which acts as both source and sink for available nutrients of soil. Therefore, the soil organic carbon turnover is also dependent on total carbon stored in the microbial biomass of the soil. Estimating the microbial biomass carbon will act as an early indicator of soil carbon turnover as affected by anthropogenic interventions. Previously, microbial biomass carbon has been estimated by overnight fumigation of soils using chloroform, followed by extraction with potassium sulphate and then estimation of the total organic carbon by titration (Vance et al. 1987). The fumigation of the soil with chloroform causes membrane disruption of the microbial biomass, and hence, all the carbon present in the microbial biomass gets incorporated into the soil, which is then extracted and the amount of carbon is measured. In a slight modification of the technique, rather than estimating the total carbon content of the K_2SO_4 extracts by titration, the extracts are subjected to isotope-ratio-mass spectrophotometry (IR-MS), which can measure at a time organic carbon, organic nitrogen and $\delta\ ^{13}C$ signatures (Paetsch et al. 2018). The estimation of the microbial biomass carbon using the IR-MS gives us the idea of the soil carbon dynamics as influenced by the microbial biomass and to investigate shifts in soil carbon stores.

15.4.4 Estimation of C Sequestration Genes and Pathways

The influxes and effluxes of the carbon from the environment to the soil and from the soil to the environment are regulated by soil microbial communities (Calderón et al. 2017). Therefore, in order to model or simulate the biogeochemical cycling of the carbon in an ecosystem, it is very important to understand the composition of the microbial communities and its specific functional guilds (Schimel and Schaeffer 2012; Bhatnagar et al. 2018). Correlating the biogeochemical cycling of carbon with the microbial communities' structure and function is nevertheless easier and cost-effective due to the advent of the next-generation sequencing tools and techniques (Cardenas and Tiedje 2008). Among the latest high-throughput techniques for studying soil microbial communities; Geo Chip 4.0 and metagenomics are the most popular ones. GeoChip (v4) has been developed to analyse the functional diversity of the microbial community, and the system is designed as a microarray-based gene chip, which contains about 82,000 probes for 141,995 gene sequences assigned to 410 gene families associated with carrying out biogeochemical cycling of carbon, nitrogen and phosphorous, xenobiotic degradation, etc. (Tu et al. 2014). For studying the influence of microbes on the carbon cycling in an ecosystem, the chip has been loaded with gene sequences/CDS belonging to 41 genes/enzyme categories of C cycling; the gene categories include probes for detecting genes responsible for CO_2 fixation such as *aclB, cbbM* and *cbbL* and for organic carbon, degradation includes genes such as *phn*, *phd* and *lin* (Hügler et al. 2010; Liang et al. 2010). Metagenomics is an area of genomics, which involves deciphering the structural and functional diversity of the bacteria without even culturing them (Handelsman 2004). The study involves the use of latest next-generation sequencing (NGS) platforms for performing DNA sequencing of environmental DNA. Many of the popular choice of NGS platforms includes Illumina's™ HiSeq, MiSeq and NextSeq, ABI's™ IonTorrent, PacBIO™ SMRT and Oxford™ Nanopore 'minion' platform (Bleidorn 2016). Metagenomic studies had been successfully implemented in understanding the pattern of microbial communities as influenced by the physicochemical characteristics of the soil. For instance, after using the metagenomics-based community studies, it has been observed that there was a differential abundance of *Acidobacteria* sub-group when forest area was converted to pasture land; in another study, it was found that soil's physicochemical property of the forest area has a significant effect on the bacterial and fungal structural diversity; thus, it can be said that microbial community dynamics is strongly correlated with the environmental influences (Navarrete et al. 2015; Tripathi et al. 2016; Neilson et al. 2017). The whole metagenome sequencing involves sequencing of shotgun libraries of DNA, and the generated data have information about the composition of bacterial taxa and the functional genes. A core set of carbon-metabolizing genes had been identified in a bioenergy grassland soil using whole metagenomics sequencing (Howe et al. 2016).

15.5 Manipulation of Carbon Dynamics in Tropical and Subtropical Soils

Abiotic and biotic factors such as soil pH, organic carbon content, soil aeration, soil moisture and soil nutrient status are the major governing factors that influence the microbial community structure (Fierer 2017). Apart from these factors, various agricultural practices such as tillage, addition of chemical and biofertilizers, and addition and removal of plant biomass have also got an impact on the existing soil microbial communities (Gougoulias et al. 2014; Hu and He 2018). Further, the carbon stocks of the soil is getting depleted at a faster rate, all due to intensive crop cultivation practices, soil weathering, afforestation and global warming. Therefore, strategies should be devised to manipulate carbon dynamics so that the soil carbon pool can be replenished. As per the scope of the chapter, two strategies are briefly discussed:

15.5.1 Soil Transplantation

The strategy is mainly influenced by the already established technique of gut microbiome transplantation, under which the gut microbiome of a healthy individual is transplanted into the unhealthy ones for curing them from lifestyle diseases (Gupta et al. 2016). Likewise, in the case of soil transplant, soils from the more ecological productive niches are transplanted to more degraded lands for improving their biological characteristics and replenishing their soil microbiome (Bond-Lamberty et al. 2016). Many long-term experiments involving soil transplantation had transformed the soil microbiota structure and function and improved its productivity. For instance, long-term soil transplantation experiment carried out at subtropical regions of China showed improved microbial richness and increased soil productivity (Liang et al. 2015). Ling et al. (2016) reported that long-term replenishment of the soils with organic amendments has a deep impact on transforming the inherent soil microbiome and its function; it was found that there was a strong networked association of soil microbiomes as compared to the chemically amended soils.

15.5.2 Prokaryotes as Storage of Captured Carbon Stocks

Atmospheric CO_2 content has been rising at an exponential rate leading to the problem of global warming; on the other hand, soil organic pool is getting depleted (Boykoff et al. 2018; Wood and Bradford 2018). Both the problems of global warming as well as the maintenance of soil organic carbon stocks can be taken care of by prokaryote-mediated carbon dioxide capture and storage or biological carbon sequestration (Thakur et al. 2018). The biological sequestration of carbon involves a group of autotrophic bacteria, biomineralizers like ureolytic bacteria and sulphate-reducing bacteria (Bhagat et al. 2018; Reddy and Joshi 2018; Thakur et al. 2018). The enrichment of these CO_2-capturing and -storing communities in soil has a potential to increase the soil organic carbon reserves.

15.6 Conclusion

The advent of new and innovative tools and techniques in genomics, proteomics and metabolomics has enriched the understanding of carbon cycling in tropical and subtropical soils. Amalgamation of the developed knowledge base will be helpful in predicting anthropogenic and climatic effects on carbon sequestration and cycling in tropic and subtropical regions.

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16 Soil Organic Carbon Stock of Some Upland Use System Under Tropical Monsoon Climate and Their Interrelationship with Soil Water Retention

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Abstract

Soil organic matter is the most important component of soil, contributing to soil biological, chemical and physical properties. A study was undertaken to assess the organic carbon stock of dominant land use/systems in the upland of the eastern region (Kadalipal watershed, Dhenkanal, Odisha, India). The dominant land use systems selected were forest grazing land (C_0), maize (C_1), rice (C_2), groundnut (C_3), cucumber (C_4), okra (C_5), cowpea (C_6), cashew plantation (C_7) and barren land (C_8). A correlation matrix was developed among SOC, water retention at field capacity, permanent wilting point, bulk density, particle size distribution (sand, silt and clay) and pH. The R^2 and slope of different relationships (single/multiple/regression) were computed. The organic carbon and water retention at saturation, field capacity (−33 kPa) and permanent wilting point (−1500 kPa) were grouped depth-wise, and the R^2 and slope of the relationship between water retention at field capacity and permanent wilting points of the particular depth and SOC of respective layers were derived. Soil water retention at field capacity (−33 kPa) was found to be correlated with SOC at 0–0.15 m depths only rather than the SOC of whole profile. Soil pH, bulk density and porosity had significant relationship ($P \leq 0.05$) with SOC content. From this fact, it can be concluded that organic carbon content appeared to be an important soil property to improve the estimation of soil water retention at lower suction values. No significant relation was observed between organic carbon at different depths and soil water retention at higher suction (−1500 kPa, PWP). This may be related to the fact that the structure-forming ability of organic matter affects soil water retention at water content close to field capacity to a larger extent than water retention close to wilting point.

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Keywords
Soil organic carbon · Soil water retention · Tropical monsoon climate · Upland use system

16.1 Introduction

In wake of global warming and climate change, sequestration of carbons from atmosphere and reduction of its emission are the two options to minimize the rate of global warming and thus climate change. Carbon sequestration is one of the mechanisms for long-term mitigation of carbon and global warming; however, the extent of carbon storage in soil depends on the type of vegetation it supports, edaphic and climatic factors of the specific area (Paustian et al. 1998; Reichle et al. 1999; Palumbo et al. 2004; Koul and Panwar 2012). Soil carbon is a component of two important pools, namely soil organic carbon (SOC) and soil inorganic carbon. SOC pool is the predominant form of carbon in soil of tropical monsoon, humid and sub-humid regions. Soil organic matter rejuvenates degraded soils, increases biomass production and reduces the rate of enrichment of atmospheric CO_2 (Lal 2004). It is thus imperative to have information on appropriate site-specific land use and cropping systems to enhance carbon uptake by plants and storage in soils. Due to carbon sequestration and modifications of management practices, soil organic matter changes, which may affect soil structure, adsorption properties and soil water retention properties (Rawls et al. 2003). Soil water retention is a major soil hydraulic property that determines available water capacity of soils and greatly affects cropping pattern and length of the growing period of a region.

Contradictory reports are available on the effects of changes in soil organic matter on soil water retention. Beke and McCormick (1985) and Peterson et al. (1968) observed the usefulness of organic matter content data to estimate soil water retention at −1500 kPa (Permanent Wilting Point) but not at −33 kPa (Field Capacity). Bauer and Black (1981), De Jong (1983), Jamison and Kroth (1958) and Riley (1979) found that the organic matter had a role in estimating soil water retention at both −33 kPa and − 1500 kPa, whereas Lal (1979) had not found any role of soil organic matter in soil water retention because of having low organic matter in their samples. Although sporadic work has been done on the above-mentioned aspects, still there is a paucity of information of SOC stocks of different upland use systems of eastern India and interrelationship of SOC of different depths with soil water retention. Keeping the importance of above points in view, this study assessed particle size distribution, SOC stocks and water retention properties of some upland cropping systems of eastern India, and a correlation matrix was developed by correlating soil water retention at −33 kPa and − 1500 kPa with particle sizes (clay, sand and silt), SOC and some other soil properties. A simulation model that relies on particle size distribution, SOC can use their relationships for determining soil water retention properties.

16.2 Study Site and Details

The study site (Fig. 16.1) is located in the mid-central table land zone of Odisha, India (in Dhenkanal district; latitude 20°60′ North and longitude of 85°57′ East). The height of the site is 69 m above sea level. The climate of the study area belongs to tropical monsoon climate. The average maximum temperature varies from 27.0 °C in January to 36.7 °C in May; the minimum temperature ranges between 13.9 °C in December and 21.4 °C in May. The region receives higher average annual rainfall (1440 mm), but due to lack of appropriate water and soil management, the region has one of the lowest agricultural productivities of the country, especially from rainfed upland rice ecosystem. The total cultivated area of the district is 205,607 ha, out of which 50% is rainfed upland (103,696 ha).

Nine major land use/cropping systems of upland of the region (Kadalipal watershed, Dhenkanal, Odisha, India), namely, forest grazing land (C_0), maize (C_1), rice (C_2), groundnut (C_3), cucumber (C_4), okra (C_5), cowpea (C_6), cashew plantation (C_7) and barren land (C_8), were selected for assessing their carbon (C) stock and C sequestration potentials in the profile. Soil samples were collected from each land use/cropping system at 0–0.15 m, 0.15–0.30 m, 0.30–0.45 m, 0.45–0.60 m,

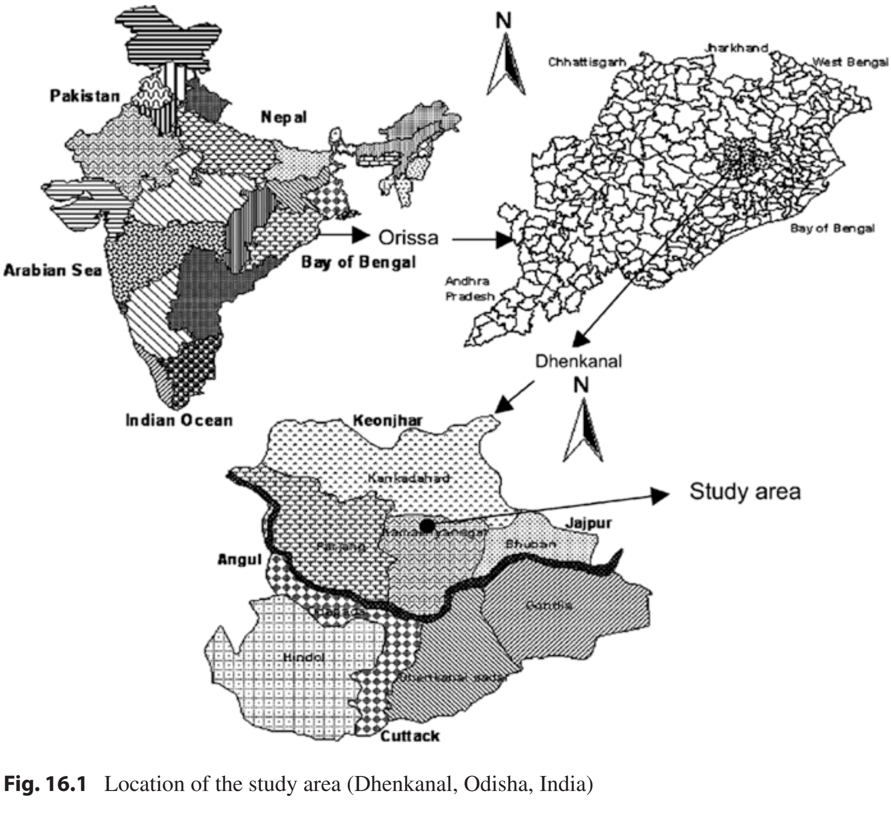

Fig. 16.1 Location of the study area (Dhenkanal, Odisha, India)

0.60–0.9 m and 0.90–1.20 m depths for laboratory analyses. Three soil profiles were dug and collected in each land use system, and the results were averaged. For determining bulk density, the undisturbed core samples were taken at respective depths with the help of 5 cm inner diameter and 5.1 cm height stainless steel cores. Along with undisturbed core samples, sufficient quantities of disturbed soil samples were taken from each depth within the profile for the analysis of soil pH, particle size distribution (percentages of sand, silt and clay), organic carbon content and soil water retention at different suctions. Particle size distribution was analysed by the Bouyoucos hydrometer method. The disturbed soil samples were placed in a refrigerated container to minimize any mineralization of organic matter prior to determination of organic carbon content. Soil organic carbon (%) was analysed using the Walkley and Black (1934) method and SOC pool of the profile (Mg ha^{-1}) was computed by multiplying the SOC concentration (g kg^{-1}) by the bulk density (Mg m^{-3}), depth (m) and factor by 10. The soil pH was determined in distilled water at a ratio of 1:2 (soil:water).

The water content at different suctions, namely −33 kPa (field capacity), −100 kPa, −300 kPa, −500 kPa, −1000 kPa and −1500 kPa (permanent wilting point), was measured using pressure plate apparatus (Soil Moisture Equipment Corporation, USA) (Klute 1986), and soil moisture characteristics curve (matric suction–soil moisture relationship) for each land use systems and depths were derived. The relationship between clay, sand and silt with water retention at field capacity (−33 kPa) and permanent wilting point (−1500 kPa) were established. A correlation matrix was developed among SOC, water retention at field capacity, permanent wilting point, bulk density, particle size distribution (sand, silt and clay) and pH. The R^2 and slope of different relationships (single/multiple/regression) were computed. The organic carbon and water retention at saturation, field capacity (−33 kPa) and permanent wilting point (−1500 kPa) were grouped depth-wise and the R^2 and slope of the relationship between water retention at field capacity and permanent wilting points of the particular depth and SOC of that layer were derived.

16.3 Particle Size Distribution and Bulk Density

The depth-wise particle size distribution (sand, silt and clay) and bulk density of the soil samples were analysed (Table 16.1). The average clay content in the soil profile ranged from 23.8% in C_0 (grazing land) to 32.6% in C_6 (cowpea). The sand content varied between 42.8% in C_6 (cowpea) and 60.1% in C_8 (barren soil). An overview of soil texture of the samples revealed that sandy clay loam texture constituted about 60% of all samples in different cropping systems and at different depths. Clay loam, sandy loam and loamy texture represented 20%, 15% and 5%, respectively. Bulk density of the surface layer ranged from 1.39 mg m^{-3} in C_7 (cashew plantations) to 1.48 mg m^{-3} in forest grazing land (C_0). The forest grazing land (C_0) and uncultivated open barren land (C_8) showed relatively higher bulk density apparently from compaction from raindrops and reduced root activity. Barren uncultivated soils were observed to be more compact, as it had not been cultivated since long. Presence of

Table 16.1 Particle size distribution and bulk density of different land use/cropping systems

Land use	Soil depth (m)	Clay (%)	Silt (%)	Sand (%)	Soil texture	Bulk density (kg m^{-3})
C_0	0–0.15	28	16	56	SCL	1.48
	0.15–0.30	26	20	54	SCL	1.49
	0.30–0.45	20	18	62	SL	1.43
	0.45–0.60	32	17	51	SCL	1.52
	0.60–0.90	33	25	42	CL	1.54
	0.90–1.20	33	18	49	SCL	1.54
C_1	0–0.15	25	16	59	SCL	1.49
	0.15–0.30	28	16	56	SCL	1.49
	0.30–0.45	27	32	41	L	1.5
	0.45–0.60	29	22	49	SCL	1.51
	0.60–0.90	19	22	59	SL	1.45
	0.90–1.20	32	25	43	CL	1.53
C_2	0–0.15	27	26	47	SCL	1.45
	0.15–0.30	19	23	58	SL	1.43
	0.30–0.45	30	16	54	SCL	1.5
	0.45–0.60	20	18	62	SL	1.43
	0.60–0.90	34	19	47	SCL	1.54
	0.90–1.20	33	22	45	SCL	1.55
C_3	0–0.15	18	28	54	SL	1.41
	0.15–0.30	28	28	44	CL	1.42
	0.30–0.45	28	16	56	SCL	1.45
	0.45–0.60	16	22	62	SL	1.43
	0.60–0.90	31	24	45	CL	1.54
	0.90–1.20	32	18	50	SCL	1.54
C_4	0–0.15	23	20	57	SCL	1.46
	0.15–0.30	26	21	53	SCL	1.48
	0.30–0.45	32	28	40	CL	1.51
	0.45–0.60	21	16	63	SCL	1.4
	0.60–0.90	32	20	48	SCL	1.55
	0.90–1.20	35	23	42	CL	1.56
C_5	0–0.15	28	19	53	SCL	1.45
	0.15–0.30	28	17	55	SL	1.44
	0.30–0.45	28	20	52	SCL	1.48
	0.45–0.60	23	27	50	SCL	1.45
	0.60–0.90	34	26	40	CL	1.54
	0.90–1.20	36	28	36	CL	1.55
C_6	0–0.15	30	23	47	SCL	1.40
	0.15–0.30	32	23	45	SCL	1.46
	0.30–0.45	29	25	46	SCL	1.45
	0.45–0.60	34	24	42	CL	1.47
	0.60–0.90	35	23	42	CL	1.48
	0.90–1.20	35	30	35	CL	1.5

(continued)

Table 16.1 (continued)

Land use	Soil depth (m)	Clay (%)	Silt (%)	Sand (%)	Soil texture	Bulk density (kg m^{-3})
C_7	0–0.15	23	27	50	SCL	1.39
	0.15–0.30	19	35	46	L	1.41
	0.30–0.45	23	30	47	L	1.45
	0.45–0.60	30	25	45	SCL	1.48
	0.60–0.90	31	28	41	CL	1.5
	0.90–1.20	32	21	47	SCL	1.51
C_8	0–0.15	19	15	66	SL	1.47
	0.15–0.30	19	19	62	SL	1.48
	0.30–0.45	23	18	59	SCL	1.48
	0.45–0.60	23	15	62	SCL	1.48
	0.60–0.90	21	19	60	SCL	1.50
	0.90–1.20	28	17	55	SCL	1.50

Forest grazing land (C_0), maize (C_1), rice (C_2), groundnut (C_3), cucumber (C_4), okra (C_5), cowpea (C_6), cashew nut plantation (C_7) and barren land (C_8)
SCL sandy clay loam, *CL* clay loam, *L* loam, *SL* sandy loam

sparse vegetation on it leads to less organic matter returned to soil and hence creates more compactness. Among crop fields, the bulk density of surface layers (0–0.15 m and 0.15–0.30 m) of legume cultivated plots (C_3 and C_6) was lower (1.40–1.41 Mg m^{-2}) than that of cereals (C_1 and C_2) and vegetables (C_4 and C_5). Incorporation of biomass of legumes might be one of the reasons for creating surface layers with low bulk density. Bulk density increased as the depth of profile sampling increased. The soils of cashew plantation had relatively lower bulk density (1.39–1.41 mg m^{-3}) at upper layers (0–0.35 m) than soils of other sites. Litter contribution from the cashew plant might be the reason for the relatively higher porosity on the surface (0–0.30 m) and less bulk density. Bulk density increased with increasing depth in most cases, which might be attributed to higher porosity of surface soils. Lower bulk density in surface layers can also be correlated with more organic content, which leads to better structure and more porosity. Increased bulk density with increasing depth was also observed by Christine (2006) and Koul and Panwar (2012).

16.4 Soil Organic Carbon

Variations in organic carbon content of the soils of different land use cropping systems of the study site were observed (Table 16.2). The average soil organic carbon (SOC) content in the soil profiles is low, ranging from 0.20% in uncultivated barren land (C_8) to 0.84% in cashew plantation, and reflects the range in values of rainfed Alfisols of the region. The SOC was lower in crop fields and decreased with soil depth in almost all the treatments. The organic carbon at surface (0–0.15 and 0.15–0.30 m) layers ranged from 0.85 to 1.04, 0.46 to 0.60, 0.45 to 0.58, 0.68 to 0.74,

Table 16.2 Soil organic carbon (%) content at different depths under different land use classes

Land use	0–0.15 m	0.15–0.30 m	0.30–0.45 m	0.45–0.60 m	0.60–0.90 m	0.90–1.2 m	Average
C_0	$^{B}0.88$	$^{B}0.82$	$^{B}0.49$	$^{C}0.32$	$^{B}0.36$	$^{C}0.27$	$^{B}0.64$
C_1	$^{D}0.60$	$^{E}0.46$	$^{D}0.39$	$^{B}0.43$	$^{D}0.20$	$^{E}0.18$	$^{E}0.38$
C_2	$^{D}0.58$	$^{E}0.45$	$^{E}0.34$	$^{D}0.28$	$^{D}0.24$	$^{D}0.21$	$^{F}0.35$
C_3	$^{C}0.74$	$^{C}0.68$	$^{A}0.60$	$^{A}0.54$	$^{A}0.45$	$^{A}0.43$	$^{C}0.57$
C_4	$^{D}0.57$	$^{D}0.53$	$^{C}0.46$	$^{D}0.27$	$^{A}0.49$	$^{D}0.20$	$^{B}0.42$
C_5	$^{D}0.65$	$^{D}0.55$	$^{C}0.50$	$^{C}0.32$	$^{C}0.26$	$^{E}0.17$	$^{E}0.41$
C_6	$^{C}0.78$	$^{C}0.68$	$^{B}0.54$	$^{B}0.43$	$^{B}0.37$	$^{B}0.29$	$^{D}0.52$
C_7	$^{A}0.95$	$^{A}0.87$	$^{B}0.52$	$^{B}0.46$	$^{C}0.29$	$^{C}0.25$	$^{A}0.84$
C_8	$^{E}0.32$	$^{F}0.24$	$^{F}0.19$	$^{E}0.17$	$^{D}0.16$	$^{F}0.14$	$^{G}0.20$

The values in the column followed by the same letters are not significant at 5% level of significance based on Duncan's multiple range test (DMRT)

Forest grazing land (C_0), maize (C_1), rice (C_2), groundnut (C_3), cucumber (C_4), okra (C_5), cowpea (C_6), cashew nut plantation (C_7) and barren land (C_8)

0.53 to 0.57, 0.55 to 0.65, 0.68 to 0.78, 1.09 to 1.35% in C_0,C_1, C_2, C3, C_4, C_5, C_6, C_7 and C_8 treatments, respectively, whereas organic carbon at 0.90–1.20 m depth was 0.36, 0.18, 0.21, 0.43, 0.20, 0.17, 0.29, 0.45 and 0.14% only for the above-mentioned nine respective treatments. SOC content decreased with increase in soil depth, signifying the importance of upper layer in stocking SOC. Among crop-cultivated fields, soil organic carbon content (SOC) in soil profile was low in the C_1, C_2, C_4 and C_5 cropping systems as compared to other treatments. Continuous tillage and cultivation of these nutrient-exhaustive crops favoured rapid rate of mineralization compared to that of accumulation of SOC in these fields. As a result, these treatments recorded the lowest carbon storage due to faster mineralization of organic carbon. Among field crops, the surface layer of groundnut (C_3)- and cowpea (C_6)-cultivated fields showed higher SOC content, namely, 0.74% and 0.78%, respectively, at surface layers. It appears that cropping with legumes holds promise for greater accumulation of SOC in the long term. These legume crops shed a large proportion of foliage with characteristic lignified tissues and litter added to the soil mineralizes slowly to increase the stock of carbon in the soil. The average SOC content within the profile was 0.66, 0.38, 0.35, 0.57, 0.42, 0.41, 0.52, 0.84, 0.20% in C_0 (forest grazing land), C_1 (maize), C_2 (rice), C_3 (groundnut), C_4 (cucumber), C_5 (okra), C_6 (cowpea), C_7 (cashew nut) and C_8 (uncultivated barren soil), respectively. Treatment C_7 (cashew plantation) recorded the highest SOC (1.35 and 1.10% at 0–0.15 and 0.15–0.30 m, depths, respectively). Litter contribution from the cashew plantation may be the reason for the relatively higher SOC content of surface layers.

The profile soil organic carbon (PSOC) pool was also determined from the SOC content, bulk density and soil depth as per the procedure mentioned in the methodology. The PSOC stock within 1.2 m depth was 111.1, 59.1, 94.8, 70.2, 62.8, 80.2, 128.4 and 30.61 mg ha^{-1} for C_0, C_1, C_2, C_3, C_4, C_5, C_6, C_7 and C_8 treatments, respectively (Fig. 16.2).

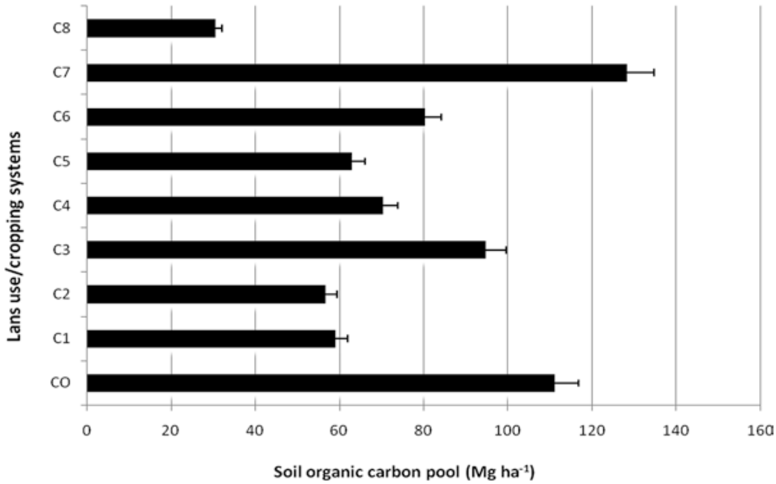

Fig. 16.2 Soil organic carbon pool under different land use systems

16.5 Soil Water Retention Characteristics

The soil water retention characteristic curves were developed by relating moisture content data at −33 kPa, (field capacity), −100 kPa, −300 kPa, −500 kPa, −1000 kPa and −1500 kPa (wilting point) and corresponding suction values. These characteristic curves were found to be fitted well in power function (Fig. 16.3). The soil metric suction–moisture content relationship curve displayed a sharp decrease in moisture content from initially higher to lower values, from −33 kPa to −100 kPa or −300 kPa following a gradual decline until −500 kPa, and the change became negligible thereafter. It was also revealed that the higher the clay and organic carbon content, the greater was the moisture retention capacity on the surface layers (0–0.30 m).

The soil water retention ($m^3\ m^{-3}$) at field capacity (FC) and permanent wilting point (PWP) of different land use/cropping systems were also recorded (Tables 16.3 and 16.4). The water retention at field capacity at surface (0–0.15 m) layers was 0.278, 0.314, 0.302, 0.292, 0.288, 0.299, 0.311, 0.344 and 0.264 $m^3\ m^{-3}$ in C_0, C_1, C_2, C_3, C_4, C_5, C_6, C_7 and C_8 treatments, respectively. Differences in clay and SOC might have played a crucial role for variation in soil moisture content. The relationship between soil water retention at field capacity and permanent wilting point with soil texture of the whole profile was established (Figs. 16.4a, 16.4b, 16.4c and 16.5).

Clay was found to be the most dominant factor to determine water retention at FC and PWP and positively related to water retention at FC and PWP with the R^2 of 0.634 and 0.662, respectively. The sand content was negatively related to soil moisture retention as expected with R^2 of 0.508 and 0.463 for FC and PWP, respectively. The silt content did not show any significant relationship with soil water retention.

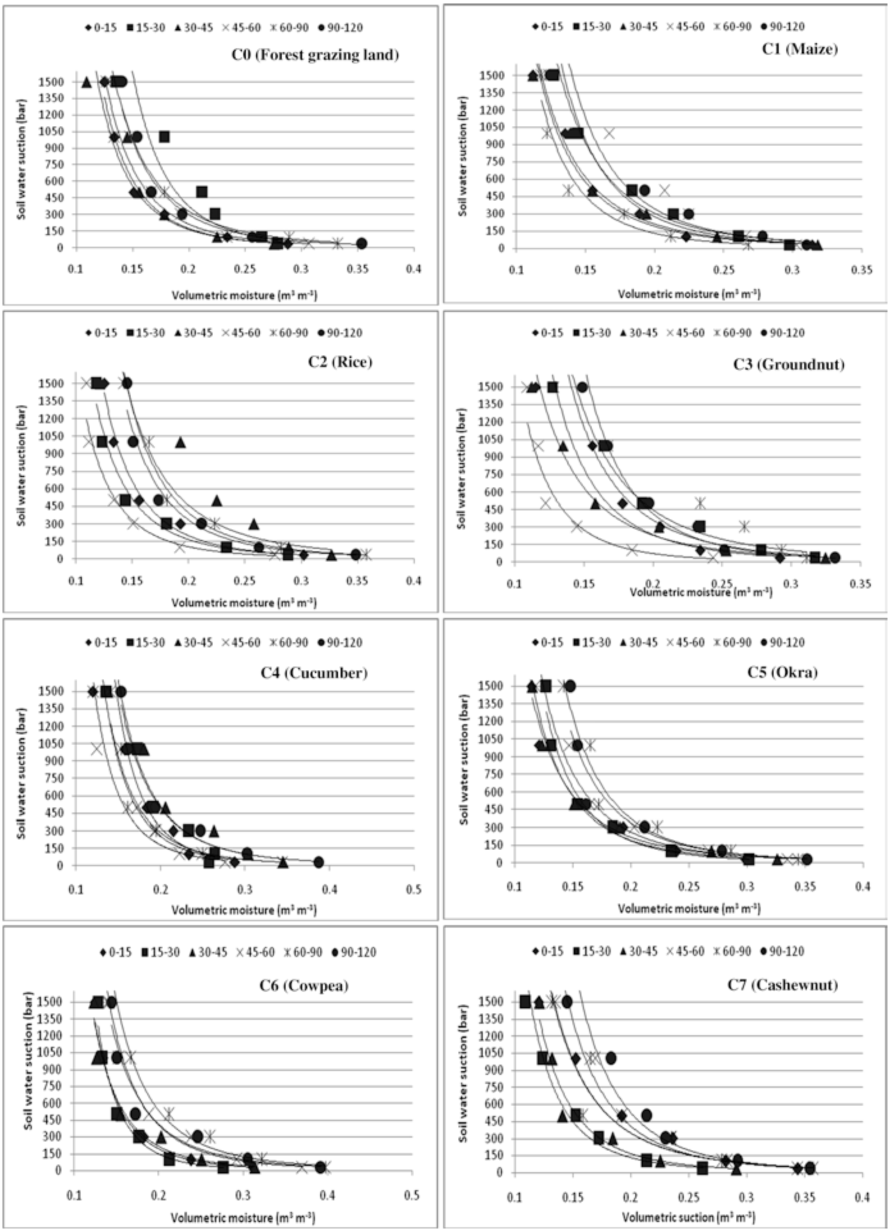

Fig. 16.3 Soil water retention characteristic curve under different land use systems

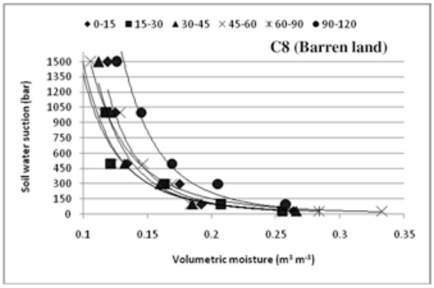

Fig. 16.3 (continued)

Table 16.3 Soil water retention at field capacity (−33 kPa) under different land use systems

Land use	0–0.15 m	0.15–0.30 m	0.30–0.45 m	0.45–0.60 m	0.60–0.90 m	0.90–1.2 m
C_0	$^{C}0.278$	$^{D}0.269$	$^{C}0.276$	$^{C}0.307$	$^{C}0.332$	$^{B}0.354$
C_1	$^{B}0.314$	$^{B}0.298$	$^{B}0.318$	$^{C}0.303$	$^{B}0.268$	$^{C}0.310$
C_2	$^{B}0.302$	$^{C}0.288$	$^{B}0.327$	$^{D}0.277$	$^{B}0.358$	$^{B}0.348$
C_3	$^{B}0.292$	$^{B}0.317$	$^{B}0.325$	$^{E}0.244$	$^{C}0.311$	$^{C}0.332$
C_4	$^{C}0.288$	$^{D}0.257$	$^{A}0.345$	$^{D}0.277$	$^{B}0.344$	$^{A}0.387$
C_5	$^{B}0.299$	$^{B}0.302$	$^{B}0.326$	$^{B}0.335$	$^{B}0.354$	$^{B}0.352$
C_6	$^{B}0.311$	$^{C}0.277$	$^{B}0.314$	$^{A}0.375$	$^{A}0.398$	$^{A}0.392$
C_7	$^{A}0.344$	$^{A}0.343$	$^{B}0.291$	$^{B}0.344$	$^{B}0.357$	$^{B}0.355$
C_8	$^{C}0.264$	^{D}C0.255	$^{C}0.266$	$^{B}0.333$	$^{D}0.285$	$^{D}0.255$

The values in the column followed by the same letters are not significant at 5% level of significance based on Duncan's multiple range test (DMRT)
Forest grazing land (C_0), maize (C_1), rice (C_2), groundnut (C_3), cucumber (C_4), okra (C_5), cowpea (C_6), cashew nut plantation (C_7) and barren land (C_8)

Table 16.4 Soil water retention at permanent wilting point (−1500 kPa) under different land use systems

Land use	0–0.15 m	0.15–0.30 m	0.30–0.45 m	0.45–0.60 m	0.60–0.90 m	0.90–1.2 m
C_0	$^{A}0.125$	$^{A}0.136$	$^{B}0.107$	$^{A}0.127$	$^{A}0.137$	$^{A}0.142$
C_1	$^{A}0.112$	$^{A}0.127$	$^{B}0.112$	$^{A}0.123$	$^{B}0.118$	$^{B}0.124$
C_2	$^{A}0.125$	$^{A}0.118$	$^{A}0.121$	$^{B}0.109$	$^{A}0.143$	$^{A}0.145$
C_3	$^{B}0.115$	$^{A}0.127$	$^{A}0.112$	$^{B}0.109$	$^{B}0.128$	$^{A}0.149$
C_4	$^{A}0.121$	$^{A}0.136$	$^{A}0.138$	$^{A}0.121$	$^{A}0.141$	$^{A}0.144$
C_5	$^{B}0.114$	$^{A}0.127$	$^{B}0.115$	$^{B}0.118$	$^{A}0.142$	$^{A}0.148$
C_6	$^{A}0.125$	$^{A}0.128$	$^{A}0.123$	$^{A}0.139$	$^{A}0.142$	$^{A}0.144$
C_7	$^{A}0.120$	$^{A}0.119$	$^{A}0.121$	$^{A}0.135$	$^{A}0.132$	$^{A}0.145$
C_8	$^{C}0.109$	$^{B}0.098$	$^{B}0.112$	$^{B}0.106$	$^{C}0.098$	$^{B}0.126$

The values in the column followed by the same letters are not significant at 5% level of significance based on Duncan's' multiple range test (DMRT)
Forest grazing land (C_0), maize (C_1), rice (C_2), groundnut (C_3), cucumber (C_4), okra (C_5), cowpea (C_6), cashew nut plantation (C_7) and barren land (C_8)

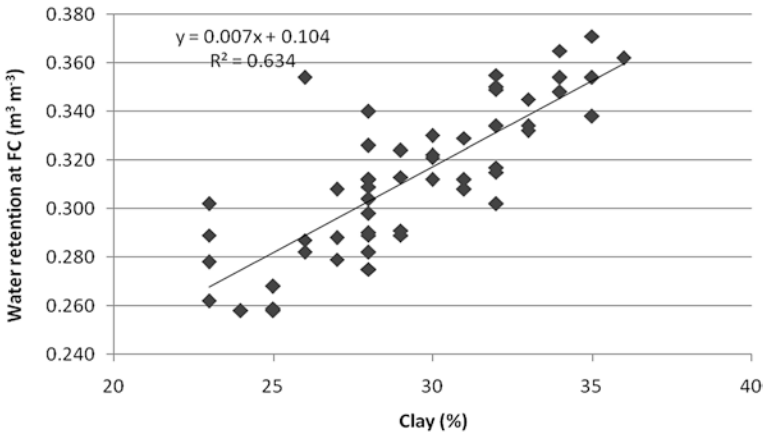

Fig. 16.4a Relation between clay (%) and water content at FC (−33 kPa)

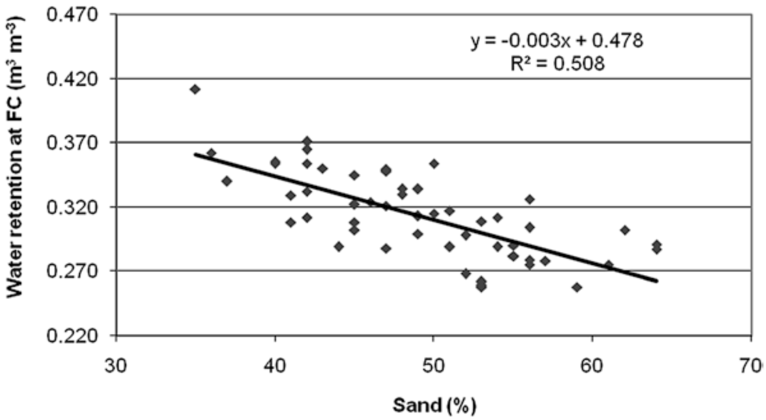

Fig. 16.4b Relation between sand (%) and water content at FC (−33 kPa)

16.6 Relationship between SOC, Soil Moisture Retention and Other Soil Properties

The correlation matrix among organic carbon, sand, silt, clay and pH was established to develop pseudo-transfer functions in order to determine soil water retention at −33 kPa and −1500 kPa (Table 16.5a, 16.5b). The R^2 and slope of the relationship between water retention at field capacity, PWP and other soil properties were also determined (Table 16.6). It was observed that organic carbon alone is not a good predictor of water retention, but when it was coupled with clay, the R^2 value increased (0.407). When SOC was associated with sand, silt, bulk density and pH, the R^2 value further increased. (0.512). When layer-wise SOC and water retention at

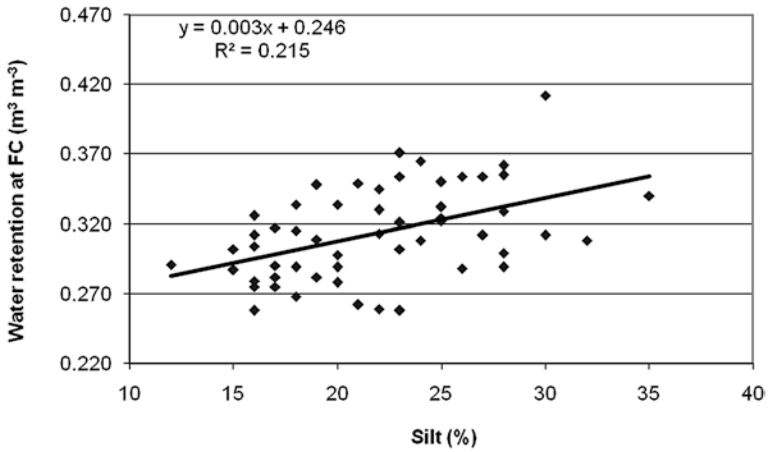

Fig. 16.4c Relation between silt (%) and water content at FC (−33 kPa)

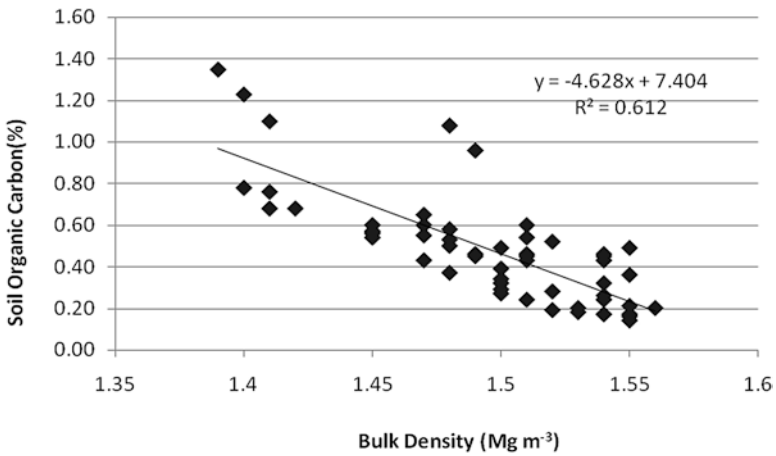

Fig. 16.5 Relationship between bulk density and soil organic carbon

FC and PWP were correlated, it was observed that soil water retention at field capacity (−33 kPa) was significantly correlated with SOC for 0–0.15 m depth with the R^2 value of 0.566, but the SOC of the whole profile was not found significant. Beyond that, no correlation was observed between SOC and water retention (Table 16.6). It might be due to the fact that SOC decreased but water retention increased due to more clay content at higher depths.

No significant relation was observed between organic carbon at different depths and soil water retention at higher suction (−1500 kPa, PWP) (Table 16.6). From this fact, it can be concluded that organic carbon content appeared to be an important soil property to improve estimation of soil water retention from particle size distribution at lower suction values.

Table 16.5a Correlation matrix among water retention at field capacity, soil organic carbon (SOC) and other soil properties

Soil properties	Field capacity ($m^3 m^{-3}$)	SOC (%)	Clay (%)	Silt (%)	Sand (%)	Bulk density (mg m^{-3})	pH
Field capacity ($m^3 m^{-3}$)	1.00	−0.0848	0.620∗	0.459	0.672∗	0.088	0.290
SOC (%)	0.0848	1.00	−0.355	0.312	0.056	−0.796∗	−0.790∗
Clay (%)	0.620∗	−0.355	1.00	0.182	−0.655∗	0.435	0.559∗
Silt (%)	0.459	0.312	0.182	1.00	0.861∗	−0.3007	−0.129
Sand (%)	−0.672∗	−0.056	−0.655∗	−0.861∗	1.00	0.006	−0.188
Bulk density (mg m^{-3})	0.088	−0.796∗	0.435	0.300	0.006	1.00	0.736∗
pH	0.290	−0.790∗	0.559∗	−0.129	−0.188	0.736∗	1.00

Table 16.5b Correlation matrix among water retention at permanent wilting point (PWP), soil organic carbon (SOC) and other soil properties

Soil properties	PWP ($m^3 m^{-3}$)	SOC (%)	Clay (%)	Silt (%)	Sand (%)	Bulk density (mg m^{-3})	pH
PWP ($m^3 m^{-3}$)	1.00	0.0003	0.667∗	0.392	0.645∗	0.0556	0.162
SOC (%)	0.0003	1.00	−0.355	0.312	−0.056	−0.796∗	−0.790∗
Clay (%)	0.667∗	−0.355	1.00	0.182	−0.655∗	0.435	0.559∗
Silt (%)	0.392	0.312	0.182	1.00	−0.861∗	−0.300	−0.129
Sand (%)	−0.645∗	−0.056	−0.655∗	−0.861∗	1.00	0.006	−0.188
Bulk density (mg m^{-3})	0.055	−0.796∗	0.435	−0.300	0.006	1.00	0.736∗
pH	0.162	−0.790∗	0.559∗	−0.129	−0.188	0.736∗	1.00
Porosity (%)	0.113	0.599∗	−0.187	0.415	−0.221	−0.764∗	−0.439

∗Significant at 5% probability level
PWP permanent wilting point (−1500 kPa)

This may be related to the fact that the structure-forming effect of organic matter affects soil water retention at water content close to field capacity to a larger extent than water retention close to wilting point. At higher suction, soil water retention was more significantly correlated with clay, which dominates over all other factors. It was also observed that SOC of the soil profile as a whole was not significantly correlated with clay, sand or water retention at FC and PWP but had significant correlation with soil profile bulk density, porosity and pH (Figs. 16.5, 16.6 and 16.7).

Table 16.6 Slope and R^2 value of the depth-wise relationship between soil organic carbon (%) and water retention at Θ_{FC} (−33 KPa) and Θ_{PWP} (−1500 KPa)

	Θ_{FC} (−33 KPa)		Θ_{PWP} (−1500 KPa)	
Predictors	R^2	Slope	R^2	Slope
SOC at 0–0.15 m depth	0.566*	0.054	0.276	0.011
SOC at 0.15–0.30 m depth	0.393	0.061	0.223	0.021
SOC at 0.30–0.45 m depth	0.151	0.015	0.201	0.029
SOC at 0.45–0.60 m depth	0.024	0.031	0.123	0.028
SOC at 0.60–0.90 m depth	0.266	0.124	0.415	0.107
SOC at 0.90–1.20 m depth	0.204	0.125	0.126	0.042

*Significant at 5% probability level
SOC = soil organic carbon (%); Θs (0 KPa) = moisture content at maximum saturation ($m^3\ m^{-3}$); Θ_{FC} (−33 KPa) = moisture content at field capacity ($m^3\ m^{-3}$); Θ_{PWP} (−1500 KPa) = moisture content at permanent wilting point ($m^3\ m^{-3}$)

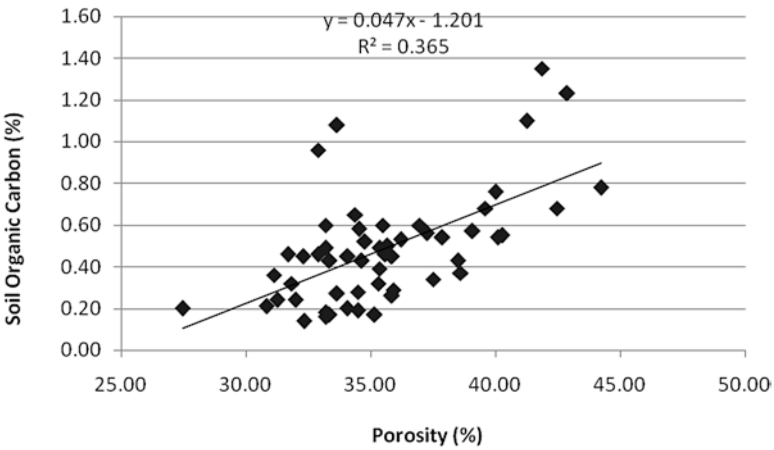

Fig. 16.6 Relationship between porosity and soil organic carbon

16.7 Conclusion

The study provided data on relative contributions of different upland cropping systems to carbon storage. Treatment C_7 (cashew plantation) recorded the highest soil organic carbon (1.35 and 1.10% at 0–0.15 and 0.15–0.30 m, depths respectively). Litter contribution from the cashew plantation may be the reason for the relatively higher SOC content. Soil organic carbon (SOC) content in soil profile was low in maize and rice-, cucumber- and okra-cultivated plots compared to that of legumes. Continuous tillage and cultivation of these nutrient-exhaustive crops favoured the rapid rate of mineralization rather than that of accumulation of SOC. Legumes hold promise for greater accumulation of SOC in the long term. These grain legume crops shed a large proportion of foliage with characteristic lignified tissues, and litter added to the soil mineralizes slowly to increase the stock of carbon in the soil.

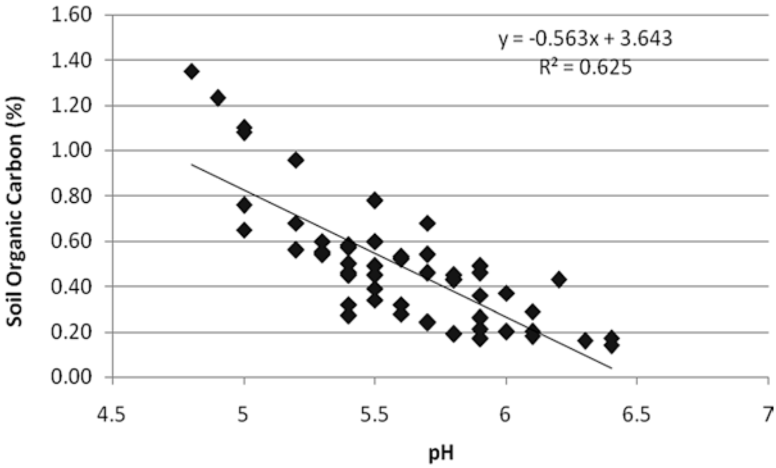

Fig. 16.7 Relationship between soil pH and soil organic carbon

Barren soil had the lowest organic carbon stock; therefore, land use practices that may remove vegetation and cause erosion should be avoided from the stand point of soil health and rate of CO_2 increase in the atmosphere. It may, therefore, be necessary for policy initiatives on land use management to consider alternative cropping systems that address the food security problem while maintaining environmental quality. The focus should be to encourage farmers to incorporate legume crops in their farming systems.

Soil water retention at field capacity (−33 kPa) was found to be correlated with SOC at 0–0.15 m depths only rather than the SOC of the whole profile. Soil pH, bulk density and porosity had a significant relationship ($P \leq 0.05$) with SOC content. From this fact, it can be concluded that organic carbon content appeared to be an important soil property to improve estimation of soil water retention at lower suction values. No significant relation was observed between organic carbon at different depths and soil water retention at higher suction (−1500 kPa, PWP). This may be related to the fact that the structure-forming ability of organic matter affects soil water retention at water content close to field capacity to a larger extent than water retention close to wilting point.

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Part IV

Pastures, Grasslands, Forests and Farming Systems

Soil Organic Carbon Dynamics in Tropical and Subtropical Grassland Ecosystem

17

N. S. Pasricha and P. K. Ghosh

Abstract

Grassland ecosystems occupy a vast area on the Earth's land surface and play a significant role in mitigating the climate change and global warming by sequestering atmospheric CO_2. As much as 20% of the total terrestrial C is stored in their root zone as soil organic carbon. However, through anthropogenic activities, these grasslands can become a source of CO_2 emissions to the atmosphere. CO_2 flux from grasslands is highly influenced by factors such as soil moisture, soil temperature and amount of organic carbon in the soil. A third of total C captured annually by the aboveground vegetation may be lost though CO_2 emissions as observed in *Imperata* grasslands of northeast India, which, otherwise exhibits a significantly high capacity to store SOC stocks in the absence of intensified grazing and burning events. Southern grasslands of China, on the other hand, have been reported to be a weak C sink as examined on the basis of spatiotemporal C cycle. These grasslands act as a C sink during the wet season but as a source of CO_2 during the dry season. Net preservation and stabilization of C, however, depends on the impact of type of land management, which can be judged from the changes in the labile or free C fractions. These labile C pools of SOC are the first to get affected by disturbances of the grasslands through different management practices. Grazing and burning together can significantly increase CO_2 fluxes as observed in Andean grasslands. However, under undisturbed native conditions, temperature and moisture are the major drivers of SOM decomposition. With the introduction of high-yielding grass species and with liberal use of chemical fertilizers, grazing land intensification has been found to rather promote SOC sequestrations in Andean grassland ecosystems. Much of the C added to the soil under such conditions is in the form of labile C fractions, which are

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highly prone to decomposition with release of CO_2. A rapid transfer of plant inputs through active and intermediate C pools into mineral-dominated pools is the ultimate outcome required for building and stabilizing the SOC stocks. Such results have been observed with high-yielding tropical perennial C4 grass species in the least soil disturbance production systems. Grazer effects have been reported to shift from negative to positive with decreasing precipitation, increasing fineness of soil texture, changing dominating grass species from C3 to C4 and, of course, decreasing grazing intensity.

Keywords

Carbon dynamics · CO_2 flux · Grass species · Grassland ecosystems · Grazing intensity

17.1 Introduction

Grasslands, covering about 40% (33×10^6 km^2) of total land area around the world, play an important role in balancing the global C budget (Scurlock and Hall 1998; Wang and Fang 2009) and act both as a sink for C storage in their root zone as soil organic matter (SOM) and as a source of CO_2 for the atmosphere when not managed properly (Nagy et al. 2007). About 10% of the total global terrestrial biomass is supported by grasslands and contributes towards the global pool of SOC to the extent of 20–30%. Since the 1980s to 2014, about one-quarter of fossil fuel, land use and animal CO_2 emissions have been sequestered by natural terrestrial ecosystems, helping to curtail both the pace and the magnitude of global climate change (Ciais et al. 2014). Grasslands can thus contribute towards climate change mitigation by sequestering and storing C in their root zone (Abdalla et al. 2018). In properly managed grasslands, C stored in the root zone improves soil health and facilitates greater storage of moisture in the soil profile by improving the infiltration rate and protecting against run-off losses of water and soil erosion (Pasricha 2017). Overgrazing and improper management of grasslands may lead to soil C depletion and reduction in soil potential for plant growth. Soil C has a positive effect on soil physical, chemical and biological conditions. However, large-scale land use changes by conversion of grasslands and forest cover into cultivated lands play a greater role as a source rather than as a sink and release CO_2 to the environment. Such land conversions are more common in tropical and subtropical regions of the world, including Africa, South and Southeast Asia. A high population growth rate in these countries is accelerating conversion of grasslands and forests to cultivated lands to meet the increased food demands.

Grasslands account for about 20% of the total C both in soil and in vegetation on Earth and, therefore, play an important role in the relationship of total global C cycle and budget of grasslands. Emphasizing the role of grasslands in storing C in the root zone, it is stated that SOC in grasslands and savannahs represents one of the largest reservoirs of C on Earth. With changing climate, there will be more water deficit in soil and frequency of droughts and heat wave will increase. Under such situations, grasslands may emerge competitively more successful CO_2 sinks than the forests. While tree species are more vulnerable to heat and water stress due to climate change, posing threats to C storage in forest regions in the future, adaptive capability of grass species to extreme weather events is more consistent with evolution of grass species of drought tolerance and adaptation to wildfire events (Vicente-Serrano 2013; Cranine et al. 2013) These changes in climate may affect different grass species differently, and C4-dominated grasslands may prove more sustainable sinks for CO_2 than C3-dominated grasslands. Resilience of grasslands to rising temperature, droughts and fire events coupled with preferential banking of C to belowground sinks in the grassland root zones help to preserve sequestered terrestrial C and prevent it from re-entering the atmosphere. Uncontrolled high-intensity grazing under such conditions will enhance SOM decomposition, resulting in increased CO_2 releases to the atmosphere and turn grasslands into C sources rather than C sink (McSherry and Ritchie 2013). With increasing social costs of climate change, the potential market value of C is estimated to be as high as \$105/Mg CO_2 by 2025 (Dietz and Stern 2015). This indicates that with emerging markets, managing grasslands and agricultural soils, SOC storage may provide substantial opportunities for both environmental and economic sustainability (Crow et al. 2018). Grasslands are under constant threat due to conversion to cultivation land for food crops, and it is especially so in tropical and subtropical regions of the world where population growth pressure is high. These ecosystems are further subject to the vagaries of changing climate and global warming through rising temperature, causing increasingly more water deficits, drought events and changing rainfall pattern (Pasricha 2015). In comparison to temperate regions, there is far less reported information on grasslands, savannahs and pastures in tropical and subtropical regions. In this chapter, we attempted to consolidate the latest published information of the role of grasslands in sequestering C and its storage in the root zone of tropical and subtropical regions.

17.2 Estimated Carbon Accumulation

Although the amount of carbon stored in the root zone of grasslands depends on a number of biotic and abiotic factors, Long et al. (1992) reported around 144 g C/m^2/yr. on average at several grassland sites across tropical and subtropical regions of Kenya, Mexico and Thailand. If protected from fire and overgrazing, these grasslands can serve as an effective sink for atmospheric C. African grasslands and savannahs are more efficient sequesters of C because of C4-dominated grass species in these regions. Under similar conditions, grass species with C4 type of photosynthetic pathway can accumulate more aboveground and belowground biomass than the C3 species (Fisher et al. 1994, 1995). Most of the grasslands have been reported to have originated from deforestation and abandoned agricultural systems as in India (Thokchom and Yadav 2016). The carbon level in these grasslands depends on the successive levels of grazing, burning and harvesting. Northeast India, representing

Table 17.1 Estimated C stocks in *Imperata* grasslands in Northeast India (Thokchom and Yadav 2016)

Component	Total C stock (t/ha)	% of total stock
Aboveground biomass	5.40	8.1
Belowground biomass	5.77	5.6
SOC (0–30 cm)	55.94	83.3

Table 17.2 Carbon stocks in the belowground biomass in comparison to carbon stocks in other tropical and subtropical regions

Location/type of grassland	C stocks (t/ha)	References
*Imperat*a, NE India	5.77	Thokchom and Yadav (2016)
Leymus chinensis grasslands, N China	5.57	He et al. (2008)
Neotropical savannahs, Brazil	6.75	Delitti et al. (2001)
Cerrado wet grasslands, Brazil	2.70	Fidelis et al. (2013)

a high rainfall area, supports vast tracts of *Imperata* grasslands. As in other parts of tropical and subtropical Asia, these grasslands occupy a vast area covering around 35×10^3 km^2. The *Imperata* grasslands in India are highly leached, acidic in reaction and poor in fertility clay loam soils. On an average, total soil organic carbon stocks at the 0–30 cm depth of these grasslands have been reported to be 55.94 t/ha (Table 17.1).

These authors have reported annual rates of aboveground and belowground C accumulation estimated at 11.85 and 11.71 t/ha/year, respectively, giving around a total of 23.56 t/ha/year. Carbon stocks in the belowground biomass of *Imperata* vis-à-vis other grasslands in the tropical and subtropical regions of the world are shown in Table 17.2.

Because of the poor soil conditions with low fertility, humid grasslands of northeastern India with aboveground biomass in the range of 221–813 g DM/m^2 is far lower than that of the Bundelkhand region at 721–5960 g DM/m^2. But it is relatively higher than that in the western *Garhwal* region, Himalayas (16–373 g DM/m^2). More than 80% of the soil organic C in the root zone of the pastures soil combination was the organic C as observed by Thokchom and Yadav (2016) for *Imperata* grasslands. Similar were the results for Ni (2002) in the grasslands of China. Zhang et al. (2017) reported that the total grassland area in China is around 3.95×10^6 km^2, which is approximately 40% of China's terrestrial area. Southern grasslands are an integral part of the grassland ecosystem and play an important role in the terrestrial C cycle of China. Annual C budget in this region varied from −8.12 to 6.16 Tg C/year with annual average of 0.45 Tg C/year during the study period, 1961–2013. They observed that a total amount of 23.83 Tg C sequestered in this region, which shows that this region is a weak C sink. In fact, this southern grassland ecosystem of China basically acts as a sink during the wet season but as a C source in the dry season. It is clear that temperature and rainfall are the major driving factors determining the C budget dynamics on the seasonal scale, while soil moisture content is the main driving force when C budget is worked on an annual basis scale.

17.3 Effect of Grazing Intensity

Grassland ecosystems play an important role in livestock production and are a source of livelihood for a significant sector of people, especially in the developing countries of tropics and subtropics. Almost 50% of green forage requirement of milch animals in these countries come from grasslands. Herbivores are reported to have dramatically different effects on SOC, both positive and negative depending on soil type, precipitation, grass species composition and grazing intensity (Pineiro et al. 2010; McSherry and Ritchie 2013). Intensity of livestock grazing has a major impact on SOC storage in grassland agroecosystem. However, storing C in the grasslands is strongly dependent on grazing intensity besides grass species and type of herbivores supported by them. If not managed properly, grasslands can act as a source of CO_2 rather than its sink for greenhouse gases mainly due to overgrazing (Powlson et al. 2011).

Abdalla et al. (2018), from their vast review of existing information across different agro-climatic zones of the world, concluded that grazing intensity below the carrying capacity of the systems results in a decrease in SOC storage, although its impact on SOC is climate dependent. To consolidate the published information of the effect of intensity of grazing, it is necessary to include the effect of heterogeneity in grass types/species, and variation in the environmental factors of different sites/regions. All grazing intensity levels, which have been tried, increased SOC stocks (+76%) in the moist–warm climate regions, while there was a reduction (−19%) under moist–cool regimes. However, under dry–warm and dry–cool climates, only low and low-to-medium grazing intensities were associated with increased SOC stocks. They further reported that high grazing intensity significantly increased SOC for C4-dominated grasslands compared to C3 and C3 + C4 mixed grasslands. Therefore, in order to protect grasslands from degradation, grazing intensity and management practices should be optimized according to climate region and grassland type (C3, C4 or C3 + C4) (Abdalla et al. 2018). Constant high-intensity grazing can ultimately lead to elimination of some less competitive grass species and lead to establishment of other species (Pineiro et al. 2010). High-intensity grazing may help in enhancing C sequestration if the annual average rainfall is low (< 600 mm), and this effect may vary with soil type. A linear regression of annual net plant productivity (NPP) remaining available as a possible OC input to the soil, with calculated grazing intensity (GI) and climate zone ($R^2 = 0.67$; $P < 0.001$) demonstrated that SOC stock under the moist–cool climatic zone is much higher than under other climatic regimes (Fig. 17.1). The second higher climatic zone, in SOC, is moist–warm (MW) but with much higher standard deviation (Abdalla et al. 2018). Wang et al. (2017) also reported that composition of grass species and soil conditions in the Tibet pastures were affected by not only grazing intensity but also local environmental factors. Ignoring the regional climate zones, higher GI (below the carrying capacity of the systems) was generally associated with a decrease in SOC stocks. Similar results have been reported by Lu et al. (2017) and Zhou et al. (2017). Constant intensive grazing, by decreasing net primary productivity, may result in altogether loss of large-leaved grass species, giving way to

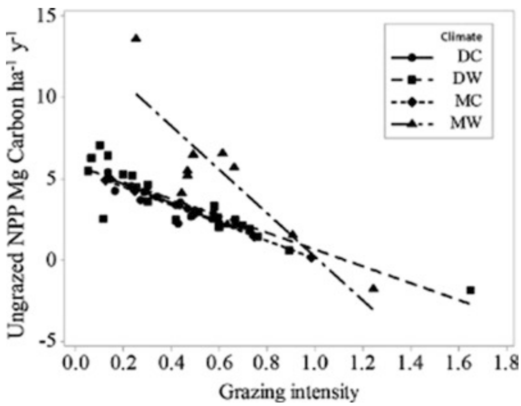

Fig. 17.1 Regression of un-grazed NPP (Mg C/ha/year) to grazing intensity calculated from NPP and number of animal units (value greater than zero and averaged) for each climate zone (*DC* dry–cool, *DW* dry–wet, *MC* moist–cool, *MW* moist–warm) (Abdalla et al. 2018)

dominance of less palatable narrow-leaved grass species (Shengjie et al. 2017). Impact of the level of GI on SOC is climate dependent, so the same GI level may have different impact on SOC in different climate zones.

17.4 Effect of Grass Species

Grass species with C4-type photosynthesis process are more efficient users of sunlight and produce higher aboveground and belowground biomass than C3 grass species. C4-dominated grasslands and savannahs are more common in the tropical and subtropical regions of the world. C4-type grasses generally contain highest levels of lignin and cellulose, which are generally recalcitrant to decomposition and produce extensive aboveground litter that is subject to frequent fire events during the extended dry season. Ritchie (2014) tried to solve as to why C4-type grasses are typically dominant in Serengeti and elsewhere respond differently to moderately intense grazing than C3-type grasses. High GI in dry areas or in C3-dominated grasslands reduces C storage in soil and makes it a more vulnerable to the vagaries of climate change. However, C sequestration in C4 grasslands increases under such conditions. Ritchie (2014) worked on a model that would apply mainly to grasslands in the tropical regions, suggesting two factors commonly under management control, that is, grazing and fire can have a large impact on soil C stocks in C4 grasslands and savannahs. Management practices that help reduction in fire incidences in fire-prone areas and resorting to controlled grazing in overgrazed areas can help restoring the degraded grasslands in the areas (Schipper et al. 2007). Adoption of such management practices can affect positive building of SOM and soil C across vast areas of developing world, as tropical grasslands and savannahs account for at least 10% of the Earth's surface and primarily occur in developing countries. The model, as proposed by Ritchie (2014) with the inclusion of plant compensation component to grazing intensity and fire, may help explain why grazing in C4 grass-dominated grasslands can help sequester soil C (McSherry and

Ritchie 2013); this may advance our understanding of soil C dynamics in tropical grasslands (Ritchie 2014). According to McSherry and Ritchie (2013), variables such as soil texture, precipitation, grass type, grazing intensity, study duration and sampling depth can explain almost 85% of a large variation (±150 g m^{-2}) in grazing effects. There is significant interaction between soil texture and precipitation, grass type and grazing intensity. They further observed that an increase in mean annual precipitation of 600 mm resulted in a 24% decrease in grazer effect on fine-textured soils, while on light-textured sandy soils, the same increase in precipitation produced a 22% increase in grazer effect size on SOC. Increasing GI increased SOC by 6–7% on C4-dominated and C4 + C3 mixed grasslands but decreased SOC by an average of 18% in C3-dominated grasslands.

17.5 Effect of Increasing Atmospheric Temperature

Increasing atmospheric temperature is likely to affect plant community globally. A selective effect may result in the elimination of more vulnerable grass species, leaving only more tolerant one to ultimately dominate. Global surface temperature has risen by approximately 0.8 °C over the last century and is predicted to increase by 1.4–5.8 °C during the twenty-first century (IPCC 2007). Such rise in temperature may expand the plant growth period, higher fecundity, greater biomass allocation towards belowground biomass and possible shift towards tree-dominated biomass (Scheiter and Higgins 2009). The effect of rising temperature will be different depending on whether it is C3- or C4-dominated grassland. In fact, C4-dominated grasslands are 40% more efficient in converting photosynthetically active radiation into biomass than C3-dominated grass species (Long 1999) Increase in the frequency of extreme weather events, change in pattern and total precipitation and rise in sea level have been cited as clear evidence for climate change and global warming (Dhillon and von Wuehlisch 2013; Pasricha 2015, 2017), due to mainly anthropogenic release of greenhouse gases to the environment in terms of both distribution and diversity (Scheiter and Higgins 2009). Such rise in atmospheric temperatures is reported to have greater impact on tropical and subtropical regions where grass species already occupy a narrow region owing to thermal specialization (Laurance et al. 2011). Perez et al. (2016) stated that because of these reasons, tropical and subtropical regions are likely to suffer maximum loss in biodiversity with rise in climate temperature. Buhrmann et al. (2016) emphasized more research investigations on the impact of rise in temperature on grasslands because of their higher diversity (Boval and Dixon 2012), especially in tropical and subtropical regions of the world, where they occupy around 20% of the land cover (Parr et al. 2014). With the help of open-top chambers (OTCs), Buhrmann et al. (2016) observed a significant increase in combined graminoid and shrubs aboveground productivity in experiments done in Kwazulu-Natal Saudstone Sowveld (KZNSS). Belowground biomass remained unaffected by rise in temperature. Elevated temperature increased annual graminoid AGP by ±19.9% and decreased forbs AGP by ±9% (Fig. 17.2).

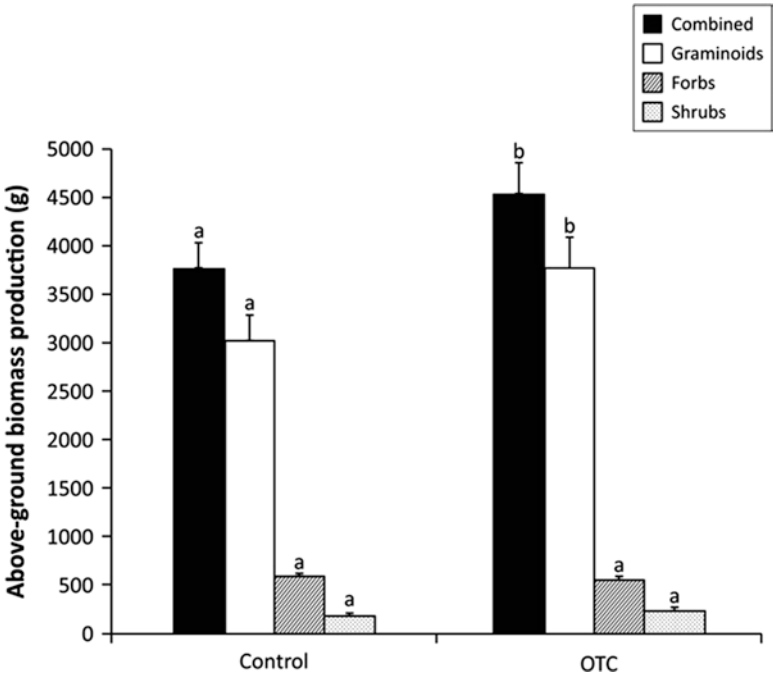

Fig. 17.2 Annual aboveground biomass production (g) for individual and all life forms combined. Values are presented as mean ± sd ($n = 20$). Values labelled with different letters are significantly different ($P < 0.05$, Wilcoxon signed rank test) when compared with life forms between temperature treatments (OTC = open temperature chambers)

This effect of elevated temperature was significantly higher in spring and autumn. On the other hand, shrub AGP was significantly higher in summer and autumn. In fact, spring and summer represent major growing seasons in subtropical grasslands. It is of significance to note that elevated temperatures may also increase biomass production during periods of low productivity and low rainfall. Crawley et al. (2005) also observed increase in grass biomass, but there was reduction in the forb and shrub AGP with rise in temperatures. Carlsen et al. (2000) also suggested that grasses, in forming dense swards, could possibly cause reduction in the quality and quantity of light reaching forb species below. Continuous growth and production of high-density grasslands may provide a poor habitat for native forbs, resulting, ultimately, in their elimination. Effect of elevated temperatures can be successfully investigated *in situ* using the open temperature chambers technique (Buhrmann et al. 2016). These studies can further elucidate as to how the elevated temperatures are likely to influence species composition and abundance. This may help evolve better management practices for conservation of tropical and subtropical grasslands and savannahs.

C4-dominated grasslands respond positively to elevated temperatures in terms of AGP (Morgan et al. 2011). Typically, C4 grass species dominate tropical and subtropical grasslands and savannahs (Still et al. 2003) because of their higher thermal thresholds than those for C3 species. Further change in grassland structure with increasing temperatures can be expected due to greater efficiency of C4 species for soil moisture; particularly at low moisture levels, C4 species are successful, further eliminating the less-efficient C3 species and therefore their selective elimination with time. Savannahs are the central biome in the transition between grasslands and forests, and they are characterized by the coexistence of two types of vegetation, highly shade-intolerant and fire-tolerant C4 grass species and C3 trees (Baudena et al. 2015). C4 grass species can out-compete trees in the driest environment while tree growth is water-limited. Fire events are expected to decrease under increased CO_2 concentration, given that C3 trees are favoured of C4 grasses in increased CO_2 concentration. This shows that transition between forests, savannahs and grasslands is expected to undergo major changes in future due to climate change and global warming (Baudena et al. 2015).

17.6 CO_2 Fluxes from Grasslands

Soil storage of C in the grasslands is the net outcome of the accumulation as a result of aboveground and belowground vegetative biomass addition and its loss as CO_2 through root respiration and microbial decomposition of soil organic matter. Main factors responsible for soil loss of CO_2 are temperature, soil moisture and amount of soil organic C in the root zone. Thokchom and Yadav (2016) worked out a relationship between the amount of CO_2 flux and soil temperature, (x1), soil moisture (x2) and amount of SOC (x3) as

$$Y = -683.4 + 1.229\text{x1} + 3.557\text{x2} \\ + 498.5\text{x3}\left[r\left(\text{x1}\right) = 0.81;, r\left(\text{x2}\right) = 0.65;, r\left(\text{x3}\right) = 0.97;,\ \text{at}P = 0.01\right].$$

Imperata grasslands under high rainfall can capture about 24 t C/ha in vegetation through photosynthesis, while 6.95 t/ha is lost to the atmosphere as CO_2 through root respiration and microbial activity under the existing conditions of grazing intensity. A net amount of 16.6 t C/ha/yr. is, thus, a significant amount for *Imperata* grasslands. These observations are indicative of significant capacity of these grasslands in retaining C in their root zone as SOM and show their sink capacity for CO_2. Similarly, Peruvian tropical Montana grasslands are a large sink and a source of atmospheric CO_2. Large-scale release of CO_2 has been reported by Oliver et al. (2017) from these grasslands mainly through anthropogenic disturbances of these grasslands. These authors investigated quantitative stabilization and decomposition of SOM to predict the impact of land management in the tropics. Tropical Montane grasslands are widespread in Peru and cover almost a fourth of the total land area in this country (Feeley and Silman 2010). Both burning or fire events and uncontrolled grazing significantly increase the soil CO_2 fluxes and decomposition rates (Oliver

Table 17.3 Mean soil C content (Mg C/ha) for two depths as influenced by land management system of fire and grazing for two sites in the Andes montage grasslands (Oliveras et al. 2014)

Management practice	Location/site				Mean of two sites	
	Akjanaco		Wayquecha			
	0–20 cm	20–30 cm	0–20 cm	20–30 cm	0–20 cm	20–30 cm
Grazed–burnt	117 ± 17	136 ± 30	107 ± 8	123 ± 10	112 ± 12.5	129 ± 20
Not grazed–burnt	170 ± 24	182 ± 24	131 ± 18	175 ± 47	150 ± 20.5	178 ± 34.5
Grazed–not burnt	130 ± 8	144 ± 16	125 ± 25	126 ± 24	127.5 ± 16.5	135 ± 20
Not grazed–not burnt	166 ± 22	238 ± 33	125 ± 26	140 ± 31	145.5 ± 24	189 ± 32

et al. 2017). They, however, did not observe much change in C stocks of these grasslands with land use, but both grazing and burning significantly reduced the stocks, especially labile SOM fraction. This reduction in the labile SOM fraction was surprisingly more in the lower horizon of 10–20 cm and 20–30 cm depths.

Annual burning of tropical Andes montane grasslands is a tradition to support traditional cattle grazing. Fires for agricultural clearing and maintenance of the highly productive forage grasses are of considerable importance in the Andes tropical montane grassland ecosystem and for the livelihood of people. This system of burnt grazing was traditionally alright until most recently when because of excessively more grazing and greater frequency of fire events due to global warming, and climate change has become a matter of concern due to increased loss of soil organic matter as CO_2 to the atmosphere (Cockrane and Ryan 2009). Oliveras et al. (2014) reported that this practice of fire and grazing resulted in a sharp decrease in their net productivity (NPP) and decrease in the soil C content (Table 17.3). These data for the two sites and two depths, although statistically not significant, showed a sharp decrease with grazing.

This shows that the burning alone or grazing alone may enhance soil respiration and decomposition rates when these land management practices are considered separately, with soil temperature identified as the main environmental driver in each of these two treatments. Surprisingly, when both burning and grazing treatments are used together, soil temperature may not correlate well with soil respiration. The combination of burning and grazing can produce higher soil respiration rate than the two treatments independently. A similar pattern has been reported by Ward et al. (2007). However, drivers of such an increase in soil respiration are less understood, and influence of grazing and burning together has been reported to have confounding effects (Michelsen et al. 2004). Burning and grazing together act synergistically and may obscure the influence of temperature, which is otherwise is the major driver, due to the action of other complex processes and drivers.

Implications of land use intensification on C response of grasslands are important components of SOC management. Generally, improved or controlled grazing

Table 17.4 Effect of grazing land intensification on soil organic C stocks and ^{13}C values (Silveira et al. 2014)

Site	Total C (t/ha)		^{13}C (%)	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm
Native rangeland	13.9	10.2	−22.4	−22.7
Silvopasture	22.9	21.1	−20.3	−20.9
Improved pasture	21.2	22.7	−14.7	−18.8
S.E.	1.9	1.7	0.8	0.2

land management strategies aimed at increasing aboveground biomass yield with little attention for belowground C accumulation. However, intensive land use management including use of high-yielding grass species with liberal use of chemical fertilizers affects not only the aboveground biomass but also increases the belowground C input (Liu et al. 2011a, b). Silveira et al. (2014) studied the long-term effect on SOC dynamics in the subtropical ecosystem of converting native rangeland ecosystem into intensively managed system and observed a significant effect on SOC and N stocks, and ^{13}C signature with intensification of the grazing land. Relatively higher above- and belowground biomass as a result of intensification with liberal use as compared to native rangeland with warm season grass as native vegetation, the ^{13}C value in 0–10 cm depth varied from −22.4 (native rangeland) to −14.7 (improved pasture), indicating the proportion of recently incorporated C4-derived C was more pronounced in improved pasture than in other ecosystems (Table 17.4). A similar trend was observed in 10–20 cm depth as well.

There was greater C mineralization due to grazing land intensification. These data show that most of the C associated with the improved pasture was present in the forms that were readily degradable than in less intensively managed ecosystems as in native rangelands. Silveira et al. (2014) concluded that although intensification management helps increasing more storage of C in soil, but a greater proportion of it is in readily decomposable labile C products. Labile C is less stable in soil, as it is free C and subject to mineralization to liberate CO_2 to the atmosphere. Light fraction (LF) or labile organic matter may make up to 30% of the total C stocks in the Peruvian Andes grasslands (Oliver et al. 2017), but in Brazil and Puerto Rico grasslands, this fraction is relatively small and ranges from 4% to 12% of the total C stocks (Potes et al. 2012). In the other tropical and subtropical regions, this fraction is low because of low elevation location of these grasslands. However, in high elevation grasslands, for example, in permafrost meadow ecosystems in Tibetan Plateau, the free LF is as high as 27% of the total C socks (Dorfer et al. 2013). In a review of 22 grassland studies, Gregorich et al. (2006) reported an average fraction of labile C as 13% with range between 18% and 55%. This wide range has been attributed by the authors to land use history and methodological differences.

Grazing has been reported to significantly affect the LF by reducing the aboveground biomass, resulting in lower incorporation of detritus into the soil. This phenomenon has also been observed in the grassland studies by Cao et al. (2013). Light fraction, free or labile organic C is not very stable in the soil and subject to rapid mineralization because of its dynamic nature and sensitive response to land management and land use changes (Zimmermann et al. 2007; Cao et al. 2013). The decrease in LF with grazing may not affect the total C stocks. Crow et al. (2018) investigated belowground C dynamics following conversion of grassland into high-yielding tropical perennial C4 grass in a zero-till production system. Rapid transfer of plant inputs through active and intermediate C pools into mineral dominated pools is the ultimate outcome desired for building stable soil organic C stocks. In an attempt to quantify changes in C pools and project the chemical composition of the aggregate-protected pools, Crow et al. (2018) observed an increase in multiple C pools with different ecosystem functions and turnover increase following cultivation. Immediately available microbial substrate and active C fractions increased by 12% and 30%, respectively, over time, and soil C accumulated significantly in multiple physical fractions. Soil organic matter as a dynamic C pool responds to disturbances such as land preparation for cultivation and subsequent crop choice or management practices. Crow et al. (2018) observed that rapid transfer of the fresh root-derived input to stable pool suggests that soil C under zero-till management may be resilient to disturbances. Tropical, perennial C4 grass cultivation with zero-tillage, *ratoon* harvest management practices are strong candidates for lignocellulosic bio-fuel feed stock in tropical regions. Maximizing the stabilization of C through interaction with mineral surface and within aggregates is a central component to recommendation for long-term soil C management for climate change mitigation (Lal 2013).

Temperature plays an important role as a driver for CO_2 evolution from the grasslands. CO_2 release from two grassland sites as a measure of soil respiration and SOM decomposition rates were lower for the site, which was located at higher elevation in the montane region, this has been attributed to lower temperature, which was 4 °C lower at higher elevation (Oliveras et al. 2014; Oliver et al. 2017). There existed a positive correlation between temperature and soil respiration. Although the SOM decomposition rates in Akijanaco correlated with CO_2 fluxes suggesting that decay was a good predictor of CO_2 flux, but this may not be true always. In the lower elevation site, CO_2 fluxes did not correlate with decomposition rates, implying that autotrophic respiration or other environmental factors may have a stronger influence on soil respiration (Oliver et al. 2017).

17.7 Conclusion

Grasslands occupy a vast area at global level and play an important role in relation to total global C cycle. But a large-scale conversion of grasslands to cultivated soils for food production in the tropical and subtropical regions of the world is a matter of greatest concern. Almost 43–73% of the total SOC losses can occur during the first 4 years of conversion. Most of these losses are from the labile pool of SOC, which is potentially vulnerable to degradation upon land use and land cover changes. Such anthropogenic perturbances can not only alter the C sink capacity but also render structural composition of the resultant organic matter in the grassland soils.

Grazing below the carrying capacity of the grassland systems results in a decrease in SOC storage, although its impact on SOC is climate dependent. Rise in atmospheric temperatures in future due to climate change may affect grasslands differently by affecting the growth of different grass species. Graminoids and shrubs appear to benefit from elevated temperatures, whilst forbs decrease in abundance, possibly tough competition and/or direct physiological effect. Extreme heat waves and frequent drought events with climate change is showing decreasing extent and capacity of forests as a C sink, especially in semiarid regions of the world, which constitute about 41% of Earth's land surface. By using a set of modelling experiments, grasslands have been shown to be comparatively more resilient than forests in response to twenty-first-century changes in climate. This has important implications for designing climate-smart Cap and Trade-offset policies. The resilience of grasslands to rising temperatures, drought and fire helps to preserve sequestered terrestrial C in the root-zone of grassland soil and prevent it from re-entering atmosphere.

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18 Tropical Grasslands as Potential Carbon Sink

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Abstract

Grasslands, an important natural resource, include a wide variety of ecosystems and cover around 26% of the world's total land area. Soils of grassland store a large amount of carbon, with global carbon stocks estimated at about 343 Pg C. Besides, grasslands play a significant role in climate change mitigation through sequestering carbon from the atmosphere. Globally, the estimated carbon sequestration potential of soils lies between 0.4 and 1.2 Pg C per year, of which 0.01–0.30 Pg C per year is from grasslands. But grassland *per se* does not result in a carbon sink or sequestration. Carbon sequestration can be enhanced in grasslands by adopting appropriate management practices like controlled and improved grazing management, sowing favourable forage species, fertilizer application and irrigation, restoration of degraded grasslands, etc. However, there are certain limitations/constraints that hamper adopting of those practices, enhancing carbon sequestration in grasslands. The limitations include incessant degradation of grasslands, climate change, paucity of genuine data on carbon stock of grasslands, particularly from developing countries, etc., which need to be resolved in the future.

Keywords

Carbon sequestrations · Climate change · Grasslands · Grazing management · Pasture management

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18.1 Introduction

Around 26% of the world's total land area and 80% of agricultural land are covered by grassland resources/pastures. Over the years, these grasslands have been considered as one of the foundations of human activities and civilizations through supporting livestock grazing and production. The same trend is continuing even today, particularly in developing countries including India, where 68% of grassland resources exist. These grasslands have been utilized for maintaining livestock to produce meat and milk and, to a lesser extent, fibre and draught power. It has been observed that there are numerous regional, national and global issues with which utilization of grasslands are inextricably connected. These include the function of grasslands to reduce greenhouse gas (GHG) emissions, as water catchments, and the preservation of ecosystem biodiversity without much adverse effects to meet the increased global demand for food. Providing household security and greater ability to deal with seasonal fluctuations like crop failure and other disasters, contributing to soil fertility recycling of by-products and reduction of wastes and crop yields especially in marginal situations, controlling weed and crop pests and diseases, provision of fuel as manure and biogas, catchment areas for water supply to control runoff and to maintain water quality and opportunities for tourism as an industry are the major ecological services by grassland-based livestock production (Boval and Dixon 2012).

In India also, these grassland resources are now under pressure to produce more and more livestock by grazing more intensively, and they have become vulnerable to climate change. As a result of past practices, it has been observed that 7.5% of the world's grasslands have already been degraded due to high grazing pressure or overgrazing. Cultivation of native grasslands/pastures contributes to the transfer of about 0.8 mg of soil C to the atmosphere annually. Soil organic matter lost due to conversion of native grassland resources to cultivable land is also extensive. Removal of large amounts of aboveground biomass, continuous heavy grazing pressure and poor grazing management practices are important human-controlled attributes that influence grassland production and have led to the depletion of soil carbon stocks. But such depletion of soil carbon stock can potentially be reversed following good grassland management practices.

18.2 Grasslands and Carbon Cycle

Carbon is an element usually found on Earth in different forms. It is an essential element for all forms of life. Globally, carbon is held in a variety of different stocks such as oceans, fossil deposits, terrestrial system and atmosphere. In the terrestrial system, carbon is stored in forests, forest soils, grasslands/pastures, agriculture, swamps, wetlands, etc. But the delicate carbon balance maintained by nature has been overturned by anthropogenic factors. Extraction of fossil fuels from the earth and many other human-induced activities are overloading the atmosphere with CO_2 and other greenhouse gases, thereby raising serious issues including the very survival of the human race. At present, human activity adds about 7 billion tons of CO_2

into the air every year. Indeed, the global C cycle is closely linked to the greenhouse effect. Excessive quantities of greenhouse gases disturb the balance of transfer of heat through the atmosphere. Usually, solar radiation absorbed by space cools the Earth. The presence of excessive anthropogenic greenhouse gases (mostly CO_2 from fossil fuel burning) in the atmosphere reduces the Earth's ability to cool to outer space through infrared radiation.

Carbon moves continuously among air, plants and soils, and changes to any of these three components invariably affect the balance amongst them. During the process of photosynthesis, plants capture atmospheric CO_2 and store the carbon in their living tissues, both above and below the ground. Part of this organic carbon is stored in the soil as plant parts die and decompose, and part is lost back to the atmosphere as gaseous carbon emissions through plant respiration and decomposition. Herbaceous plants of grassland contribute to grassland carbon stores primarily through the growth and sloughing of roots, a cyclical process in case of perennial species, especially when grazed by animals. When such a plant is pruned back, as happens with grazing, a roughly equivalent amount of roots dies off (adding carbon to the soil) because the remaining top-growth can no longer photosynthesize sufficient food to feed the plant's entire root system. On the contrary, if adequate rests are given from grazing, both roots and top-growth recover and the cycle begin again. This is why when good grazing practices are followed for animals, perennial grasses can live and reproduce for many years with an ongoing cycle of pruning, root-sloughing and regeneration, contributing more and more carbon to the soil. Human-induced disturbance to the carbon cycle occurs by both direct and indirect ways. Direct effects include the addition of new carbon to the active carbon cycle through the combustion of fossil fuels and land use change, leading to changes in the vegetation structure and distribution. Indirect human effects on the carbon cycle include change in other major global biogeochemical cycle, alteration of the atmospheric composition through the additions of pollutant as CO_2 and change in the biodiversity of landscapes and species. Currently, about three-quarters of the direct human-induced disturbances to the global carbon cycle are due to fossil fuel combustion.

When considered at the global level, there is about two times more carbon in soil organic matter than the amount present in the atmosphere, and as a result, a relatively small change in soil organic matter can have a large impact on CO_2 in the air (Janzen et al. 2002). The large amount of land area covered by grassland resources as well as the relatively unexplored potential for grasslands soils to store carbon has augmented interest in the carbon cycles of these ecosystems. Areas where more carbon is absorbed than given off are referred to as carbon sinks and include areas such as forests, agro-ecosystems and grasslands. Grasslands store around 34% of the global terrestrial stock of carbon, while forests and agro-ecosystems store around 39% and 17%, respectively (World Resources Institute 2000). Moreover, in forests, the vegetation is the primary source of carbon storage, whereas in grasslands, most of the carbon is stored in the soil. This is the reason that to stop and/or reduce rising concentrations of CO_2 in the atmosphere, countries at the global level are actively seeking means and ways to increase carbon storage on land, and therefore, grasslands have become an important factor.

18.3 Carbon in Grasslands

Grasslands, a mixture of grass, clover and other leguminous species, dicotyledons, herbs and shrubs usually act as carbon sink. Thus, both tropical and temperate natural grasslands play a significant role in the global carbon cycle. Indeed, grasslands are one of the most widespread vegetation types throughout the world, covering 15 million km^2 in the tropics and 9 million km^2 in the temperate regions; together, they constitute around one-fifth of the world's land surface. Grassland ecosystems are far from uniform, ranging from the natural savannahs of Africa to the prairies and steppes of North America and Russia and from the derived savannahs found on many continents to the sown pastures of Europe and Latin America.

It has been reported that soils of these grasslands store a large amount of carbon, with global carbon stocks estimated at about 343 Pg C, which is about 50% more than the amount stored in forests (FAO 2010). Grasslands also play an important role in climate change mitigation through sequestering carbon from the atmosphere. It was estimated that the soil organic carbon sequestration potential of the world's grasslands is 0.01–0.3 Pg C per year (O'Mara 2012). But still it is a matter of debate as to whether grassland carbon sequestration is finite, with the time period required to reach a new equilibrium dependent on previous land use and soil clay content. While few studies in relation to the time scale for grassland carbon equilibrium indicated 30–40 years, other studies have indicated that grasslands have a large potential to store carbon, and they may act as a carbon sink for longer periods of time (Scurlock and Hall 1998). Grasslands and savannahs with their belowground carbon storage, seasonal burning, regrowth and tree–grass dynamics are major factors in the global carbon cycle. Although carbon stocks, productivities and turnover time are subjected to considerable uncertainty, on the basis of present evidence, it is expected that these biomes constitute an annual sink of about 0.5 Pg carbon. However, the future sink in the context of climate change is much less certain and will be governed by management practices/regimes with extreme values ranging from – 2 to +2 Pg carbon per year.

The *Imperata* grasslands of the tropical region are a vast underutilized natural resource (about 35 million ha in Asia); India is the second-largest area holder of such grasslands. These grasslands are exploited as thatching materials for monetary benefits. A systematic study in Barak Valley of northeast India revealed that SOC accumulation was greater during the summer season (Table 18.1), with more C

Table 18.1 Carbon budget data in relation to seasons in *Imperata* grasslands (Pathak et al. 2015)

Season	SOC (g m^{-2})	SOC accumulation (g C m^{-2} month^{-1})	CIAB (g C m^{-2} month^{-1})	CIBB (g C m^{-2} month^{-1})	CO_2 efflux (g C m^{-2} month^{-1})
Autumn	23.02	0	6.78	30.98	16.93
Winter	23.02	0	0.436	11.82	13.93
Summer	25.54	2.52	2.04	22.34	31.85
Rainy	24.7	0.84	14.31	24.79	29.06

SOC Soil organic carbon, *CIAB* C input from aboveground biomass, *CIBB* C input from belowground biomass, *RS* soil CO_2 efflux/soil respiration

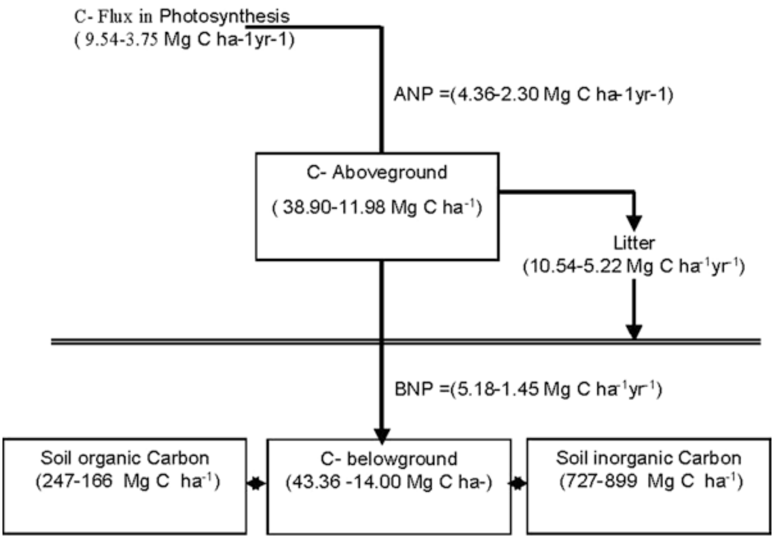

Fig. 18.1 Carbon budget of *Sporobolus marginatus* and *Desmostachya bipinnata* natural vegetations. The values in compartments represent the carbon stock (mg C ha^{-1} $year^{-1}$), and the values on the arrows represent carbon flow (mg C ha^{-1} $year^{-1}$); ANP: Aboveground net production and BNP: Belowground net production. (Jangra et al. 2010)

input of 14.3 g C m^{-2} $month^{-1}$ from aboveground biomass and 30.9 g C m^{-2} $month^{-1}$ from belowground biomass. Carbon budget analysis with respect to seasons revealed that *Imperata* grasslands acted as the C source during the winter and summer but served as sink during the autumn and rainy seasons (Pathak et al. 2015). However, annual C budget indicated *Imperata* grasslands as a net sink of 38.45 g C m^{-2} $year^{-1}$ (0.40 mg C ha^{-1} $year^{-1}$). Another study carried out in *Sporobolus marginatus*- and *Desmostachya bipinnata*-dominated grassland ecosystems in sodic soils of north-western India envisaged that these natural grassland vegetations on salt-affected soils have the potential for carbon sequestration from 247 to 166 mg C ha^{-1} over a period of 15 years (Fig. 18.1) by increasing plant biomass production, improving soil organic matter as well as carbon stability in soil aggregates. Stabilization of carbon within the soil microaggregates and predominance of illite and montmorillonite in the clay were also greater in these grasslands (Jangra et al. 2010).

SOC in the grasslands at different altitudes has been recorded in the Uttarakhand state of India (Gupta and Sharma 2013). SOC pool of 142.14 t ha^{-1} was found above 2500 m altitude, 105.28 t ha^{-1} between 2001 and 2500 m, 97.80 t ha^{-1} between 1501 and 2000 m and 41.15 t ha^{-1} between 1001 and 1500 m altitude. The minimum amount of 37.09 t ha^{-1} was found between 501 and 1000 m altitude. The higher temperature and restricted moisture availability at up to 1500 m altitude than those at high-altitude grasslands might be responsible for lower SOC pool present between 501 and 1500 m altitude. Temperate climate favours organic carbon accumulation in the soil. Hence, grasslands above 1501 m altitude had reasonably higher SOC pool.

Indeed, the carbon sequestration of any grassland ecosystem is a function of biomass production capacity, which in turn depends on the interaction between edaphic, climatic and topographic factors of a site. Also, the habitats of wild animals along with grassland habitat management practices play a crucial role in regulating the carbon budget of the ecosystem. This is why the observations recorded at one place may not be applicable or replicated to another site or place. A study was conducted in Gorumara National Park of West Bengal, which has distinct habitat diversity, with substratum dominated by sandy, sandy loam and loamy soils and marshy area. The existence of diversified habitats controlled the rate of decomposition of organic matter generated by wild animals, leaf litter, fallen removed over wood materials and the burnt out plant materials. The carbon sequestration in Chepti (*Themeda arundinacea,* a perennial grass) collected from sandy substratum was 2.18 kg m^{-2} $year^{-1}$, while the value was 3.46 kg m^{-2} $year^{-1}$ collected from sandy loam type of substratum. In case of Daddha (*Saccharum narenga,* a herbaceous perennial plant species), the sequestration rate was 3.14 kg m^{-2} $year^{-1}$ and 3.66 kg m^{-2} $year^{-1}$ from sandy type and sandy loam type of substratum, respectively, indicating the sandy loam substratum in both the systems as a better sink of carbon (Ghatak et al. 2015).

On the contrary, grasslands of temperate regions are usually considered as C sinks (Abberton et al. 2010; Acharya et al. 2012). In Europe, C sequestrations were observed up to 52 g C m^{-2} $year^{-1}$ for established grassland and 144 g C m^{-2} $year^{-1}$ for conversion of arable land to grassland. In France, a meta-analysis revealed that, on average, for a 0–30 cm soil depth, C sequestration reached 44 g C m^{-2} $year^{-1}$ over 20 years. This was around half the rate (95 g C m^{-2} $year^{-1}$) at which C is lost over a 20-year period following conversion of permanent grassland to an annual cropland (Soussana et al. 2004). However, temperate pastures in the northeast USA are highly productive; they can potentially act as significant C sinks. But these pastures are subjected to relatively high biomass removal through preserved forage (hay) or animal grazing. For the first 8 years after conversion from ploughed fields to pastures, the pastures were only a small net sink for C at 19 g C m^{-2} $year^{-1}$, but when biomass removal and manure deposition were included to calculate net biome productivity, the pasture was a net source of 81 g C m^{-2} $year^{-1}$. When grasslands were properly managed in the USA, C sequestration was found to be 10–90 g C m^{-2} $year^{-1}$ depending on the level of change adopted. In the recent past, it has been reported that most grassland areas across the Europe are net sources of greenhouse gases in terms of their total global warming potential because the beneficial effect of sequestering C in soils is outweighed by the emissions of N_2O from soils and CH_4 from animals being allowed to graze in the pastures (Levy et al. 2007).

18.4 Enhancing Carbon Sink in Grasslands

A carbon sink is considered as an environment in which carbon influx from the atmosphere exceeds carbon efflux to the atmosphere per unit area and unit time. In the context of ecosystems, sinks occur where photosynthesis exceeds respiration, or net primary productivity (NPP) exceeds decomposition. Theory regarding ecological succession in grasslands suggests that NPP and decomposition are at equilibrium in either late successional ecosystems or at intermediate stages of succession. Ecosystems with high biomass-to-soil carbon ratios like tropical forests/vegetations have large carbon pools but are also subjected to high turnover and thus rapid losses or gains of carbon. Ecosystems with low biomass-to-soil carbon ratios like temperate grasslands may have small carbon pools but low turnover rates and low potential for substantial carbon loss and thus serve as effective carbon sinks. Out of the total global mitigation potential of 5.5–6 Pg CO_2 equivalent year^{-1}, almost 1.5 Pg was related to grazing/pasture resources management. There are a number of practices that could contribute to reduced greenhouse gas emissions and enhanced sinks in grazing lands/pastures. Management practices used to increase livestock-forage production also have the potential to augment soil carbon stocks, thus sequestering atmospheric carbon in soils (O'Mara 2012). Different management practices that contribute to carbon sequestration in grasslands are highlighted here.

18.4.1 Grazing Management

Both under- and overgrazing have the potential to reduce carbon sequestration and lead to carbon loss from soils, although the effects may be inconsistent. The effects of grazing are mediated by changes in the removal, growth, carbon allocation and flora in pastures, and carbon input from animal excreta, which affect the amount of carbon deposited in soils. The grazing process even affects the rate of turnover/decomposition of the aboveground component of the plant community. Under light and heavy grazing, shoot turnover has been recorded at 36% and 39% compared to 28% in ungrazed exclosures. It is predicted that animal grazing may enhance physical breakdown, soil incorporation and decomposition rate of litter and standing dead plant materials (Schuman et al. 2002). Besides, grazing may stimulate root respiration and root exudation rates. Hence, sustainable grazing management increases carbon inputs and carbon stocks without necessarily reducing forage production. Improved grazing management, which increases production, also leads to an average increase of 0.35 mg C ha^{-1} year^{-1}of soil carbon stocks.

18.4.2 Nutrient Management

A positive correlation between C sequestration and N fertilization has been the normal trend in the managed grasslands. When comparisons were made between management systems, it was observed that the intensively managed grasslands sequestered over 2 mg C ha^{-1} year^{-1} more than extensive systems. Addition of nutrients based on plants' requirements can avoid excess applications, which otherwise would result in unnecessarily high nitrous oxide emissions. This is naturally the easiest way in intensively managed pastures that receive nitrogen fertilizer or organic manures. But it is comparatively difficult in extensively managed pastures/

grazing resources where the main nutrient additions are deposition of excreta by grazing animals, which are not as easily controlled. Similarly, application of other nutrients, where pastures/grasslands were deficient, also enhanced organic C storage (Conant et al. 2001). However, the benefits of increased soil C sequestration must be compared with the C costs of fertilizer production in order to determine the net effect on the atmosphere (Schuman et al. 2002).

18.4.3 Increased Forage/Pasture Productivity

Adopting practices such as fertilization and irrigation, which improves the productivity of pastures, also increases carbon storage in soils. There may be some offsetting of these gains by nitrous oxide emissions from nitrogenous fertilizers and manures, and the energy used in irrigation. However, fertilizer application is found to stimulate litter production, thereby enhancing soil C storage. Application of 40 kg N ha^{-1} resulted in significant increase in dry forage yield and total organic carbon (TOC) content of the soil in natural pastures (Rai et al. 2013), with a TOC build-up rate of 1.5 times more than what was observed in natural grasslands (0.74 g kg^{-1} $year^{-1}$). Increased plant production of the tall grass prairie was observed following N fertilizer application, which resulted in an increase in soil C of 1.6 mg ha^{-1} (Rice 2000).

18.4.4 Fire Management

Fire is traditionally used to control and improve pastures. It emits greenhouse gases, particularly methane and nitrous oxide, along with ozone production, smoke aerosols and reduction of tree and shrub cover, resulting in less carbon storage in soil and biomass. When properly managed, annual burning followed by animal grazing on the tall grass prairie is found to increase soil C storage to the extent of 2.2 mg ha^{-1} after 10 years (Rice 2000).

18.4.5 Introducing Favourable Forage Species

Enhancing species diversity and, specifically, introducing favourable forage species like new deep-rooted grasses with higher productivity into the species mix have been reported to increase soil carbon on low-productivity pastures and savannahs (Tilman et al. 2006). Indeed, forage species, which are better adapted to local climate, more resilient to grazing, more resistant to drought and able to enhance soil fertility through greater carbon inputs and then carbon sequestration, need to be considered. A study was carried out with introduction of 12 different range legumes in natural grasslands to compare their carbon input potentials (Table 18.2). It was recorded that introduction of *Macroptilium lathyroides* in natural grasslands resulted in 1.29 times increase in TOC as compared to that in natural grasslands. Other

Table 18.2 Effect of range legumes on forage yield of natural grassland and organic carbon in the soil (Rai et al. 2013)

Treatments	Forage dry matter yield (mg ha^{-1})	TOC (g kg^{-1})	SOC build-up rate (g kg^{-1} year^{-1})
Natural grassland	3.3	7.78	0.74
Alysicarpus rugosus	4.2	7.55	0.67
Atylosia scarabaeoides	4.1	9.22	1.22
Clitoria ternatea	4.4	7.47	0.64
Dolichos lablab	4.7	10.07	1.51
Desmodium tortuosum	4.2	9.72	1.39
Glycine javanica	3.8	8.58	1.01
Macroptilium atropurpureum	4.1	7.99	0.81
Macroptilium lathyroides	4.9	11.05	1.83
Mimosa invisa	3.7	8.91	1.12
Stizolobium deeringianum	4.0	8.10	0.85
Stylosanthes guianensis	4.2	10.53	1.66
Stylosanthes humilis	4.0	8.22	0.89
Vigna luteola	4.2	9.15	1.20

legumes also increased the total organic carbon (TOC) of soil. Maximum increase in TOC and soil organic carbon (SOC) build-up rate was observed with *Macroptilium lathyroides* (42%) followed by *Stylosanthes guianensis*. Except *Alysicarpus rugosus* and *Clitoria ternatea,* the rate of TOC build-up was higher in legume-incorporated grasslands than in the natural grasslands (Rai et al. 2013).

18.4.6 Adoption of Silvipasture Practices

When agroforestry systems like silvipastures are introduced in suitable locations, carbon is sequestered in tree biomass as well as in soil (Table 18.3). It promotes carbon uptake by lengthening the growing season, expanding the niches from which water and soil nutrients are drawn and, in the case of nitrogen fixing species, enhancing soil fertility. Improved management in existing agroforestry systems has the potential to sequester around 0.012 Tg C year^{-1}. Agroforestry systems are considered to have a higher potential to sequester C than pastures or field crops (Kirby and Potvin 2007). This hypothesis is based on the fact that introduction of trees in pasture will result in greater net aboveground as well as belowground C sequestration (Haile et al. 2008; Singh and Gill 2014). Abundant litters and/or pruning biomass returned to the soil combined with the decay of roots, contributing to the improvement of soil physical and chemical properties, which in turn enhance C sequestration.

Table 18.3 Soil carbon sequestration in different agroforestry systems (Nair et al. 2009; Rai et al. 2013)

Agro forestry system/species	Age (year)	Soil depth (cm)	Soil C (mg ha^{-1})
Agro forestry (*Pseudotsuga menziesii* + *Trifolium subterraneum*)	11	0–45	95.89
Agrisilviculture (*Gmelina arborea* + field crops)	5	0–60	27.4
Silvopastoral system: (*Acacia mangium* + *Arachis pintoi*)	10–16	0–100	173
Silvopastoral system: (*Brachiaria brizantha* + *Cordia alliodora* + *Guazuma ulmifolia*)	10–16	0–100	132[a]
Alley cropping system: *Erythrina poeppigiana* + Maize and bean (*Phaseolus vulgaris*)	19	0–40	1.62
Fodder bank (*Gliricidia sepium*, *Pterocarpus lucens* and *P. erinaceus*)	6–9	0–100	33.4
Tree-based pastures: Slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*)	8–40	0–125	6.9–24.2
Gliricidia sepium + maize (*Zea mays*)	10	0–200	123

[a]Carbon sequestration potential, which is based on C-stock estimates

18.5 Carbon Sequestration in Grasslands and Limitations

The management practices, which contribute to the restoration of degraded grasslands such as planting grasses, improved fertility, application of organic manures, reducing tillage and retaining crop residues and conserving water are expected to increase soil carbon stock or sequestration. However, in grasslands, carbon assimilation is directed towards the production of forage biomass by manipulating species composition and growing conditions. These grassland ecosystems are major source as well as sink for the three main biogenic greenhouse gases: CO_2, nitrous oxide (N_2O) and methane (CH_4). In undisturbed grasslands/pastures, carbon uptake through photosynthesis exceeds losses from respiration and the carbon balance becomes positive. On the contrary, the carbon balance becomes negative in degraded grasslands/pastures. Indeed, the basic processes governing the carbon balance of grasslands are similar to those of other ecosystems like forests. But biomass in grasslands, being largely herbaceous, is a small, transient carbon pool, and hence, soils constitute the dominant carbon stock and owned certain limitations (Mengistu and Mekuriaw 2014; Ghosh and Mahanta 2014).

18.5.1 Incessant Degradation of Grasslands

Grassland degradation is incessantly occurring under all climates and farming systems, which has resulted in a series of environment problems including soil erosion, degradation of vegetation, carbon release from organic matter decomposition, loss of biodiversity owing to habitat changes and impaired water cycles. This is usually related to a mismatch between the grazing pressure of animals and the carrying capacity of the pasture/grasslands. In fact, the land/animal ratio should continuously be adjusted keeping in view the conditions of the pasture, particularly in dry climates when biomass production is highly variable, but in reality, such adjustment is practiced only in very few cases, specifically in arid and semiarid regions where communal grazing is widespread.

18.5.2 Changing Climate

Climate change impacts to grasslands include increased seasonal, annual, minimum and maximum temperature and changing precipitation patterns. Because these ecosystems are relatively dry with a strong seasonal climate, they are sensitive to climatic changes and vulnerable to climatic regime shifts. The primary production in natural grasslands is comparatively low and also varies considerably based on sites and precipitation. Even where rainfall goes up to 900 mm per year or high, almost all of the precipitation falls during the distinct rainy seasons, and evapotranspiration demands exceed precipitation during most of the year. Hence, precipitation, and thus production, varies significantly from year to year, with coefficients of variation being as high as 60% in some of the drier areas. But grassland management practices that sequester C tend to make systems more resilient to climate variation and climate change. It was reported that increased soil organic matter (SOM) and carbon stocks improve yields, enhance soil fertility and reduce dependency on external nitrogen inputs.

18.5.3 Paucity of Information from Developing Countries

There are very few long-term studies on carbon sequestration of grasslands/pastures from developed. Accordingly, there is paucity of information/data from developed countries, which limits the creation of strong accounting systems that offer the same utility for quantifying soil carbon sequestration in developed and developing countries. Indeed, lack of accurate information can lead to greater uncertainty in estimates of soil carbon stock changes and ultimately result in climate-driven bias because the majority of studies from developed countries are related to temperate regions.

18.5.4 Policy Implementation Issues

It is true that there are proven management practices that promote carbon sequestration in grasslands, which also lead to enhanced productivity. But the policies required to encourage adoption of those practices in grasslands are very less than policies for forest and agricultural lands. This is especially true for practices that promote increased primary productivity or livestock production and practices that arrest grassland degradation. When emissions are reduced from grassland, it is likely to help not only in maintaining carbon stocks but also in sustaining the livelihoods of resource-poor people making a living from grasslands.

18.6 Conclusion

It is frequently said that grasslands are a perpetual sink for carbon, and that just maintaining grasslands will yield a net carbon sink. But it is unacceptable that grasslands act as a perpetual carbon sink, and the most likely explanation for observed grassland carbon sinks over short periods is inheritance effects of land use and land management prior to the start of flux measurement periods. Simply having grassland does not result in a carbon sink, but judicious management or previously poorly managed grasslands can increase the sink capacity. Since the grasslands are a large store of carbon, and that it is easier and faster for soils to lose or gain carbon, it is an important management target to maintain these stocks. Even there is considerable potential to increase this further through adoption of appropriate management practices like grazing land management (e.g. through managing livestock grazing intensity, improved productivity, etc.) and restoration of degraded grasslands. Grassland adaptation to climate change will be inconsistent, with possible increases or decreases in productivity and increases or decreases in soil carbon stores. Although a great deal of work has been done in recent years, estimates of carbon storage/stock in terrestrial ecosystems worldwide vary widely and more work is still required.

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19 Agroforestry for Carbon Sequestration in Tropical India

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Abstract

Our atmosphere naturally contains CO_2, CH_4, N_2O, water vapor, and other gases creating a natural greenhouse effect. But increased concentrations of these gases in the atmosphere have created an imbalance and have enhanced the greenhouse effect causing warming of the globe. Global warming will adversely affect hundreds of millions of people and will pose serious threats to the global food system and to rural livelihoods. Global warming is mainly the result of rising CO_2 levels in the Earth's atmosphere. CO_2 concentration in the atmosphere is increasing at greater pace from decade to decade. To assure food security, adaptation, and mitigation to climate change is unavoidable. Many organizations worldwide are working for lowering CO_2 concentration through various strategies like reduction in energy use, developing low- or no-carbon fuel, and CO_2 sequestration by forestry/agroforestry and engineering techniques. Agroforestry has been recognized as a means to reduce CO_2 emissions and enhance carbon sinks. Agroforestry systems (AFS) offer important opportunities of creating synergies between both adaptation and mitigation actions. Recent studies under various AFS in diverse ecological conditions showed that these systems increase and conserve aboveground and soil carbon stocks and also have an important role in increasing livelihood security and reducing vulnerability to climate change. The potential of agroforestry systems to accumulate C is estimated to 0.29–15.21 Mg ha^{-1} $year^{-1}$. The carbon sequestration potential of AFS can be enhanced by stabilizing soil organic carbon through possible mechanisms including biochemical recalcitrance and physical protection and also reducing C losses. Furthermore, effectiveness of AFS to carbon sequestration depends on structure and functions of different component, environmental, and socio-economic factors. Carbon sequestration can be quanti-

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fied by destructive or nondestructive methods. Implementing agroforestry on farmers' fields for carbon sequestration will have major challenges which deserve to be addressed in an effective manner.

Keywords
Agroforestry · Carbon sequestration · Management practices · Tropical region

19.1 Introduction

Climate change is the single biggest environmental and humanitarian crisis of our time. The earth's atmosphere is overloaded with heat-trapping greenhouse gases (GHGs), namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are threatening large-scale disruptions in climate with disastrous consequences. Change in climate is changing our economy, health, and communities in diverse ways. The global mean annual temperature at the end of the twentieth century, due to GHG accumulation in the atmosphere, has increased by 0.4–0.76 °C above that recorded at the end of the nineteenth century (IPCC 2007); however, presently it is increasing at the rate of 1.5 °C. Agriculture, change in land use, and forestry account for 25–30% of global anthropogenic GHG emissions to the atmosphere (IPCC 2007). The agricultural sector alone is responsible for about 10–12% of total non-CO_2 anthropogenic GHG emissions (FAOSTAT 2013). Global climate change and warming of the atmosphere may lead to greater variability in rainfall, rise in sea level, increased incidence of extreme weather events such as floods and droughts, heavy and intense storms, and decrease in crop yields in some of the tropical regions, threatening the livelihoods of communities living in the climatically vulnerable regions of the world. These changes are already being experienced by India and other parts of the world. The frequent droughts, flooding, and other weather vagaries in many parts of the country are affecting the livelihood of millions of people in general and small and marginal farmers in particular.

Carbon dioxide (CO_2) is the most important GHG. Although at the molecular scale carbon dioxide is not the strongest greenhouse gas, it is emitted in the greatest amounts from anthropogenic activities. Annual emissions of CO_2 have grown by about 80% between 1970 and 2004, from 21 to 38 Gt, and represented 77% of total anthropogenic GHG emissions. Since the industrial revolution, atmospheric CO_2 is increasing at greater pace from decade to decade. For the past 10 years, the average annual rate of increase is 2.07 ppm. This rate of increase is more than double the rate in 1960s (CO_2 now.org). The GHGs emissions should be reduced by 50–80% by 2050 to avoid the adverse consequences of global warming. There are three strategies of lowering CO_2 concentration from the atmosphere: (i) reducing the global energy use, (ii) developing low- or no-carbon fuel, and (iii) sequestering CO_2 from point sources or from the atmosphere through natural (vegetation/soils) and engineering techniques (Schrag 2007). There is a growing interest in the role of various types of land-use systems in stabilizing the atmospheric CO_2 concentration and reducing the CO_2 emissions or on increasing the carbon sink. India has made a number of efforts to address climate change. The government has launched the National Action Plan on Climate Change (NAPCC) in June 2008 to achieve its goals and deal with the issues related to climate change. In order to assess the impact of climate change/variability on agriculture, the Government of India through the Indian Council of Agricultural Research (ICAR) launched a flagship network project "National Initiative on Climate Resilient Agriculture" (NICRA), which is now referred as "National Innovations in Climate Resilient Agriculture" (NICRA). Many programmes and schemes have been initiated by the government and its scientific organizations to offset carbon emission. The Green India Mission is one of them with a target to achieve 33% tree cover of the total geographical area through agroforestry and social forestry as envisaged in National Forest Policy. The idea of reducing CO_2 from the atmosphere through forest conservation and management was discussed as early as in 1970s. But it was in 1990s that international action was initiated in this direction. In 1992, several countries agreed to the United Nations Framework Convention on Climate Change (UNFCCC), with the major objectives of developing national inventories of greenhouse gas emissions and sinks and reducing the emission of greenhouse gases (FAO 2001). Since the Clean Development Mechanism (CDM) under the Kyoto Protocol allows industrialized countries with a GHG reduction commitment to invest in mitigation projects in developing and least developed countries, there is an attractive opportunity for small and marginal farmers in these countries, who are the major practitioners of agroforestry, to benefit economically from their agroforestry practices (Nair et al. 2009); however, the mechanism is yet to be established for the economic benefits of farmers.

In the present-day context, agroforestry's contribution to climate change adaptation and mitigation through carbon sequestration is of relevance as countries develop mechanisms for Reducing Emissions from Deforestation and forest Degradation (REDD+). A large portion of country's population is still not secure for food, nutrition, fodder, and need of fuelwood, and agroforestry is well known to immensely contribute to address these challenges. In addition, agroforestry is a well-established remedy against extreme weather conditions resulting in failure of crops leading to a total loss of farmers' income. Being resistant to climate variations (drought, flood, heat and cold stress, etc.), trees ensure availability of nutritive food, fodder, and fuel when food crops are partially or fully destroyed. Climate change vulnerability map exhibits extreme to high vulnerability for the majority areas of South Asian countries. Agroforestry has an important role in reducing vulnerability, increasing resilience of farming systems, and buffering households against climate-related risks. Agroforestry is an integrated response to the threat of climate change as it supports both mitigation and adaptation ("mitigadaptation" – Van Noordwijk et al. 2011). Agroforestry generates adaptation benefits through its impact on reducing soil and water erosion, improving water management, and reducing crop output variability. Planting trees and shrubs also increases carbon sequestered both above and below the ground, thereby contributing to GHG mitigation (Verchot et al. 2007). As a mitigadaptation strategy, agroforestry offers additionally over the other options of mitigation, which comes from its conservation value and services to the environment

(Newaj and Dhyani 2008). Agroforestry systems (AFS) provide environmental services in addition to the economic gains and other contributions (Dhyani 2012). Globally, more than 70 countries have identified agroforestry as one of the important tools to adapt to or mitigate climate change (Richards et al. 2016). In India, evidence is now emerging that agroforestry systems are promising land-use system to increase and conserve aboveground and soil carbon stocks to mitigate climate change. There are ample evidences to show that the overall (biomass) productivity, soil fertility improvement, soil conservation, nutrient cycling, microclimate improvement, and carbon sequestration potential of an agroforestry system are generally greater than that of an annual system (Dhyani et al. 2009). Thus, the role of agroforestry as a carbon sequestration strategy has raised considerable expectations.

19.2 Agroforestry and Carbon Sequestration

The long-term C cycle that describes the biogeochemical cycling of C among surface systems consisting of oceans, the atmosphere, biosphere, and soil controls the atmospheric CO_2 concentration over geological timescales of more than 100,000 years (Berner 2003). The short-term C cycle over decades and centuries is of greater importance than the long-term cycle in forest, agroforestry systems (AFS), and agricultural ecosystems (Nair et al. 2010). The important processes of this cycle are the fixation of atmospheric CO_2 in plants through photosynthesis and return of part of that C to the atmosphere through plant, animal, and microbial respiration as CO_2 under aerobic and CH_4 under anaerobic conditions (Fig. 19.1). The other responsible factors for CO_2 emission are vegetation fire, burning of fossils and fuels, burning and land cleaning for cultivation, etc., but much of this emitted carbon is recaptured in subsequent regrowth of the vegetation (Lorenz and Lal 2010; Nair et al. 2010).

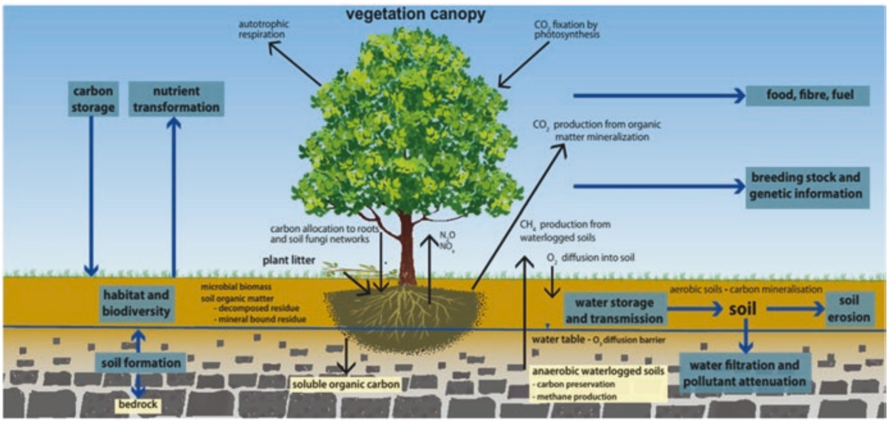

Fig. 19.1 Soil–plant–carbon interrelationships and associated ecosystem services (Victoria et al. 2012)

19.3 Carbon Sequestration Potential of Agroforestry Systems

Today, AFS has become a well-established approach to integrated land management, not only for renewable resource production but also for ecological and environmental considerations. It provides a win–win opportunity to combine the twin objectives of climate change adaptation and mitigation. Although AFS is not primarily designed for carbon sequestration, there are many recent studies that substantiate the evidence that agroforestry systems can play a major role in storing carbon in aboveground biomass (Murthy et al. 2013) and in soil and in belowground biomass (Nair et al. 2009). Agroforestry represents the combination of crops with trees which play an important role in C sequestration (Takimoto et al. 2009); with an increase in the number of trees (high tree density) in a system, the overall biomass production per unit area of land will be higher, which in turn may promote more C storage in aboveground and belowground biomass.

A significant fraction of the atmospheric C could be captured and stored in plant biomass and in soils with adoption of agroforestry systems. However, increasing C stocks in a given period of time is just one step; the fate of those stocks is what ultimately determines sequestration. In AFS, C sequestration is a dynamic process and can be divided into phases for the sake of understanding. At establishment, many systems are likely to be sources of GHGs (loss of C and N from vegetation and soil). Then follow a quick accumulation phase and a maturation period when tons of C are stored in the boles, stems, roots of trees, and in the soil (Saha and Jha 2012). At the end of the rotation period, when the trees are harvested and the land returned to cropping (sequential systems), part of the C gets released back to the atmosphere (Dixon 1995). Therefore, effective sequestration can only be considered if there is a positive net C balance from an initial stock after a few decades. In fact, many recent research findings reported that sequestration of atmospheric carbon was higher by agroforestry systems than treeless agriculture or pasture land-use systems under similar ecological conditions (Haile et al. 2008; Nair et al. 2009; Ajit et al. 2013).

The carbon sequestration potential of agroforestry systems has been successfully established theoretically; however field measurements to validate these concepts are limited. The inherent variability in the estimates of potential carbon storage in agroforestry systems and the lack of uniform methodologies has made comparisons difficult (Jose 2009). The fact that agroforestry systems can function as both source and sink of carbon has been presented in many literatures (Dixon 1995; Montagnini and Nair 2004). There is also clear evidence to suggest that the type of agroforestry system influences greatly the source or sink role of trees. According to the IPCC (2007), agroforestry systems offer important opportunities of creating synergies between both adaptation and mitigation actions with a technical mitigation potential of 1.1–2.2 Pg C in terrestrial ecosystems over the next 50 years. According to Murthy et al. (2013), the potential of AFS to accumulate C is estimated to be 12–228 Mg ha^{-1}, with an average of 95 Mg ha^{-1} (Table 19.1). However, the amount of C in any AFS depends on the structure and function of the different component

Table 19.1 Carbon storage potential[a] of agroforestry systems in different ecoregions of the world (Murthy et al. 2013)

Continent	Ecoregion	System	Carbon storage potential (Mg C ha^{-1})
Africa	Humid tropical high	Agrosilvicultural	29–53
South America	Humid tropical low dry lowlands	Agrosilvicultural	39–102, 39–195
Southeast Asia	Humid tropical dry lowlands	Agrosilvicultural	12–228, 68–81
Australia	Humid tropical low	Silvipastoral	28–51
North America	Humid tropical high humid tropical low dry lowlands	Silvipastoral	133–154
			104–198
			90–175
Northern Asia	Humid tropical low	Silvipastoral	15–18

[a]Carbon storage values were standardized to a 50-year rotation

within the systems and across species and geography (Albrecht and Kandji 2003; Newaj and Dhyani 2008). Besides the potential of AFS to accumulate and sequester carbon, these systems could evolve into a technological alternative for reducing deforestation rates in tropical and subtropical zones while also offering a wide variety of products and services to rural communities (de Jong et al. 1995). Furthermore, the effectiveness of agroforestry systems in sequestering carbon depends on both environmental and socio-economic factors of a particular area (Mutuo et al. 2005).

Carbon sequestration (CS) in terrestrial pools includes the aboveground plant biomass, such as timber and fuelwood, and belowground biomass, such as roots, soil microorganisms, and the relatively stable forms of organic and inorganic C in soils and deeper subsurface environments. The Soil Science Society of America (SSSA) recognizes that C is sequestered in two ways in soils: direct and indirect (SSSA 2001). Direct soil CS occurs by inorganic chemical reactions that convert CO_2 into soil inorganic C compounds such as calcium and magnesium carbonates. Indirect CS occurs by the process of photosynthesis which captures CO_2 from the atmosphere and stores as plant biomass. Some of this plant biomass is then deposited as soil organic carbon (SOC) during decomposition processes. The amount of soil C sequestered at a site reflects the long-term balance between C uptake and release mechanisms (Nair et al. 2010). It is clear from the above that carbon sequestration occurs in two major segments of the agroforestry system: aboveground and belowground. Each can be partitioned into various subsegments: the former into specific plant parts (stem, leaves, etc., of trees and crop components) and the later into living biomass such as roots and other belowground plant parts, soil organisms, and C stored in various soil horizons. The total amount sequestered in each part differs greatly depending on a number of factors, including the region, the type of system (and the nature of components and age of perennials such as trees), site quality, and previous land use. On average, the soil and aboveground parts are estimated to hold major portions, roughly 60% and 30%, respectively, of the total C stored in tree-based land-use systems (Lal 2005, 2008).

19.3.1 Aboveground Carbon Sequestration

According to Nair et al. (2010), aboveground C storage is the incorporation of C into plant parts either in the harvested product or in the in situ remaining living parts. The aboveground biomass (AGB) that is not removed from the site is eventually reincorporated into the soil as plant residues and organic matter. A summary of mean vegetation (above- and belowground) CS rates in some major AFSs around the world (Table 19.2) presented by Nair et al. (2009) shows that the estimates of

Table 19.2 Mean vegetation (above- and belowground) carbon sequestration potential[a] of prominent agroforestry systems[d]

Agroforestry/land-use system[b]	Age[c] (year)	Mean vegetation C ($Mg\ ha^{-1}\ year^{-1}$)	Source
Fodder bank, Ségou, Mali, W African Sahel	7.5	0.29	Takimoto et al. (2008b)
Live fence, Ségou, Mali, W African Sahel	8	0.59	Takimoto et al. (2008b)
Tree-based intercropping, Canada	13	0.83	Peichl et al. (2006)
Parklands, Ségou, Mali, W African Sahel	35	1.09	Takimoto et al. (2008b)
Agrisilviculture, Chhattisgarh, India	5	3.23	Swamy and Puri (2005)
Silvopasture, W Oregon, USA	11	1.11	Sharrow and Ismail (2004)
Silvopastoralism, Kurukshetra, India	6	1.37	Kaur et al. (2002)
Silvopastoralism, Kerala, India	5	6.55	Kumar et al. (1998)
Cacao agroforests, Mekoe, Cameroon	26	5.85	Duguma et al. (2001)
Cacao agroforests, Turrialba, Costa Rica	10	11.08	Beer et al. (1990)
Shaded coffee, SW Togo	13	6.31	Dossa et al. (2008)
Agroforestry woodlots, Puerto Rico	4	12.04	Parrotta (1999)
Agroforestry woodlots, Kerala, India	8.8	6.53	Kumar et al. (1998)
Home and outfield gardens	23.2	4.29	Kirby and Potvin (2007)
Indonesian home gardens, Sumatra	13.4	8.00	Roshetko et al. (2002)
Mixed species stands, Puerto Rico	41	5.21	Parrotta (1999)
Block plantation, Karnataka, India	7–10	3.71	Ajit et al. (2014)

[a]Though reported as carbon sequestration potential, the values are based on C-stock estimates
[b]Values for similar systems (in terms of location and age) were pooled wherever possible regardless of species
[c]"Age" of the system, though not clearly defined, is assumed to be the number of years since the establishment of the tree component in the system
[d]These systems were selected from many reports of this nature to provide a broad spectrum of agroforestry systems (live fences to multistrata systems) in different geographical regions
Modified Nair et al. (2009)

CSP in AFSs are highly variable, ranging from 0.29 to 15.21 Mg C ha^{-1} $year^{-1}$. The range of CS shows direct manifestation of the ecological production potential of the system, depending on a number of factors, including site characteristics, land-use types, species involved, stand age, and management practices. Agroforestry systems on humid and tropical sites have higher potential to carbon sequestration than the arid, semiarid, and temperate sites. Considering that aboveground CS estimates are direct expressions of AGB production, the basic mechanism of the two functions (CS and AGB production) is the same: uptake of atmospheric CO_2 during photosynthesis and transfer of fixed C into vegetation (sequestration involves the additional step of "secure storage" of such fixed C).

Many studies are available in published literature on carbon sequestration potential of various trees species in AFS (Newaj et al. 2014; Table 19.3) in India. In such studies most common tree density was in the range of 312 to 800 trees per hectare (usually preferred by the farmers in planted AFS), and the reported CSP varied from

Table 19.3 Carbon sequestration potential (CSP) of trees in India (Newaj et al. 2014)

Location	Agroforestry system	Tree species	No. of tree per hectare	Age (year)	CSP (Mg C ha^{-1} $year^{-1}$)	References
Himachal Pradesh	Agrihorticulture	Fruit trees	69	–	12.15	Goswami et al. (2013)
Khammam, Andhra Pradesh	Agrisilviculture	*L. leucocephala*	4444	4	14.42	Prasad et al. (2012)
			10,000	4	15.51	
SBS Nagar, Punjab	Agrisilviculture	*P. deltoids*	740	7	9.40	Chauhan et al. (2010)
Dehradun, Uttarakhand	Silviculture	*E. tereticornis*	2500	3.5	4.40	Dhyani et al. (1996)
			2777*	2.5	5.90	
Kurukshetra, Haryana	Silvipasture	*A. nilotica*	1250	7	2.81	Kaur et al. (2002)
		D. sissoo	1250	7	5.37	
		P. juliflora	1250	7	6.50	
Chandigarh	Agrisilviculture	*L. leucocephala*	10,666	6	10.48	Mittal and Singh (1989)
Tripura	Silviculture	*T. grandis*	444	20	3.32	Negi et al. (1990)
		G. arborea	452	20	3.95	
Tarai region Uttarakhand	Silviculture	*T. grandis*	570	10	3.74	Negi et al. (1995)
			500	20	2.25	
			494	30	2.87	
Jhansi, Uttar Pradesh	Agrisilviculture	*A. procera*	312	7	3.70	Newaj and Dhyani (2008)

(continued)

Table 19.3 (continued)

Location	Agroforestry system	Tree species	No. of tree per hectare	Age (year)	CSP (Mg C ha^{-1} $year^{-1}$)	References
Jhansi, Uttar Pradesh	Agrisilviculture	*A. pendula*	1666	5.3	0.43	Rai et al. (2002)
Jhansi, Uttar Pradesh	Silviculture	*A. procera*	312	10	1.79	Rai et al. (2000)
		A. amara	312	10	1.00	
		A. pendula	312	10	0.95	
		D. sissoo	312	10	2.55	
		D. cinerea	312	10	1.05	
		E. officinalis	312	10	1.55	
		H. binata	312	10	0.58	
		M. azaderach	312	10	0.49	
Hyderabad, Andhra Pradesh	Silviculture	*L. leucocephala*	2500	9	10.32	Rao et al. (2000)
		E. camaldulensis	2500	9	8.01	
		D. sissoo	2500	9	11.47	
		A. lebbeck	625	9	0.62	
		A. albida	1111	9	0.82	
		A. tortilis	1111	9	0.39	
		A. auriculiformis	2500	9	8.64	
Hyderabad, Andhra Pradesh	Agrisilviculture	*L. leucocephala*	11,111	4	2.77	Rao et al. (1991)
			6666	4	1.90	
Raipur Chhattisgarh	Agrisilviculture	*G. arborea*	592	5	3.23	Swamy and Puri (2005)
Coimbatore Tamil Nadu	Agrisilviculture	*C. equisetifolia*	833	4	1.57	Viswanath et al. (2004)
Kerala	Home garden	Mixed tree spp.	667	71	1.60	Saha et al. (2009)

*Average of the 1111 and 4444 trees/ha

0.49 to 9.4 Mg C ha^{-1} $year^{-1}$, although for the complete picture of all the studied systems considered together (irrespective of tree densities), the CSP varied from 0.39 to 11.47 Mg C ha^{-1} $year^{-1}$ (age varied from 2.5 to 30 years). Studies conducted in different parts of the world reported carbon sequestration potential of different AFS in the range of 0.29 to 15.21 Mg C ha^{-1} $year^{-1}$ in above ground and 30 to 300 Mg C ha^{-1} up to 1 m of soil depth (Nair et al. 2010). Thus the existing trees on farmers' fields not only add some income to small and marginal farmers but also help in mitigating global warming by enhancing carbon sequestration potential of Indian agriculture (Ajit et al. 2013; Dhyani et al. 2016).

19.3.2 Belowground (Soils) Carbon Sequestration

It is a well-established fact that soils play a vital role in the global C cycle. The soil C pool comprises soil organic C (SOC) estimated at 1550 Pg and soil inorganic C approximately 750 Pg both to 1 m depth (Batjes 1996). This total 2300 Pg soil C pool is three times the atmospheric pool (770 Pg) and 3.8 times the vegetation pool (610 Pg); a reduction in soil C pool by 1 Pg is equivalent to an atmospheric enrichment of CO_2 by 0.47 ppmv (Lal 2001). Thus, every change in soil C pool would have a significant effect on the global C budget. The historical amount of CO_2–C emitted into the atmosphere from the terrestrial ecosystems is estimated to be approx. 136–55 Pg, of which soils account for approx. 78–12 Pg (Lal 2007). The literature on soil carbon sequestration (SCS) potential of AFS is scanty, although rather plentiful reports are available on the potential role of agricultural soils to sequester C. Review the available information on SCS in AFS worldwide, summarized by Nair et al. (2009) in Table 19.4.

Studies on carbon sequestration in soil revealed a general trend of increasing SCS in agroforestry compared to other land-use practices (with the exception of forests). Furthermore, it is noted that the estimated values of SCS in AFS varied greatly and were a reflection of several factors including biophysical and socio-economic characteristics of the system and sampling methods/procedures (Nair et al. 2010).

Belowground biomass of trees in the form of roots comprises about one-fifth to one-fourth of the total living biomass, and there is a constant addition of organic matter to the soil through decaying dead roots (Dhyani and Tripathi 2000), which leads to increases in the C status of the soil. Accumulation of 2.91% organic C was observed under areca nut + jackfruit + black pepper + cinnamon (tejpatra) followed by 1.85% under areca nut + betelvine + miscellaneous trees as against 0.78% only in a degraded land in the same period. MPTS like *Alnus nepalensis*, *Parkia roxburghii*, *Michelia oblonga*, *Pinus kesiya*, and *Gmelina arborea* with greater surface cover, constant leaf litter fall, and extensive root systems increased soil organic carbon by 96.2%, enhanced aggregate stability by 24.0%, improved available soil moisture by 33.2%, and in turn reduced soil erosion by 39.5%. Soils under *Acacia auriculiformis*, *Leucaena leucocephala*, and *Gmelina arborea* always have high humification rate, while soils under the canopy of *Acacia auriculiformis*, *Michelia champaca*, *Tectona grandis*, and *Dalbergia sissoo* show low humification of the organic matter. Such improvements in soil quality under tree-based AFS have a direct bearing on long-term sustainability and productivity of soil (Subba Rao and Saha 2014).

19.3.3 Agroforestry: Role in CO_2 Sequestration – Some Research Initiatives

The Central Agroforestry Research Institute (CAFRI), Jhansi, has been working on CS potential of various agroforestry systems since 2000 through in-house and

Table 19.4 Soil organic carbon (SOC) stock reported in various agroforestry systems[a] (Nair et al. 2010)

Agroforestry system/species	Location	Age (year)	Soil depth (cm)	Soil C (Mg ha^{-1})	References
Mixed stands, *Eucalyptus* + *Casuarina* (C), C + *Leucaena* (L), *Eucalyptus* + L	Puerto Rico	4	0–40	61.9, 56.6, and 61.7	Parrotta (1999)
Agroforest (*Pseudotsuga menziesii* + *Trifolium subterraneum* L.	Western Oregon, USA	11	0–45	95.89	Sharrow and Ismail (2004)
Agrisilviculture (*Gmelina arborea* Roxb. + eight field crops)	Chhattisgarh, Central India	5	0–60	27.4	Swamy and Puri (2005)
Tree-based intercropping: hybrid poplar + barley	Ontario, Canada	13	0–20	78.5	Peichl et al. (2006)
Silvopastoral system: *Acacia mangium* Willd. + *Arachis pintoi* Krapov. & W. C. Gregg	Pocora, Atlantic coast, Costa Rica	10–16	0–100	173	Amezquita et al. (2005)
Alley cropping *Leucaena* – 4-m wide rows	Western Nigeria	5	0–10	13.6	Lal (2005)
Alley cropping: hybrid poplar + wheat, soybeans, and maize rotation	Southern Canada	13	0–40	125	Oelbermann et al. (2004)
Alley cropping system: *Erythrina poeppigiana* (Walp.) O. F. Cook + maize and bean (*Phaseolus vulgaris* L.)	Costa Rica	19	0–40	162	Oelbermann et al. (2004)
Gliricidia sepium + maize	Zomba, Malawi	10	0–200	123	Makumba et al. (2007)
Agroforest (home and outfield gardens)	Ipetı´-Embera, Panama		0–40	45.0	Kirby and Potvin (2007)
Shaded coffee, *Coffea robusta L. Linden* + *Albizia* spp.	South western Togo	13	0–40	97.27	Dossa et al. (2008)
Silvopasture: slash pine (*Pinus elliottii* Engelm.) + bahiagrass (*Paspalum notatum* Flügge)	Florida, USA	8–40	0–125	6.9–24.2	Haile et al. (2008)
Faidherbia albida (Delile) A. Chev. parkland	Ségou, Mali	35	0–100	33.3	Takimoto et al. (2008a)
Live fence (*Acacia nilotica* (L.)	Ségou, Mali	8	0–100	24	Takimoto et al. (2008a)
Willd., *Acacia senegal* (L.)					
Willd., *Bauhinia rufescens* L., *Lawsonia inermis* L., and *Ziziphus mauritiana* Lam.)					

(continued)

Table 19.4 (continued)

Agroforestry system/species	Location	Age (year)	Soil depth (cm)	Soil C (Mg ha^{-1})	References
Fodder bank Sahel (*Gliricidia sepium* (Jacq.) Kunth ex Walp., *Pterocarpus lucens* Willd. and *P. erinaceus* Poir.)	Ségou, Mali	6–9	0–100	33.4	Takimoto et al. (2008a)
Home gardens	Kerala, India	35	0–100	101–126	Saha et al. (2009)
Dehesa system	Central Spain	30	0–100	27–50	Howlett (2009)
Shaded cacao systems	Bahia, Brazil	30	0–100	302	Gama-Rodrigues et al. (2010)

Values for similar systems (in terms of location and age) were pooled wherever possible regardless of species

externally aided projects. The research conducted under the projects estimated carbon sequestered and CO_2 equivalent carbon sequestered in *Albizia procera*, *Dalbergia sissoo*, *Hardwickia binata*, and *Emblica officinalis*–based agroforestry systems for their rotation period (30, 50, 45, and 25 years, respectively) using CO_2FIX model. In northwestern India using GIS and RS, the spectral signatures for poplar and *Eucalyptus* were generated and the area under these two agroforestry systems was estimated. The work on mitigating potential of agroforestry system on climate change was carried out to estimate the carbon sequestration potential of agroforestry practices in Bundelkhand region. Under NICRA project, carbon sequestration potential of existing agroforestry systems in farmer's field has been estimated so far for 51 districts in 16 states (Uttar Pradesh, Gujarat, Bihar, West Bengal, Rajasthan, Punjab, Haryana, Himachal Pradesh, Maharashtra, Tamil Nadu, Andhra Pradesh, Karnataka, Madhya Pradesh, Chhattisgarh, Orissa, and Telangana). The achievement made so far indicated the number of trees on farmer's field is 18.42 trees per hectare in these states. The net carbon sequestered in agroforestry system existing on farmer's field under different states is 11.35 Mg C ha^{-1} from baseline over a simulated period of 30 years. The carbon sequestration potential (CSP) of agroforestry system is 0.35 Mg C ha^{-1} year^{-1}and the total CSP is 7.230 million tons of C in these states (Newaj et al. 2017). Thus, the existing agroforestry systems on farmers' fields are estimated to mitigate more than 33% of the total GHG emissions from agriculture sector annually at the country level (Ajit et al. 2016). On the basis of research conducted so far, agroforestry practices applicable to different suitable sites for sequestering atmospheric carbon in wood biomass as well as soils can be selected as stated below.

19.4 Enhancing Carbon Sequestration Through Agroforestry

19.4.1 Stabilization of Carbon in Soil

Stabilization of carbon is as much essential as fixing it. Developing strategies to sequester organic carbon (C) in soils depend on understanding the key factors that affect soil organic carbon (SOC) stabilization and the capacity of individual soils to stabilize additional SOC. The sequestration of stable SOC has been attributed to several possible mechanisms including biochemical recalcitrance, physical protection or inaccessibility, and the formation of organo-mineral complexes involving fine (clay–silt) soil particles (Baldock and Skjemstad 2000; von Lutzow et al. 2006; Dungait et al. 2012; Beare et al. 2014). The SOC associated with fine soil particles is generally regarded has highly stable, with a relatively long turnover time and slow response to changes in management (Beare et al. 2014). It also represents a large proportion of the total SOC in most soils and therefore serves as a useful measure of the stable organic C. A number of studies have shown that total SOC content is strongly and positively correlated with the amount of fine mineral particles in soils. This relationship is generally attributed to the role that the fine fraction plays in providing mineral surface for the formation of organo-mineral complexes. Besides fine fractions, many land-use practices such as no till, manure and compost additions, and enhanced residue return are used to increase soil organic carbon (SOC) content (Feng et al. 2013). Major sources of SOC are C inputs from plant roots (e.g. lignin, suberin, and rhizodeposition), mycorrhizal fungi, and illuviation through bioturbation and leaching (Nguyen 2003; Wallander et al. 2004; Rasse et al. 2005).

19.4.2 Increasing Carbon and Reducing Its Losses from Soil

There are wide management options and farming practices available that can increase SOC levels by either increasing inputs or decreasing losses, for example, stubble retention (Table 19.5). Inputs can also be increased by direct additions of organic materials, namely, composts, manures, and other recycled organic materials.

Table 19.5 Management practices that increase soil organic carbon (Chan 2008)

Management category	Management practices to increase soil carbon
Crop management	Soil fertility enhancement, better rotation, erosion control, irrigation
Conservation tillage	Stubble retention, reduced tillage, no tillage
Pasture management	Fertilizer management, grazing management, earthworm introduction, irrigation, improved grass species, introduction of legumes, sown pasture, introduction of perennial pastures
Organic amendments	Animal manure, green manure, recycled organics, vermicompost

Theoretically, any management practice that can increase production from an area of land should lead to increase in SOC storage because of the increase in carbon inputs. Farmers are familiar with practices such as fertilizer application, improved rotations, improved cultivars, and irrigation which can lead to large yield increases. Productivity increases can also be achieved by crop intensification practices such as double cropping, opportunity cropping, and multiple cropping. However, it should be noted that some of these yield-increasing practices involve the use of fertilizers and irrigation water which require large energy consumption and therefore increase carbon dioxide emission (Chan 2008).

Conservation farming is gaining worldwide acceptance rapidly as a farming practice to improve soil and water conservation. In cropping, cultivation is either reduced (reduced tillage) or completely eliminated (no tillage), and stubble (crop residue) is retained in the field. Reduced tillage reduces carbon losses (from both reduced cultivation and reduced fossil fuel usage) and stubble retention increases carbon inputs to the soil; both of these lead to SOC increases.

19.5 Limitations for Carbon Sequestration

It has been long believed that when trees or shrubs replace pastures or grasslands, there is an automatic increase of C stocks. Today, it is becoming increasingly clear that this does not happen all the time. For example, in a study conducted by Jackson et al. (2002) in the United States, it was shown that the invasion of grasslands by shrubs increased C in vegetation although to a much lower extent than expected. On the other hand, soil C had increased only on the drier sites and actually decreased in the wetter sites. As a result, the net C balance was marginally positive for the dry sites but negative for the wetter sites. Such findings suggest that the current land-based methods of C assessment may have led to an overestimation of C sinks in many areas of the globe (Jackson et al. 2002; Goodale and Davidson 2002). These inaccuracies will be compounded further if we consider that changes in C fluxes are likely to occur in the next 50 years as a result of shift in global climate, land use, and land cover. The magnitude and direction these changes will take remain largely unknown (Wang and Hsieh 2002). Similarly, degraded soils and wastelands occupy a large proportion of the earth's area, and there is a general belief that converting them into agroforestry would be a major global opportunity to absorb a significant portion of the atmospheric CO_2 (Dixon 1995). However, cultivating trees or crops in substandard soils still remains a challenge to growers and agriculturists. On problematic soils (saline, alkali, and acid soils) or in arid and semiarid areas, trees usually perform poorly, making such environments less suitable for agroforestry. Consequently, if biomass production is not adequate, significant positive changes in soil carbon are unlikely to occur in agroforestry systems. There have been many reports indicating unchanged, or even declining, SOM levels after high intensification (HI) on substandard soils and in dry environments (Akyeampong 1999). Moreover, in dry environments, the tree-crop competition for water usually results in low crop yields, which makes HI unattractive for dry land farmers. As shown in this review and many other studies, improved fallow is a promising technology for increasing C stocks in degraded soils. But a major problem with implementing sequential agroforestry systems in general is that farmers have to forego growing crops during the fallow phase, which can stretch on one or more cropping seasons. Pests and diseases are other key issues that deserve to be addressed more adequately if farmers want high biomass production in tropics.

19.6 Conclusion

Rising level of greenhouse gases particularly CO_2 in the atmosphere is a matter of great concern among the environmentalists and policymakers throughout the world. Among the various available options for mitigadaptation of global warming, agroforestry has emerged as a good option and is getting attraction for its high carbon sequestration potential (above- and belowground) along with ease of adaptability, profitability, and sustainability for its practitioners. The target of carbon sequestration through agroforestry can only be achieved through selection, identification, and promotion of suitable agroforestry systems, developing tree species through breeding/biotechnological tools for high carbon sequestration potential, ease of rules and laws through agroforestry policy, and by providing incentives, credit facility, and insurance cover for the agroforestry practitioners.

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Carbon Sequestration Potential of Perennial Horticultural Crops in Indian Tropics

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Abstract

Large numbers of horticultural crops are grown in India due to its wide variety of soil and climatic conditions. However, perennial horticultural crops have edge over annuals as they generally need low inputs such as water, energy, etc., and have high productivity values. India has large tracts of waste and marginal lands (96 million hectares of cultivable wasteland). These lands can be brought under perennial horticultural crops for successful and profitable commercial horticulture. Moreover, putting these marginal lands to perennial horticultural crops can enhance carbon sequestration and improve organic carbon content and health of the soils. This also rejuvenates degraded soils, improves the land productivity, enriches the diversity, and protects the environment. Horticultural crops have a great scope for sequestering more carbon in terrestrial ecosystem than agricultural or agroforestry systems. Studies reported that the carbon dioxide sequestration was significantly greater under the perennial crops as compared to annual crops. The carbon sequestration potential of different horticultural cropping systems ranked in the order of mango > cashew > rose > vegetable > medicinal and aromatic plants, and addition of more residues in perennial systems to soil records less emission of CO_2 than annual crops. As a consequence, perennial horticulture-based systems provide economic gain through carbon credits. Enhancement of carbon sequestration in perennial systems can be attained by improving soil health and through better carbon management strategies. These include planting high-biomass-producing crops, recycling crop residue, application of manures, switching from annual to perennial crops, adopting crop rotation in place of monoculture, and promotion of agroforestry systems. This chapter mainly describes the role of perennial horticultural systems in enhancing soil carbon, soil organic matter dynamics, carbon fractions, and its assessment in

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horticultural systems, carbon sequestration potential of perennial horticultural crops, and also the management options available for improving C sequestration under such system.

Keywords
Carbon sequestration · Horticultural crops · Indian tropics · Management options

20.1 Introduction

Horticulture is undergoing a boom in the country in recent years because of higher production of horticultural crops that are surpassing food grain yields and also due to increase in the consumption of fruits and vegetables due to changes in food habits. The current horticultural production is more than 300 million metric tonnes (MMTs) against food grain production of 275 MMTs. The per capita consumption of fruits and vegetables has also increased over a period because of the incremental production. Further area under perennial horticultural crops is 12.1 mha; (6.10 mha fruits, 3.22 mha plantation crops, 2.63 mha spices, and 0.14 mha nuts) with annual production of 214 mt. Though these crops occupy hardly 7% area, they contribute over 18% to the gross agricultural output in the country. Due to high remuneration/outcome from horticultural crops than the food grain crops, the attention of growers is changing now towards perennial horticultural crops. India is endowed with wide variety of soil and climatic conditions that can be suitable for growing varieties of horticultural and agricultural crops. However, horticultural crops particularly perennial crops have edge over field crops in the sense they generally need low inputs such as water, energy, etc. and have high productivity values as well.

India has large tracts of waste and marginal lands (96 mha of cultivable wasteland).The need for great utilization of available wastelands against the background of dwindling water and energy resources has focused attention to dry land, to arid and semiarid tracts, and to horticultural crops which have lesser demands for water and other inputs besides being three–four times more remunerative than field crops. Therefore, these lands can be brought under perennial horticultural crops for successful and profitable commercial horticulture. This can also help in attaining nutrition security and bringing positive change in the outlook of the growers through more profitable land use. Moreover, putting these marginal lands to perennial horticultural crops can improve organic carbon content and health of the soils. Earlier studies reported that the carbon dioxide sequestration was significantly greater under the perennial crops as compared to annual crops. It was also observed that perennial horticulture crops increase the soil organic carbon (SOC) and carbon dioxide storage than annual crops and reduce the carbon emissions to the atmosphere which helps to mitigate the global warming. Therefore, growing of perennial horticulture crops is one of the strategies to improve soil conditions which would help to sequester more organic carbon and carbon dioxide in soil as compared to annual crops.

20.2 Role of Tropical Horticultural Crops in Enhancing Soil Carbon

The quantity and quality of C inputs to soil under different tropical horticultural land-use systems may vary due to the differences in growth pattern, phenology, leaf size, number of new flushes, and decomposition rates of litters among the fruit trees. For instances, waxy surface of litchi leaves can result in long decomposition time than mango, guava, and jamun leaves. Under guava land use, there is bark fall as well as fruiting that takes place twice. During rainy season, guava fruits are normally not marketed due to insect attack. These fruits also contribute a good amount of C in soil after decomposition. Studies conducted on soil organic carbon (SOC) pool up to 30 cm soil depth under different forest and horticultural land uses in Uttarakhand state of India indicated the highest amount under forest lands followed by grasslands and orchards (mango, guava, and litchi). It was also recorded that soils under apple orchard showed maximum SOC pool at 30 cm depth followed by mango, litchi, and guava.

Depth-wise changes in the content of organic carbon under perennial tropical horticultural land-use systems, such as guava, jamun, litchi, and mango on reclaimed sodic soils, have been reported (Datta et al. 2015). The quantity of dichromate oxidizable organic carbon (OOC) varied with land uses. The highest mean OOC was recorded in soil (surface) under guava (25.9 Mg C ha^{-1}) followed by jamun (25.1 Mg C ha^{-1}) = litchi (25.0 Mg C ha^{-1}) > mango (16.5 Mg C ha^{-1}), while the total organic carbon (TOC) stock in soil was guava (28.8 Mg C ha^{-1}) > jamun (27.3 Mg C ha^{-1}) > litchi (25.7 Mg C ha^{-1}) > mango (19.2 Mg C ha^{-1}). In all the land uses, carbon content in passive pool was recorded an increase with soil depth due to its more physical, chemical, and biochemical stabilization in lower depths. Among these systems, soils under guava plantation recorded the highest SOC storage (61.0 Mg C ha^{-1}) as well as maximum passive pool C (25.3 Mg C ha^{-1}) up to 60 cm soil depth. Within a land-use system, there was a significant reduction in soil organic carbon stock along depth. A sharp decrease in the content of this pool of SOC was observed in soils between 0–20 and 20–40 cm layer under all land-use systems. The highest decrease in magnitude of SOC was in jamun (74%) followed by litchi (62%) > guava (46%) > mango (44%) in 20–40 cm soil depth compared to 0–20 cm. In all the land uses, second and third soil layer contained considerable quantities of oxidizable as well as TOC, demonstrating the importance of subsoil horizons for carbon storage.

20.3 Perennial Horticultural System and Soil Organic Carbon Equilibrium

The soil systems attain a quasi-equilibrium stage after accumulation and loss of organic matter in soil over a period of time as per prevalent land-use system. Again the soil system acquires a new equilibrium level of SOC over a period of time after each change in land-use system depending on the vegetation cover and management practice. Thus SOC levels show toothlike cycles of accumulation and loss (Batjes

1996). The rate of storage will depend on a number of factors including plantation variety, and variation is caused by climate, geography, species, and stand age (Liao et al. 2010). A period of constant land-use management is required to reach a new quasi-equilibrium value (QEV) which is a characteristic representative of the new land use, vegetation cover, management practice, climate, and soil. In case of forest systems of tropics, SOC values tend to attain QEV in 500–1000 years (Jenny 1950) and in 30–50 years in agricultural systems after forest clearing (Johnson 1995). Naitam and Bhattacharyya (2004) reported that quasi-equilibrium values of 0.7 and 0.8% SOC were attained in swell–shrink soils under horticulture and forest system, respectively, over a period of 30 years and several centuries. Unlike natural ecosystems, in horticultural systems the equilibrium is disturbed by removal of trees when the fruit trees become uneconomical and followed by new planting. Therefore, under horticultural ecosystems, the steady state of soil organic carbon frequently gets disturbed and a new steady state is attained after a period of constant management.

20.4 Soil Organic Matter Dynamics in Horticultural Systems

Major factors that influence soil organic matter dynamics in any production system include (i) the quality of the substrates added, (ii) the role of the soil microorganisms, (iii) physical protection such as in aggregation, (iv) interaction with the soil matrix such as the silts and clays as well as Ca and sesquioxides, and (v) the chemical nature of the SOM itself. These factors are interactive. Long-term studies are needed to examine the influence of these factors.

20.4.1 Carbon Inputs

The quality of carbon inputs and the rates of organic matter applied in any production systems are majorly influenced by the climate factors (temperature and precipitation), vegetation type (a woody tree such as mango, litchi, or apple; soft tissue like banana or papaya), landscape (sloppy land, level land, etc.), soil type, and orchard management practices (conservation horticulture, intensive orchard management, etc.).

The amount and quality of SOM are dependent on the amount and type of plant inputs as well as their microbial turnover before stabilization. The fresh litters or fallen plant residues on the soil are steadily modified through physical fragmentation, mineralization, soil fauna, and microbial interactions and humus formation. Decomposition process and turnover rates are largely influenced by climatic factors, organic residue type and quality, chemical and physicochemical association of organic matter with the soil mineral components, and the location of the organic matter within the soil (Jastrow and Miller 1997).The mean annual mineralization is higher in humid tropics (about 4–5%) when compared to the temperate climate (only 2%). Moreover the rate of carbon mineralization is more rapid under the intensive cultivation management than the conservation tillage or zero tillage practices within the given region. The humid tropics climatic conditions are more favourable for higher biomass production; however, it is limited by nutrient supply in the soil. In carbon sequestration point of view, the changes in quality of SOM are more vital than the changes in the quantity of SOM.

Carbon allocation within a plant depends on the interaction between source organs (mainly shoots) and sink organs (roots and fruits). This is a very complex process that comes from both regulations and interactions between various plant processes involving carbon. Carbon partitioning in plants is controlled by a number of factors that include photosynthesis, the number and location of competing sinks, storage capacity, and vascular transport. The plant architecture also plays an important role in carbon partitioning and transport within the plant. Further research is needed on the root-shoot-fruit interactions, influence of many agricultural practices such as thinning, pruning, fertilization, and irrigation and their interactions. The transport of material and signals in the plant architecture with a special focus on interactions between compounds has to be studied.

20.5 Stability of Soil Carbon

Some good management practices such as promotion of native vegetation growth, cover cropping, regular addition of organic manures/composts, crop residue recycling and incorporation, inclusion of legumes/grasses as intercrop, and even mulching can improve soil organic carbon storage in perennial horticultural systems (Wang et al. 2010; Ganeshamurthy 2009). The SOC storage changes with land-use change and changes in different OC components of soils provide information in advance about this. Stability of organic carbon in soil depends on the source of plant litter, occlusion within aggregates, incorporation in organo-mineral complexes, and location within the soil profile. However, physical fractionation is widely adapted to study OC storage and turnover in soil (Six et al. 2002; Verchot et al. 2011). Physical protection of SOM is mainly dominated in the soil aggregates, which are the secondary organo-mineral complexes of soil. Thus, changes in soil aggregates may be used to characterize the impacts of management strategies on soil carbon storage (Christensen 2001), particularly carbon stored in macroaggregates which has a stronger response to land-use change (Denef et al. 2007). To some extent, the protection of macroaggregates is considered to be fundamental for sustaining high SOC storage and has been used in many ecological models (Six et al. 2002). The responses of different fractions of soil organic matter pool to management practices vary due to their composition and association with the mineral matrix (Gregorich et al. 2006). The composition of organic matter and its association with mineral matrix influence its accessibility to decomposers and the stability in the soil environment. The labile fraction is easily decomposable. Its relative amount and the degree to which it is protected determine its degradability (Wendling et al. 2010). The more stable and recalcitrant fraction of soil organic matter contains more processed degraded material, and it is associated with soil mineral to form organo-mineral complexes (Wiesenberg et al. 2010). The stable fraction is a major sink for C storage and contains little mineralizable C (Jagadamma and Lal 2010).

20.6 Soil Carbon Fractions and Carbon Sequestration in Perennial Horticultural Systems

With respect to carbon sequestration, it is most desirable to fix atmosphere carbon in those pools having long turnover time. In terms of the residence time, the soil organic pools are divided into several homogeneous compartments. Based on carbon dynamics under perennial systems, soil carbon can be grouped into four main groups (Eswaran et al. 1995):

- Labile C or active C
- Slowly oxidizable C
- Very slowly oxidizable C
- Recalcitrant or passive C

Active or Labile Pool Formation and quality of active pool in perennial systems is influenced by climate change and type of management practices adopted that result in plant residue inputs.

Slowly Oxidizable Pool This pool is mainly associated with soil macroaggregates and influenced by soil physical properties like mineralogy and aggregates and horticultural practices.

Very Slowly Oxidizable Pool This pool is mainly associated with the soil microaggregates wherein the main controlling factor is the water stability of the aggregates.

Recalcitrant or Passive Pool This pool is mainly controlled by the soil mineralogy. Horticultural practices have little effect on its formation. The residence time of different types of organic matter, their proportion in total organic matter, and residence time of these pools of soil organic carbon are presented below (Table 20.1).

20.7 Assessment of Carbon Stocks in Horticultural System

Carbon stocks in the horticultural system can be measured through destructive and non-destructive methods. But the later has more advantage over the former. Further the carbon storage in perennial tree-cropping systems is categorized into (i) carbon

Table 20.1 Estimated ranges in the amounts and turnover time of various types of organic matter stored in soils under horticultural systems (Jastrow and Miller 1997)

Type of soil organic matter	Proportion of total organic matter (%)	Turnover time (year)	Carbon pool
Microbial biomass	2–5	0.1–0.4	Labile
Litter	–	1–3	Rapid
Particulate organic matter	18–40	5–20	Moderate
Light fraction	10–30	1–15	Moderate
Inter microaggregate[a]	20–35	5–50	Moderate to slow
Intra microaggregate[b]			
Physically sequestered	20–40	50–1000	Passive
Chemically sequestered	20–40	1000–3000	Passive

[a]Within macroaggregates but external to microaggregates including particulate, light fraction, and microbial C; [b]within microaggregates including sequestered light fraction and microbially derived C

Table 20.2 Level of accuracy and ease of implementation from measuring different carbon pools in a perennial ecosystem (Hamburg 2000)

Pool	CV	Ease of implementation
Aboveground biomass	5%–10%	Simple
Belowground biomass	10%–20%	Simple, but requires high initial investment
Soil, organic layer	10%–20%	Moderate
Soil, mineral layer	Highly variable	Difficult
Necromass	40%	Difficult

in aboveground biomass, (ii) carbon in belowground biomass, (iii) carbon in dead biomass (necromass), and (iv) carbon in soil.

All the above-mentioned carbon pools are not likely to be acceptable as sources of sequestration in a carbon market, and not all pools need to be measured at the same level of precision or at the same frequency during the life of the orchards. In the initial inventory, the relevant carbon pools must be measured to establish the baseline, but in subsequent monitoring only selected pools need to be measured, depending on the type of project (Brown 2001). The level of precision to which each pool can be measured at reasonable cost was estimated by Hamburg (2000). The table below presents a summary of these estimates. The measurement of each pool is briefly explained below (Table 20.2).

20.7.1 Aboveground Living Biomass

There are standard and well-accepted methods available for measuring aboveground biomass carbon in forested areas. These methods can be used in horticultural crops. The simplest procedure consists of measuring a sample of trees and using allometric equations to estimate biomass. Allometric equations relate tree biomass (*B*) to quantities (*Vi*) that can be measured by non-destructive means. Allometric equations have the general form:

$$B = f\left(V1, V2, \ldots, Vn\right) \quad (1)$$

The independent variables (*Vi*) may include diameter at breast height (*D*), height (*H*), and wood density (ρ). Experience with generic equations has shown that *D* explains more than 95% of the variation in tree biomass (Brown 2001). Brown (1997) has published allometric equations for tropical environments and presents wood density values for a large number of species. The assumption that 50% of aboveground living biomass is considered as C is well accepted (Hamburg 2000; Brown 2001), so it is straightforward to convert measured biomass to carbon units. Allometric methods are very robust among species and genera and can predict biomass of closed canopy forest to within ±10% uncertainty. In some special cases, it may be necessary to use destructive techniques to estimate allometric equations for a project (the techniques used to undertake these measurements are explained by Brown (1997)), but in general, parameter values available in the literature can provide acceptable levels of precision. Hence the main expense would be field measurement of trees.

20.7.2 Belowground Living Biomass

Belowground living biomass is an important pool among all and consists mostly of roots. This particular pool represents up to 40% of total biomass (Cairns et al. 1997). Direct estimation of belowground living biomass through destructive techniques is very expensive (Brown 2001). This pool can be estimated with some accuracy as that of aboveground biomass but at lower precision. Constant root/shoot ratio (R/S ratio) method is found to be the very simplest one for estimating belowground biomass. Although the R/S ratio varies with site characteristics and stand age, a range of R/S ratios can be obtained from the scientific literature (Hamburg 2000). To avoid measuring roots, a conservative approach recommended by MacDicken (1997) is to estimate root biomass at no less than 10 or 15% of aboveground biomass. Hamburg (2000) recommends a default R/S ratio for re-growing forests of 0.15 in temperate ecosystems and 0.1 in tropical ecosystems. Although ratios as high as 0.4 have been measured in temperate forests, the author recommends erring on the side of caution to avoid the possibility of crediting non-existent carbon.

20.7.3 Soil Carbon

Direct measurement of soil carbon can be expensive because of the strong effect that soil characteristics have on carbon dynamics. Hamburg (2000) argued that with the help of few generalized principles, it should be possible to quantify soil carbon to a satisfactory level of precision for biological mitigation projects. Hamburg (2000) recommends that the soil carbon be estimated to at least 1 m of depth and that measurements of soil carbon and bulk density be taken from the same sample. Fortunately, for projects that are known to have non-decreasing effects on soil carbon, it may not be necessary to measure soil carbon after the baseline is established. Information on soil oxidation rates under diverse land-use systems is already available in the literature (Brown 2001). In general, reforestation projects in waste or degraded land would tend to increase soil carbon. If the cost required for measuring this carbon pool is greater than the marginal benefit of the carbon credits obtained, the project developer would be better off not to measure this pool. The Alternatives to Slash and Burn (ASB) group have argued that most of the sequestration potential in the humid tropics is aboveground rather than in the soil. In tree-based systems planted to replace degraded pastures, they found that the time-averaged carbon stock increased by 50 t/ha in 20 years; whereas the carbon stock in soil increased by 5–15 t C/ha (Tomich et al. 1998; Palm et al. 1999). Modelling can complement measurement methods available for estimation of soil carbon (Brown 2001). Modelling techniques can be mainly worthwhile to forecast slow changes in soil carbon pools. An example of this technique developed based on soil carbon sequestration by agroforestry is presented by Wise and Cacho (2002).

20.7.4 Carbon in Dead Biomass (Necromass)

Carbon contained in dead trees, branches, leaves, and other vegetation is considered as necromass pool. It is not needed to include annual leaf litter inputs as part of the necromass pool, since this input is well adjusted by decomposition losses within the soil and the net effect is added in the measurement of the soil pool (Hamburg 2000). The volume of necromass carbon pool fluctuates substantially with the type of forest and disturbance history, and assessing this constituent precisely can be very time consuming and subject to high uncertainty. Brown (2001) states that both lying and standing dead wood is an imperative carbon pool in forests and should be measured. Methods for this constituent have been tested and require no more effort than measuring living biomass.

20.8 Soil Carbon Sequestration of Perennial Horticulture Crops

Soil carbon sequestration is not just a process of carbon tapping and storing in soil but a multipurpose strategy. It rejuvenates degraded soils, improves the land productivity, enriches the diversity, and protects the environment (Wang et al. 2010). Horticultural crops, particularly perennial crops, have a great scope for sequestering more carbon in terrestrial ecosystem than agricultural or agroforestry systems. Several researchers across the world reported that perennial horticultural system has always had an edge over annual cropping systems (Bhavya et al. 2017; Wu et al.

Table 20.3 Soil carbon storage/stocks under different horticulture land-use systems (Bhavya et al. 2017)

Horticulture land-use system	4-year-old cultivation Carbon stocks (Mg ha^{-1}) 0–15 cm	15–30 cm	30–50 cm	50–100 cm	Total (1 m depth)
Mango orchard	1374.75	1361.20	1811.24	4478.19	9025.38
Cashew orchard	1244.10	1245.02	1679.50	4075.50	8244.12
Rose block	1005.75	1003.62	1305.90	3215.22	6530.49
Vegetable block	990.00	973.35	1308.40	3110.07	6381.92
Medicinal and aromatic block	973.95	954.24	1265.00	3082.30	6275.49
SEm ±	62.22	61.45	81.56	199.45	405.45
CD at 5%	186.25	184.56	245.55	599.56	1215.66

Table 20.4 Carbon dioxide sequestration under different horticulture land-use systems (Bhavya et al. 2017)

Horticulture land-use system	4-year-old cultivation CO_2 sequestration (Mg ha^{-1}) 0–15 cm	15–30 cm	30–50 cm	50–100 cm
Mango orchard	5045.33	4995.60	6647.25	16434.95
Cashew orchard	4565.84	4569.22	6163.76	14957.08
Rose block	3691.10	3683.28	4792.65	11800.95
Vegetable block	3633.30	3572.19	4801.82	11413.95
Medicinal and aromatic block	3574.39	3502.06	4642.55	11312.04
SEm ±	228.45	227.45	300.04	733.45
CD at 5%	684.45	677.45	900.12	2194.45

2012; Shrestha and Malla, 2016; Janiola and Marin 2016; Chandran et al. 2016). For instance, the carbon sequestration potential of different cropping systems was ranked in the order of mango >cashew > rose > vegetable > medicinal and aromatic plants (Bhavya et al. 2017) and reported that addition of more residues in perennial systems to soil recorded less emission of CO_2 than annual crops. Soil carbon storage and CO_2 sequestration at different depths as influenced by different horticulture land-use systems is presented in Tables 20.3 and 20.4. Comparison among the different land uses such as perennial horticultural system and agroforestry/annual agricultural system showed that perennial horticultural system improved soil organic carbon content and stocks (Chandran et al. 2016). Carbon dioxide mitigation of agri-horticulture was found to be better than that of agriculture, horticulture, silvipasture, and forest land-use systems under all altitude levels of Himalayan region (Rajput et al. 2017). Carbon sequestration and credits of different fruit crops is given in Table 20.5. Further agri-horticulture system provides economic gains including C credits seem to be the better option. Because of their perennial nature and deep-rooting systems, orchards have the potential to increase subsoil carbon stocks below 0.3 m depth. Potential of land-use change and agroforestry (LUCF)

Table 20.5 Carbon sequestered and C credits of *Mangifera indica* (mango) and *Uapaca kirkiana* orchards

Species	Type	Age (years)	DBH class (cm)	Mean DBH (cm)	CO_2[b] (kg ha^{-1})	Value[a] ($ ha^{-1})
Mangifera indica	Grafted	6	<10	9.2	107,500	475
Uapaca kirkiana	Un-grafted	8	<10	6.98	56,500	250
	Grafted	8	<10	5.79	36,500	175

DBH diameter at breast height; [a]calculated at $4.50 per tonne of CO_2 (Ecosystem Marketplace 2010); [b]biomass calculations are after Brown (1997), carbon content is assumed to be 50% of dry biomass

and land-use change and horticulture (LUCH) activities to offset greenhouse gas emissions have been reviewed by Bloomfield and Pearson (2000).

A field experiment was carried out in a coconut garden having red sandy loam soil at ICAR-CPCRI, Kasaragod, Kerala, during May–July 2015 to study the effect of cropping system on above- and belowground carbon sequestration in a 50-year-old plantation intercropped with 7-year-old fruit crops. Among the different cropping systems, coconut (*Cocos nucifera*) + jamun (*Syzygium cumini*) system sequestered the highest aboveground carbon (60.93 t/ha) followed by coconut + mango (*Mangifera indica*) system with 56.45 C t/ha, coconut + garcinia (*Garcinia indica*) sequestered 53.02 C t/ha, whereas, coconut alone had sequestered 51.14 C t/ha. The belowground soil carbon stock in the rhizosphere of 0–60 cm depth was the highest in coconut + mango (82.47 t/ha) system followed by coconut + jamun (79.13 t/ha) and coconut + garcinia (78.69 t/ha), and it was the lowest in coconut monocrop (47.06 C t/ha). The total carbon sequestration by coconut + jamun (140.06 t/ha) is followed by coconut + mango systems (138.91 t/ha) and coconut + garcinia (131.72 t/ha), whereas it was only 98.2 C t/ha under coconut monocrop (Bhagya et al. 2017).

20.8.1 Age of Orchard: An Important Factor of Carbon Sequestration

It is required to produce nearly 2.2 tonnes of wood for sequestering 1 tonne of carbon from the atmosphere (Chaturvedi 1994). In the tropical regions, carbon sequestration by perennial trees is much faster due to the prevalence of favourable climatic conditions. The growth rates and carbon sequestration potential of perennial horticulture and plantations diminish as trees approach maturity. Fruit orchards and plantations store carbon in young and middle age, but the accumulation rates reach zero as the trees mature. Decline in the aboveground net primary production in mature orchards and plantations are due to following reasons:

- An altered balance between photosynthetic and respiring tissues
- Reducing soil nutrient availability
- Increasing stomatal limitations leading to reduced photosynthetic rates

Changes in the belowground biomass during orchard stand development and with aging of the orchards are very poorly understood. Hence, it is very difficult to speculate how this important flux may change during development of the orchards, plantations, and gardens. The long residence time of particulate organic matter from high-latitude forest soils, however, provides indirect evidence that if flux of carbon from vegetation to the soil increases, as a result of global change, these soils have the capacity to act as a carbon sink on decadal timescale.

20.8.2 Management Options for Improving C Sequestration in Horticultural Systems

Carbon sequestration in perennial horticultural crops mainly depends on their enhanced growth and productivity. The same can be attained by improving health of soil through better carbon management strategies. Hence attention towards management options to improve C sequestration should be diverted solely towards management of the soil. A net C sequestration in soil can be achieved through either by increasing carbon input to the soil or reducing carbon losses. Management practices that cause an increase in carbon input in agroecosystems are planting high biomass-producing crops, crop residue recycling, application of manures, switching from annual to perennial crops, adopting crop rotation in place of monoculture, and promotion of agroforestry systems (Nieder and Benbi 2008).

Life-cycle assessment (LCA) model can be adopted to evaluate the impacts of different sets of orchard management practices and to inform growers about the best options for mitigating GHG emissions. The following production stages are generally considered in LCA model:

- Orchard establishment (e.g. soil preparation, planting)
- Orchard management, including pruning, irrigation, tree replacement, pest control, and fertilizer use (including its production and transport)
- Orchard removal and disposal
- Postharvest processing and handling
- Transportation along the entire life cycle

The key sources of GHGs under different growth stages can be derived through LCA, and based on the results we can focus on farm management alternatives which may offer the greatest potential for lowering GHG emissions. Earlier studies indicated that nutrient management accounted for up to 40% of GHGs emissions, while irrigation accounted for up to 20%, depending on the crop. This indicates that increasing nitrogen use efficiency and improving irrigation efficiency could significantly reduce emissions. Further, open burning of orchard waste is another source of GHGs. Hence alternative disposal methods for pruning need to be found out including removal of trees by incorporating the biomass back into the soil or converting the waste to bioenergy, etc.

The most suitable soil management options should be selected based on their effects on agronomic productivity, profitability, and environmental quality. Primarily, there can be three key soil management options for managing soil organic carbon and reducing the greenhouse gas emissions (GHG):

- Preserving the current levels of soil organic carbon (SOC)
- Reinstating depleted soil organic carbon (SOC) levels
- Expanding soil organic pools beyond their historic carrying ability keeping in mind that these upsurges may be of fixed magnitude and period.

The carbon storage/sequestration potential of degraded or marginal lands is literally very high under the set of sustainable management options. There are several land management strategies for improving C sequestration in soil (Fig. 20.1). The following lists of practices either alone or in combination are proven to be the best suitable management practices for soil carbon sequestration:

Fig. 20.1 Management options for sequestering C in soils under horticultural systems

- Residue management and tillage methods (zero tillage, conservation tillage, mulching, composting, etc.)
- Nutrient and soil fertility management (all management options to improve nutrient-use efficiency)
- Appropriate water management techniques (lifesaving irrigations, surface and subsurface drainage, rainwater harvesting, etc.)
- Control of soil erosion using suitable soil and water conservation measures (soil surface amendments, mulching, contour bunding, terracing, and trenching)
- Choices of crops, cover crops, intercrops, etc.

20.9 Conclusion

Perennial fruit crops–based system is a common land-use system in several parts of the temperate and tropical region of the globe. It has a significant role on economic, nutritional, and food security of the regions. Additionally, it offers a vital environmental service through mitigation of atmospheric CO_2. Further, the perennial plant-based system has more C stock in plant biomass than in the soil. This implies that even in the future, if temperature increases, not much change will happen to the stored C than that of annual-based cropping system where more C is stored in soil. In addition, perennial horticultural-based systems will provide economic gain through carbon credits. Therefore practicing perennial-based cropping system could be a potential option to mitigate increasing atmospheric CO_2. Further improved planting materials and standardizing the number of trees per unit area with appropriate management interventions will help in the storage of more carbon in a short period on the same land management unit.

The carbon sequestration potential and environmental services offered by perennial fruit trees are remain untapped. Therefore, the emphasis of research should be to develop efficient management systems and identify suitable species and propagation protocols to enhance carbon storage and to maximize fruit productivity. More investigations are required to quantify CO_2 sequestration potential in diverse fruit trees including native fruit tree species to indigenous communities. Location centric land-use systems need to be prioritized considering carbon sequestration potential and socio-economic needs. The major focus areas for further enhancing C sequestration of cropped systems include interactions among tillage, climate, and soil type on C sequestration; contribution of above- and belowground plant biomass to SOC; total GHG emissions from C sequestration practices, since most commonly recommended management practices like integration of legumes or fertilizer applications, which augment soil carbon, may perhaps also contribute to N_2O release from soil; role of tree pruning to increase light penetration in fruit orchards for higher photosynthesis; transformation of pruned tree biomass and other horticultural wastes into biochar and their addition into the fruit orchards or plantations soils to preserve soil carbon; quantification of C sequestration in promising horticultural systems; and benefits of conservation practices beyond C sequestration need to be elucidated. Further, much attention also to be given on the different properties of biochar made under different conditions, rates of decay of biochar in soil, effects of biochar on water usage and soil microorganisms, and behaviour of biochar under different environmental conditions.

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21 Effects of Productivity and Soil Carbon Storage in Mixed Forests

B. N. Ghosh and P. K. Mishra

Abstract

Forest ecosystem stored carbon in vegetation and soil, but its quantitative values depend on soil, vegetation type, climate (rainfall and temperature), and stages of soil aggregation process. Soil organic carbon (SOC), a key component of the global C pool, plays an important role in C cycling, regulating climate, water supplies, and biodiversity, and therefore in providing the ecosystem services that are essential to human being. The global soil carbon (C) pool amounts to 2500 Gt, whereas the biotic pool is only 560 Gt. Most agricultural soils in temperate regions have lost as much as 60% of SOC and as much as 75% in tropical regions, mainly due to conversion of natural ecosystems to agricultural uses. On a global scale, C loss from soils is mainly associated with soil degradation, including accelerated erosion and mineralization, and land-use change and has amounted to 78 ± 12 Gt since 1850. Review of work revealed that carbon sequestration is the highest in the short-rotation young forest of fast-growing hardwood tree species with regular leaf shedding pattern in humid condition. Enhancing carbon sequestration in terrestrial pool could have direct environmental, economic, and social benefits for people thereby mitigating the effect of global climate change. Mechanisms of protection and dynamics of SOC in mixed forest soil, factors affecting carbon storage in mixed forest plantation, potential of carbon storage in different forest types, determination of carbon storage in different trees, and a case study of subtropical mixed forest have been focused in this chapter. Mixed forest management practices that sequester carbon and increase productivity has also been discussed, besides new areas of research to mitigate the impact on changing climate and global environment.

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Keywords
Carbon sequestration · Management practices · Mixed forest · Protection mechanism

21.1 Introduction

Tropical and subtropical planted mixed forests are rapidly expanding. They are traditionally managed for intensive, short-term objectives that often lead to long-term yield decline and reduced carbon sequestration capacity. Here we attempted to describe how it is possible to increase and sustain carbon stored in tropical and subtropical mixed forest plantations if management is switched towards more sustainable forestry. We explore possible management factors that contribute to higher forest productivity and the potentials in ecosystem C in tropical and subtropical plantations. Reforestation is promoted globally to meet the growing demand of forest products, especially in developing countries. Tropical and subtropical forests cover 7–10% of the global land area, store 40–50% of carbon present in terrestrial vegetation (Lewis et al. 2009), and also account for most of current deforestation (Table 21.1), with accumulated losses in the 1996–2010 periods of 100 million ha (FAO 2012). Since forests are a major carbon pool, their management is crucial to develop successful policies for climate change mitigation. Carbon storage versus production of timber and non-timber forest products are seen sometimes as incompatible goals to be implemented at the same time in a forest, but this view is being challenged (Paquette and Messier 2010). Clarifying if tropical and subtropical forest plantations can support multi-objective forestry and estimating how much carbon could be stored in working forest plantations would help to maximize the outcome of forest management plans while helping to reach a more sustainable development of the tropical and subtropical regions. Newly planted forests are typically established on sites that have rapid growth and access to processing facilities and growing markets. Hence, very large areas of new forest plantations have been established in tropical and subtropical countries, particularly in Africa, Latin America, and parts of Asia. In spite of such rapid growth, only 3% of the world's forest land is covered with productive forest plantations. However, this area expanded by 2 million ha annually in the 1990s and by 2.8 million ha in the 2000s (Kirilenko and Sedjo 2007).

Table 21.1 Estimates of area under tropical rainforest (FAO 2005)

	Tropical rainforest area (mha)		
Region	1980	1990	2000
Africa	289.7	241.8	224.8
Latin America	825.9	753.0	718.8
Asia	334.	287.5	187.0
Total	1450.1	1282.3	1130.6

Reforestation has been suggested not only as an effective way to restore degraded ecosystems but also as a way to mitigate elevated atmospheric CO_2, hence contributes towards the reduction of climate change (Kimmins et al. 2008). Whether and how these efforts can maximize and sustain forest C storage largely remains unexamined (Chen et al. 2009). Recent decisions by the UN Framework Convention on Climate Change have encouraged consideration of other ecosystem services while implementing REDD+ (Reducing greenhouse gas Emissions from Deforestation and forest Degradation) projects for forest carbon sequestration and storage. Therefore, selecting the most appropriate approaches for implementing multipurpose forest management in planted forests is just as important as growing more forests (Nabuurs 2007). However, few incentives and policy guidelines are available to encourage growing better forests globally, perhaps due to the lack of a clear understanding of long-term benefits from growing better forests as well as operational difficulties.

21.2 Forest Ecosystem

Forest ecosystem plays a vital role in the global carbon cycle by sequestering a substantial amount of carbon dioxide from the atmosphere (Vashum and Jayakumar 2012). Forest is the largest carbon inventory, and it deposits 1146 Gt of carbon which occupies 56% of the carbon inventory of the total terrestrial ecosystem. The Intergovernmental Panel on Climate Change identified five carbon pools of the terrestrial ecosystem involving biomass, namely, the aboveground biomass, belowground biomass, dead wood, litter, and soil organic matter. Biomass is an important building block and also acts as an indicator in carbon sequestration. Among all the carbon pools, the aboveground biomass and soil organic matter constitute the major portion of carbon dioxide (Jina et al. 2008). According to the Dixon et al. (1994), 69% of the carbon is stored as soil organic matter and 31% as living biomass; therefore, estimating the biomass in trees and soil is the first step in carbon accounting of forest ecosystem.

21.3 Mechanisms of Protection and Dynamics of SOC in Forest Soil

Tropical and subtropical forest soil biodiversity has a positive impact on the soil carbon pool and a favourable impact on soil physical and biological qualities especially with regard to soil structure, porosity, aeration, water infiltration, drainage, nutrient/elemental cycling, and organic matter pool and fluxes (Schils et al. 2008; Conant et al. 2001). Carbon sequestration in forest soils is a function of soil type and characteristics, and therefore identifies soil types that sequester substantial amounts of carbon that should be protected. In Oxisols and Ultisols, Al-humus complexes and non-crystalline Al^{3+} hydroxides are predominant aggregates as these compounds are able to protect SOC from microbial decomposition and stabilize aggregation. Aridisols display high aggregate stability associated with carbonates (Boix-Fayos et al. 2001). The increase in SOM can improve aggregation, stability of soil structure, infiltration rate, water retention, resistance to erosion, organic matter, reactivity and specific surface of soil minerals, base cation status, presence of Fe and Al oxides, pH, and redox conditions (Baritz et al. 2010).

The rate of SOC sequestration in these restorative strategies depends on the amount and quality (C:N ratio, lignin content, etc.) of biomass added, depth and proliferation of the root system, conservation-effectiveness of these measures to control erosion, and change in soil moisture and temperature regimes that decrease the biomass decomposition rate. The strategy is to select land use and soil management systems that increase biomass addition to the soil and decrease its decomposition rate, so that the quantity (A-KC) in dc/dt = -KC+ A is positive and large.

Where dC/dt is the rate of change of C as SOC pool, t is time, K is decomposition constant, and A is accretion of biomass comprising the amount of C added to the soil through crop residue, leaf litter, root biomass, and detritus material. The rate of increase in the SOC pool depends on the restorative land use (Fig. 21.1). The rotation time for fast-growing species is 12 years and 20–25 years for slow-growing species. The symbol Δ on each curve denotes the rate (ΔY/ΔX) of SOC sequestration, and it depends on the reference point or base line. The rate may be high and positive when degraded cropland is used as a reference point and slow or negative when natural tropical forest is chosen as reference. Afforestation of degraded

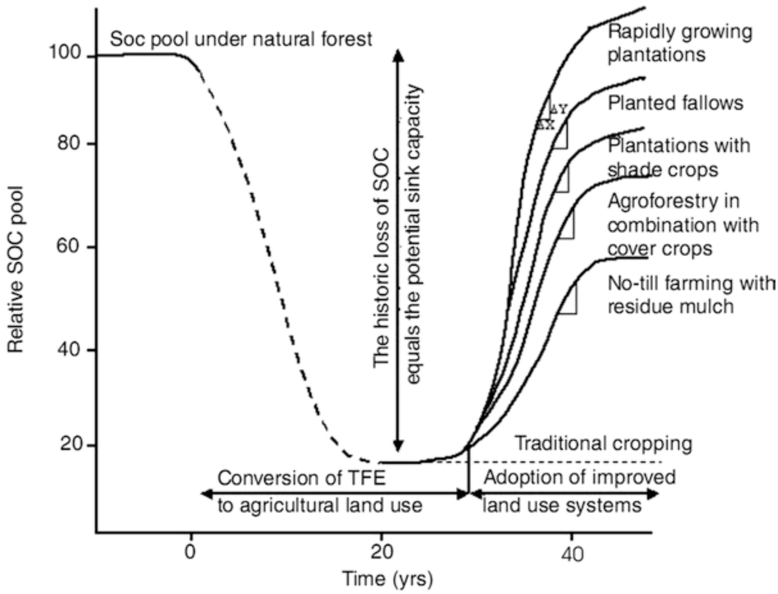

Fig. 21.1 A schematic diagram of dynamics of soil organic carbon in tropical and subtropical soils

agricultural soils with rapidly growing plantations may have SOC sequestration rate of 1 Mg C ha^{-1} $year^{-1}$ (Lal et al. 2003).

21.4 Factors Affecting Carbon Storage in Mixed Forest Plantation

21.4.1 Influence of Natural Factors

The five environmental variables are dominant for carbon dynamics at each site: light availability, temperature, soil moisture, age of tree, and altitude/slope.

21.4.2 Light

Photosynthetic photon flux density (incident light) is the most immediate environmental control on photosynthesis which increased light absorption and tree growth. Availability of light is strongly affected by cloudiness, aerosol, and low sun–angle conditions which are more effective at penetrating the deeper layers of the forest canopy.

21.4.3 Temperature

Temperature plays dominant role on seasonal processes which regulate both carbon gain and carbon loss in all types of forest, decomposition rate in soil, and SOC distribution in soil profile. The growth of forest vegetation is affected in extreme low and high temperature through regulation of photosynthesis rate.

21.4.4 Soil Moisture

Soil moisture is probably the most significant environmental variable. High soil water content tends to conserve SOM because reduced oxygen availability in wet soils slows the decomposition of SOM by soil microbes. Drier and well-aerated soils enhance rapid decomposition and accumulate less SOM. If the water content of the soil decreases, plant productivity decreases and increases the risk of forest fire.

21.4.5 Altitude/Elevation

The elevation and slope aspect play a key role in determining the temperature regime of any sites. Within one elevation, cofactors like topography, aspect, inclination of slope, and soil type affect the forest composition. The soils are well drained at higher elevations and poorly drained at lower altitude. The microenvironment of different aspects of hill slopes is influenced by the intensity and duration of available sunlight (Sharma et al. 2010). Hence, considerable variation of carbon stock exists between forests and between similar forests at different latitudes.

21.4.6 Age of Tree

Growth (and sequestration) depends on local climate, soil factors, and management, the age of tree and forest also plays an important role in carbon sink. The sequestration of carbon from the atmosphere by the tree set a maximum rate between ages 10 and 20–30. As an indication, at the age of 30 years, about 200–520 tonnes CO_2 are sequestered per ha in forests with productivity ranging from low to high. After this age, if the trees are not harvested, the sequestration rate slows down gradually until maturity at about 80–100+ years of age. In younger stands (≤ 50 years), the observed rate increase can be as little as one-third of total growth, but in older stands, it can be the majority of growth; under the expectation of the ensemble function, old forests should grow very little as they approach equilibrium (Schwalm et al. 2007; Bert and Danjon 2006). Except the wood, all the other components showed a decrease in percentage in carbon storage in these compartments, with the increase in age.

21.5 Practices That Sequester Carbon in Forest, Grassland, and Cropland

Forest	Grassland	Cropland
Protection of existing forests: Avoided deforestation preserves existing soil C stocks and prevents emissions associated with biomass burning and soil exposure by land clearing	*Improved grassland management*: Optimize stocking rates to reduce land degradation, depletion of soil organic carbon, and methane emissions through enteric fermentation	*No or reduced tillage:* Reduces the accelerated organic matter decomposition which is associated with intensive (conventional or traditional) tillage
Reforestation: Increasing tree density in degraded forests increases carbon accumulation	*Introduction of improved pasture species and legumes* to increase above- and belowground biomass production and soil organic carbon accumulation	*Mulching/residue management*: Improves soil moisture, prevents soil erosion, and increases soil organic matter when incorporated into the soil; crop residues also prevent loss of carbon from the soil system

Forest	Grassland	Cropland
Afforestation: Establishment of new forests on non-forest land (cropland, grassland, or degraded lands) increases carbon stock through the increase in aboveground biomass as well as greater organic materials input for soil decomposition	*Application of inorganic fertilizers and manure* to stimulate biomass production. -Chemical fertilizers are, however, less environmentally friendly due to nitrous oxide (N_2O) emissions associated with N fertilizers, the greenhouse cost of fertilizer production, and emissions associated with transport of fertilizers	*Application of inorganic fertilizers and manure* to stimulate biomass production. -Chemical fertilizers are, however, less environmentally friendly due to nitrous oxide (N_2O) emissions associated with N fertilizers, the greenhouse cost of fertilizer production, and emissions associated with transport of fertilizers
	Water management to increase productivity, but this has to be put in the perspective of emissions associated with the process of irrigation	*Use of cover crops/green manure* increases the biomass returned to the soil and thus increases soil carbon stock
	Introduction of earthworms to improve aeration and aid organic matter decomposition in the soil profile	*Use of improved crop varieties:* Improved crop varieties help to sequester carbon in the soil through increased above- and belowground biomass production
	Establishment of pasture on degraded land reintroduces large amounts of organic matter into the soil	*Agroforestry/tree-crop farming*: Introduction of fruit, trees, orchards, and woodlots into croplands helps to store more carbon, optimize water use, diversify production, and increase income

21.6 Potential of Carbon Storage in Different Forest Types

Forest lands are divided into three latitudinal belts: high or boreal (approximately 50–75°N and S latitude), mid or temperate (approximately 25–50°N and S latitude), and low or tropical (approximately 0–25°N and S latitude). Most of the forests are in the low latitudes (43%), followed by the high latitudes (32%) and midlatitudes. The total carbon pool in forest ecosystems was estimated to be about 1150 Gt (Dixon et al. 1994), 49% of which is in boreal forests, 14% in temperate forests, and 37% in tropical forests.

Tropical forests contain huge diversity of "hardwood" tree species. They are dominated by evergreen or semi-deciduous broadleaf species and characterized by tall stature (usually exceeding 30 m), a tightly closed canopy, and very high diversity (200–300 tree species per hectare). Evergreen trees sequester an average of 44.37 kg of CO_2 per year, while deciduous trees sequester an average of 40.87 kg of CO_2 per annum. Tropical rain forest had higher carbon stock than dry evergreen and mixed deciduous forest with 137.73 C t/ha, 70.29 C t ha^{-1} and 48.14 C t ha^{-1} (Terakunpisut

Table 21.2 Amount of carbon storage in different types of forest

Forest type	Place	Carbon stock	References
Aspen-dominated, mixed deciduous forest	USA	2.13 mg ha $year^{-1}$	Gough et al. (2008)
Northern deciduous forest	USA	2.8 mg ha $year^{-1}$	Schmid et al. (2003)
Coniferous forest	Japan	3.57 Mt CO_2 $year^{-1}$	Sanga-Ngoie et al. (2012)
Evergreen broadleaved forest	Japan	2.25 Mt CO_2 $year^{-1}$	Sanga-Ngoie et al. (2012)
Deciduous broadleaved forest	Japan	0.77 Mt CO_2 $year^{-1}$	Sanga-Ngoie et al. (2012)
Tropical savanna	UK	12 t C ha $year^{-1}$	Grace et al. (2006)

et al. 2007). Moist tropical forests are important for carbon sequestration, because of high carbon contents than in any other forest, averaging nearly 110 tonnes per acre. Tropical forest soils have only modest C levels (compared with other biomes), because the dead biomass decomposes rapidly in the warm, humid conditions and the minerals rapidly leach out of tropical forest soils. The differences in carbon dioxide storage between various types of forests are tabulated as follows (Table 21.2).

21.6.1 Determination of Carbon Storage in Different Trees

The rate of CO_2 sequestration of trees depends on several factors such as age of tree, soil nutrition, speed of growth, floral diversity composition, type of soil, type of forest, size of tree and root, leaf abscission, climatic factor, etc. Tree's growth, large diameters, and increasing height are itself an indicator of their large biomass contents in terrestrial carbon reservoir. Not all tree growth is equally suited for long-term carbon sequestration in biomass. Deciduous trees hold their leaves for 1 year, while conifers can hold needles for as long as 8 or more years. Fine roots live for days or years, depending on the species (Matamala et al. 2003). But larger roots may be more important than small roots to enhance carbon pools (Rasumussen et al. 2010). In contrast, tree trunks, large branches, and large roots, which remain on the tree for several decades or centuries, are the primary sites of carbon sequestration. The estimated rate of selected planted forest stores more carbon than mature forests, due to their rapid carbon sequestration rate, and short-rotation tree species with regular leaf shedding patterns have more capacity for carbon sequestering in litter which decomposes more rapidly than species with annual and bimodal leaf shedding patterns (Raizada et al. 2003). Fast-growing conifers may produce slow-decomposing litter leading to accumulation on forest floor; hence, there is a risk for fire damage and decline in ground flora diversity or productivity. Mixed planted forests of exotic and native species could be more efficient in sequestering carbon than monocultures, while fast-growing hardy species like *Eucalyptus* would be an ideal choice for wasteland afforestation/reforestation and softwood species for agri-silvicultural practice in soil of fertile plain areas. Carbon sequestration is highest in

Table 21.3 Amount of carbon sequestration in different tree species

Species	Carbon	References
Acacia auriculiformis	7.7 Mt C $year^{-1}$	Raizada et al. (2003)
Dalbergia sissoo	3.6 Mt C $year^{-1}$	Raizada et al. (2003)
Casuarina equisetifolia	1.9 Mt C $year^{-1}$	Raizada et al. (2003)
Gmelina arborea	1.4 Mt C $year^{-1}$	Raizada et al. (2003)
Sequoia sempervirens	5000 C t ha^{-1}	Runyon et al. (1994)
Pseudotsuga menziesii	1000 C t ha^{-1}	Runyon et al. (1994)
Cedrus deodara	469.1 C t ha^{-1}	Sharma et al. (2011)
Terminalia bellirica	327.78 C t ha^{-1}	Hangarge (2012)
Eucalyptus spp.	320.67 C t ha^{-1}	Chavan and Rasal (2011)
Acacia mangium Willd.	292.02 C t ha^{-1}	Ilyas (2013)
Bambusa balcooa	234.17 C t ha^{-1}	Borah and Chandra (2010)
Ficus amplissima	221 C t ha^{-1}	Hangarge (2012)
Tectona grandis	181 C t ha^{-1}	Sreejesh et al. (2013)
Hevea brasiliensis	136 C t ha^{-1}	Dey (2005)
Populus deltoides	115 C t ha^{-1}	Gera et al. (2006)
Mangifera indica	104.41 C t ha^{-1}	Chavan and Rasal (2012)
Quercus leucotrichophora	77.3 C t ha^{-1}	Sharma et al. (2011)
Albizia lebbeck	11.97 C t ha^{-1}	Jana et al. (2009)
Shorea robusta	8.97 C t ha^{-1}	Jana et al. (2009)

young forests and may tend to reduce as forests reach maturity. Native trees like *Azadirachta indica* (neem), *Tamarindus indica* (tamarind), *Ficus religiosa* (peepal), and *Madhuca latifolia* are considered ecologically beneficial as they have relatively high efficiency of carbon fixation; these species may be suitable for checking urban pollution and may provide a good option for maximum carbon fixation (Forrester et al. 2006). Trees in urban areas also involved in stability of natural ecosystem with increased recycling of nutrient along with maintenance of climate conditions by the biogeochemical processes. Table 21.3 shows the amount of carbon dioxide sequestration by different tree species.

21.7 A Case Study of Subtropical Mixed Forest

Traditional forest management practices in forest plantations, particularly in developing countries, generally involve application of short rotations, usage of monoculture and exotic species, and high level removal of biomass, with the main objective of maximizing short-term economic gains (Wei et al. 2012). The ecological problems associated with those traditional forestry practices have been well documented as decline in long-term productivity (Carson et al. 2013), biodiversity loss (Gibson et al. 2011), increased susceptibility to insect pests and diseases (Jactel and Brockerhoff 2007), physicochemical changes in forest soils (Liao et al. 2012), and losses of other ecological services. In the context of climate change mitigation, traditional forestry practices will lead to short-term carbon sequestration in wood products, but those gains are unlikely to be sustainable due to losses in ecosystem C linked to the above-mentioned ecological problems. Sustainable forestry practices, however, could have an important role in mitigating climate change impacts, if they are well designed and implemented (Paquette and Messier 2010). For example, transformation of conifer monocultures into mixed conifer–broadleaved plantations has been considered as an efficient strategy to sustain forest productivity and restore degraded forests (Lo et al. 2012).

China has both subtropical and temperate forests, and aggressive reforestation policies have turned it into one of the five most forest-rich countries in the world, accounting for the largest gain in forested areas globally (Lewis 2006). However, most of reforested ecosystems during the past decades in China have been by monocultures dominated by coniferous species. In subtropical China, evergreen broadleaved forests are the main native ecosystem type in the region, with a clear potential capacity for carbon sequestration (Wei et al. 2012). Among the native species, the broadleaf *Phoebe bournei* (Hemsley) Yang is one of the most valuable tree species in this subtropical region because of its high-quality wood properties, with significant economic and ecological benefits (Wang et al. 2013).

It has been observed that broadleaved plantations have significantly higher ecosystem C than conifer plantations. In addition, ecosystem C increases with plantation age and reaches maximum with intermediate stand densities of 1500–2500 trees ha^{-1}. Wei and Blanco (2014) simulated (using the FORECAST model) the regional implications of switching from traditional to sustainable management regimes, using Chinese fir (*Cunninghamia lanceolata*) plantations in subtropical China as a study case with 200 traditional short-rotation pure stands and 200 sustainably managed mixed Chinese fir–*Phoebe bournei* plantations, for 120 years. Their results showed that mixed, sustainably managed plantations have on average 67.5% more ecosystem C than traditional pure conifer plantations. If all pure plantations were gradually transformed into mixed plantations during the next 10 years, carbon stocks could rise in 2050 by 260.22 Tg C in east-central China. Assuming similar differences for temperate and boreal plantations, if sustainable forestry practices were applied to all new forest plantation types in China, stored carbon could increase by 1482.80 Tg C in 2050. Such an increase would be equivalent to a yearly sequestration rate of 40.08 Tg C $year^{-1}$, offsetting 1.9% of China's annual emissions in 2010. More importantly, this C increase can be sustained in the long-term through the maintenance of higher amounts of SOC organic carbon and the production of timber products with longer life spans.

21.8 Forest Management (Mixed) Practices for Enhanced Carbon Storage

Significant land disturbance is the major source of CO_2 emissions. Human disturbances have much more impact on forests than natural disturbances. If forested land is converted to agriculture or development or pasture, fuel wood collection, anthropogenic fire, and then often left exposed to erosion (Flint and Richards 1994). Forest management plays a significant role in carbon savings. Three broad classes of forest management actions could influence carbon conservation and sequestration in forest ecosystems: (1) decreasing deforestation and forest degradation, (2) reforestation (establishing additional areas of forest), and (3) implementation of practices which stimulate CO_2 fixation by existing forest. By improved management practices, the amount of carbon stored in soils and plants can be increased. The positive carbon forest practices are selective cutting, increased stocking, increased rotation length, uneven aged management, non-manipulation forest stands, and conservation/restoration.

21.9 Conclusion

Forest ecosystems are the prominent site to study climate change, not only in terms of total net carbon emission but also in terms of global storage capacity, important for climatic regulation. Forest ecosystem stored carbon in vegetation and soil. The accumulation will significantly vary due to the difference in biogeographical locations, biophysical parameters, etc. The total area and tree diversity of tropical forest is high and carbon storage capacity is also high compared to all other forests. Within the tropical forest, moist tropical forests sequester more carbon dioxide compared to evergreen, semi-evergreen, and deciduous forest. Temperate forests have low diversity of tree species than tropical and store much carbon in soil than vegetation because of slow decomposition rate. Carbon accumulates to high levels in boreal forest soil because of high soil moisture, high soil acidity, and slow rate of decomposition. Carbon sequestration is highest in the short-rotation young forest of fast-growing hardwood tree species with regular leaf shedding pattern in humid condition. The significance of forest conservation and management is helpful to conserve biodiversity, produce commercial wood products, mitigate climate change, improve ecotourism, increase watershed values, conserve energy, sustainable land-use practices, etc. Also trees in urban area provide mitigation of store and sequester carbon, reduce noise pollution, improve air quality, reduce consumption of electricity for heating and cooling, aesthetic contribution, contribute to human health and relaxation, and reduce stress and anxiety levels. From the above study, it is concluded that all the terrestrial tree species involve in more carbon storage and mitigating climate change. Enhancing carbon sequestration in terrestrial pool could have direct environmental, economic, and social benefits for people thereby mitigating the effect of global climate change.

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22 Forage-Based Cropping Systems and Soil Organic Carbon Storage

Arvind Kumar Rai, Srinivasan Ramakrishnan, Nirmalendu Basak, Parul Sundha, A. K. Dixit, and P. K. Ghosh

Abstract

Terrestrial ecosystem is the biggest sink storing three times more carbon that is present in the atmosphere. In tropical regions, it is difficult to maintain soil organic carbon comparable to temperate regions. However, agricultural practices such as manuring, cover cropping, intercropping, and inclusion of grass and legumes in cropping systems promote higher carbon sequestration. High-diversity mixtures of perennial grassland plant species store 500–600% more soil C and N than same species under monoculture. Productivity and soil fertility of the natural grassland can be improved by introduction of the range legumes. Inclusion of *Macroptilium lathyroides* in natural grassland fetched 1.29 times increase in soil organic carbon (SOC) as compared to natural grassland. Productivity of the *Cenchrus ciliaris* could be improved in association with the range legumes such as *Siratro*, *Stylosanthes*, and *Clitoria* and also by application of nitrogenous fertilizers. In the present chapter, attempts have been made to elucidate the role of forage-based cropping systems, nutrient management, tillage, and silvipasture systems in SOC stock and productivity of different land-use systems. Additionally, the significance of the critical carbon input in maintaining the zero change in SOC values in different cropping systems, soil orders, and agroecological zones are discussed.

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Keywords
Cropping systems · Forages and SOC stock · Grassland · Legumes · Nutrient management · Soil organic carbon storage

22.1 Introduction

Promoting carbon build-up in terrestrial ecosystem through adoption of land management practices is a potential strategy for reducing the atmospheric CO_2 concentration and offsetting the global emission from other sources. Terrestrial ecosystems store about 2100 Gt carbon in living organisms, litter, and soil organic matter, which is almost three times that currently present in the atmosphere (Trumper et al. 2009). Approximately 10% of the CO_2 in the atmosphere is cycled through the soil each year (Raich and Potter 1995). In tropical agro-ecoregion, high level of the TOC equilibrium is difficult to preserve because of faster rate of decomposition compared with temperate regions. Manure, compost, crop residue, mulching, conservation tillage, agroforestry, diverse cropping system, and cover crops are having promise for improving C sequestration (Lal 2004). The turnover of TOC in the soil depends on the quality and quantity of the plant residues returned to the soil (Mandal et al. 2007; Aoyama et al. 1999). Developing countries are presently facing a dual challenge of reducing CO_2 emissions and enhancing the gross domestic product to satisfy the domestic demands. In this context, the importance of sustainable management of soils of agroecosystems to enhance SOC stocks by sequestering atmospheric CO_2 cannot be overlooked. Therefore, soil and crop management practices must be designed to ensure sustainability of long-term cropping systems. Cropping practices have negative as well as positive effect on carbon storage and stability in farmland soils (Bruce et al. 1999; Six et al. 2002).

Soil organic carbon in intensive forage production differs from the grain crops, because almost all of its biomass is harvested for livestock feeding with little residue left in the field for recycling. But, better adaptability, fast growth, high biomass production, and greater belowground biomass addition by grasses and legumes make the fodder-based production system ideal for carbon sequestration in different land-use systems (Rai et al. 2013). A balanced application of plant nutrients, organic amendments, and inclusion of legumes can enhance and sustain SOC concentration and stock under forage-based cropping system (Srinivasarao et al. 2012a, b; Dixit et al. 2018). Agronomic practices, such as crop residue recycling (Blair et al. 2006), crop rotation and intercropping (Ghosh et al. 2012; Manna et al. 2012), and integrated nutrient management (Yadav et al. 2000; Reddy et al. 2000; Ghosh et al. 2003), can significantly increase SOC storage and soil quality. There are numerous studies on effects of cropping systems on SOC storage (Benbi and Brar 2009; Bhattacharyya et al. 2009; Ghosh et al. 2012; Brar et al. 2013). These investigations have greatly enhanced our understanding of the impacts of cropping system and management practices in grain crops on SOC storage and dynamics. Practically, there are great differences in the inputs of SOC as crop stubble and root and in its outputs as carbon decomposition in different cropping patterns.

22.2 SOC Storage in Grasses and Legume-Based Cropping System

The amount of organic C stored in soil results from the net balance between the rate of SOC inputs and rate of mineralization in each of the organic C pools. Changes in land use and soil management influence the rates of organic C sequestration in soil. Conant et al. (2001) reported the rates of sequestration of atmospheric C affected by type of management. Introduction of earthworms, sowing of improved grass species, and sowing legumes had very high rates of C storage; values obtained for these practices were 2.35, 3.04, and 0.75 Mg C ha^{-1} $year^{-1}$, respectively. Conversion from cultivated land to grassland also had high sequestration rates (1.01 Mg C ha^{-1} $year^{-1}$), likely due to prior soil C depletion following cultivation. Carbon sequestration rates for other management types like irrigation, fertilization, and grazing were 0.11, 0.3 and 0.35 Mg C ha^{-1} $year^{-1}$, respectively. Land-use changes and management options also affect the soil C content and concentration in soil profile. Amount of C that may accumulate in soil are related to several factors like productivity of the recovering vegetation, physical and biological conditions in the soil, and the past history of SOC inputs and physical disturbance. Substantial gains in SOC of grassland are also possible with management for high grass productivity. Findings from the grassland Conservation Reserve Program (CRP) for a productive of US Central Plains (Texas, Kansas, and Nebraska) showed that the SOC may accumulate at a rate of 1.1 metric tons C ha-1 year-1 to a depth of 300 cm (Gebhart et al. 1994). Results from subtropical moist forest life zones demonstrate a potential for SOC gains (33.2 g C m^{-2} $year^{-1}$) when row crops are replaced with managed pasture (Lugo et al. 1986). SOC accumulation rates in arid conditions are much lower. Key variable associated with higher rates of soil C and N accumulation in grasslands is greater root biomass accumulation (i.e. high plant C and N inputs in the soil) from the joint presence of C_4 grasses and C_3 legumes. Soils under pasture also tend to have higher root:shoot (R/S) ratio than many crops. However, perennial pastures usually have higher than annual pastures, for example, R/S ratio of *Phalaris* is 1, while sub clover is 0.45. Plant species number and/or composition also influence ecosystem productivity and nutrient dynamics. Net soil C accumulation to 60 cm soil depth in the C_4 monocultures (two-species plots containing just C_4 grasses) was less than one-third (18.7 ± 13.6 g C m^{-2} $year^{-1}$) the soil C stored in the 16-species plots within the same soil depth (64.9 ± 7.6 g C m^{-2} $year^{-1}$) after 12 years (Fornara and Tilman 2008). High-diversity mixtures of perennial grassland plant species stored 500–600% more soil C and N than monoculture plots of the same species. In a mixed pasture, joint presence of C_4 grass and C_3 legume species is a key cause of greater soil C and N. The presence of C_4 grasses and C_3 legumes increased soil C accumulation by 193 and 522%, respectively. This is because legumes have unique access to N, and C_4 grasses take up and use N efficiently, increasing belowground biomass and thus soil C and N inputs (Fornara and Tilman 2008). Legumes have high litter quality (low C:N), high litter-decomposition rates, and low nutrient-use efficiency. Because of symbiotic relationships, they have large effects on N availability and N supply rates in many N-limited natural and agricultural systems (Vitousek and Howarth 1991; Vitousek 2004).

Productivity and soil fertility of the natural grassland can be improved by introduction of the range legumes, namely *Desmodium* spp., and nitrogen management. Application of 40 kg N ha^{-1} caused significant increase in dry forage yield and TOC content of the soil. The rate of TOC build-up was 1.5 times more than the natural grassland (0.74 g kg^{-1} year^{-1}) (Rai et al. 1980). Introduction of *Macroptilium lathyroides* in natural grassland resulted 1.29 times increase in soil TOC as compared to natural grassland and nitrogen equivalence of 129% for dry biomass production (Rai et al. 1980). Other legumes also showed increased mixed biomass production and TOC. Maximum increase in TOC and SOC build-up rate was observed with *Macroptilium lathyroides* (42%) followed by *Stylosanthes guianensis*. In general, the rate of TOC build-up was higher in legume-incorporated grassland than the natural grassland. The regression equation developed between TOC and biomass production by 12 legumes showed significantly high R^2 (0.61) value except *Alysicarpus rugosus* and *Clitoria ternatea* (Fig. 22.1).

Hazra and Tripathi (1986) observed that productivity of the *Cenchrus ciliaris* could be improved by inclusion of the range legumes, for example, *Siratro*, *Stylosanthes*, and *Clitoria*. This productivity can further be improved by application of 40 kg N ha^{-1}. Increased biomass productivity of the pastures was linearly associated with increase in the TOC content and SOC stock in the surface soils (0–0.20 m). About 92–94% of variability in the SOC storage in the surface layer was explained by the biomass production of the pastures (Fig. 22.2). The efficiency of C sequestration of grass and grass + legumes mixture was increased in association of the *Hardwickia binata* (Table 22.1). Application of 40 kg N ha^{-1} resulted in 0.34–2.29 Mg ha^{-1} increase in the SOC storage of all the pasture and silvipasture systems as compared to unfertilized pastures/silvipastures. *H. binata* + *C. ciliaris* + *Clitoria* silvipasture system recorded maximum 20.1 and 22.3 Mg ha^{-1} SOC storage without and with N application, respectively.

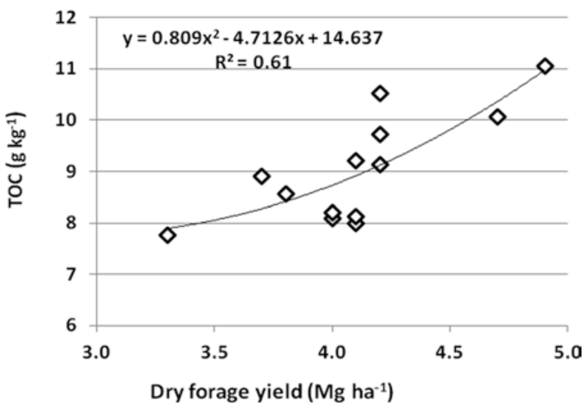

Fig. 22.1 Regression model for TOC and dry forage yield of legume planted natural grassland. [Model developed using the input data from Rai et al. (1980)]

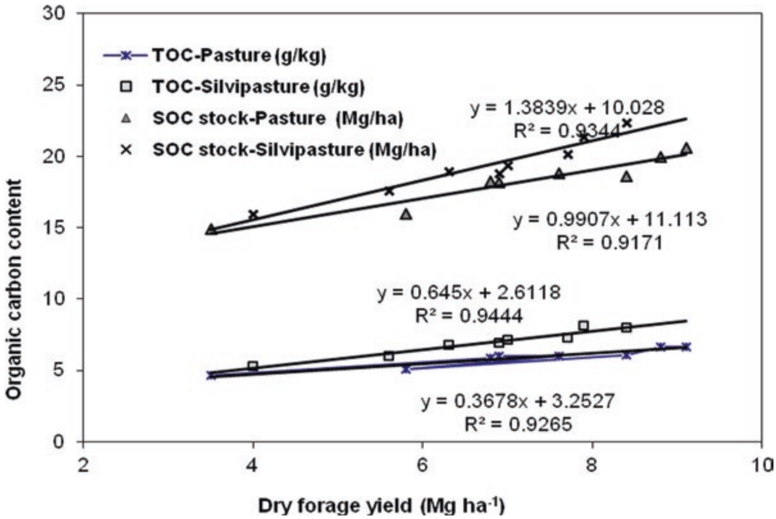

Fig. 22.2 Regression model for TOC and SOC and dry forage yield of pasture and silvipasture systems

Table 22.1 Effect of nitrogen application on soil carbon storage after 5 years of grass and grass–legume pasture and *Hardwickia binata*–based silvipasture system (Hazra and Tripathi 1986)

Grass species	Total organic carbon ($g\ kg^{-1}$)		SOC stock ($Mg\ ha^{-1}$)*		Rate of SOC build-up ($Mg\ ha^{-1}\ year^{-1}$)	
	Without N	With 40 kg N ha^{-1}	Without N	With 40 kg N ha^{-1}	Without N	With 40 kg N ha^{-1}
Cenchrus ciliaris	4.65	5.05	14.90	15.97	0.03	0.24
H. binata + *C. ciliaris*	5.32	5.98	15.96	17.59	0.24	0.57
C. ciliaris + *Siratro*	5.85	6.12	18.26	18.60	0.70	0.77
H. binata + *C. ciliaris* + *Siratro*	6.78	7.31	18.99	20.18	0.85	1.08
C. ciliaris + *Stylosanthes* spp.	5.98	6.65	18.19	19.95	0.69	1.04
H. binata + *C. ciliaris* + *Stylosanthes* spp.	7.18	8.11	19.39	21.42	0.93	1.33
C. ciliaris + *Clitoria*	5.98	6.65	18.79	20.61	0.81	1.17
H. binata + *C. ciliaris* + *Clitoria*	6.92	7.98	20.05	22.34	1.06	1.52

*0–0.20 m depth

22.2.1 Effect of Forage-Based Cropping System on SOC

Crop cultivation adversely affects the distribution and stability of soil aggregates and reduces SOC stock. The magnitude of reduction in SOC due to cropping varies among climates and cropping systems due to the differences in cropping intensity and specific management practices. Choice of crop species plays an important role in maintaining the SOC stock. Rai et al. (2013) observed that guinea grass + (cowpea–berseem) are more efficient than the other systems (Table 22.2). The TOC content, SOC stock, and SOC build-up rate were greater in groundnut–berseem–maize (F) + cowpea (F) > napier–bajra hybrid (perennial) + (cowpea–berseem) > groundnut–wheat–maize (F) + cowpea (F) > sorghum (single cut)–wheat–green gram > sorghum (multi-cut)–berseem (Table 22.2).

Rai et al. (2013) also observed the linear relationship between sustainable yield index (SYI) and different pools of C in Guinea grass (cowpea–berseem) intercropping system (Table 22.3). High R^2 values show that increase in biomass production of the cropping systems proportionately contribute to the SOC content of soil through roots, rhizodeposition, and crop stubbles. This also indicates that an ideal cropping system for C sequestration should produce and retain the abundant quantity of biomass or organic C in the soil.

22.2.2 Effect of Nutrient Management on SOC

Cropping system and nutrient management have a positive effect on SOC and TOC content in guinea grass-based cropping system. Even in the control plot, the SOC content increased more than three times over the initial value indicating a profound

Table 22.2 Long-term effect of cultivation on SOC status and build-up in different forage-based cropping system across the country

Cropping system/location	Carbon build-up rate (Mg ha^{-1} $year^{-1}$)	References
Sorghum (multi-cut)–berseem (5 years)	0.19	Kumar and Faruqui (2009)
Sorghum (single cut)–wheat–green gram (5 years)	0.24	
Groundnut–berseem–maize (F) + cowpea (F) (5 years)	0.50	
Groundnut–wheat–maize (F) + cowpea (F) (5 years)	0.38	
Napier–bajra hybrid (perennial) + (cowpea–berseem) (5 years)	0.45	
Guinea grass + (cowpea–berseem) (9 years)	1.95	Rai et al. (2013)
Sorghum–berseem (5 years)	1.17	
Cowpea–oat (grain) (5 years)	1.0	
Maize–cowpea–oat–pearl millet–oat (5 years)	0.99	

Table 22.3 Regression model of sustainable yield index (SYI) through various predictor variables (Rai et al. 2013)

Predictor variables	Constant	Coefficient	R^2	P model
Total organic carbon (g kg^{-1}soil)	0.462** ± 0.031	0.008** ± 0.002	0.74	0.0060
Very labile carbon (g kg^{-1} soil)	0.488** ± 0.031	0.016* ± 0.005	0.63	0.0178
Recalcitrant carbon (g kg^{-1} soil)	0.462** ± 0.031	0.033** ± 0.008	0.74	0.0060
Active carbon pool (g kg^{-1} soil)	0.483** ± 0.035	0.011* ± 0.004	0.60	0.0230
Passive carbon pool (g kg^{-1} soil)	0.460** ± 0.028	0.022** ± 0.005	0.78	0.0036
Carbon management index	0.475** ± 0.033	0.0002* ± 0.00006	0.67	0.0123
Carbon management index subsurface layer	0.450** ± 0.022	0.0003** ± 0.00005	0.87	0.0008
SMBC (g kg^{-1} soil)	0.329** ± 0.072	0.0004* ± 0.0001	0.68	0.0114
Dissolved organic carbon (g kg^{-1} soil)	0.446** ± 0.045	0.0009*	0.62	0.0200
Potentially mineralizable carbon (g kg^{-1} soil)	0.418** ± 0.042	0.001 ± 0.0002	0.74	0.0064

*P<0.05; **p<0.01

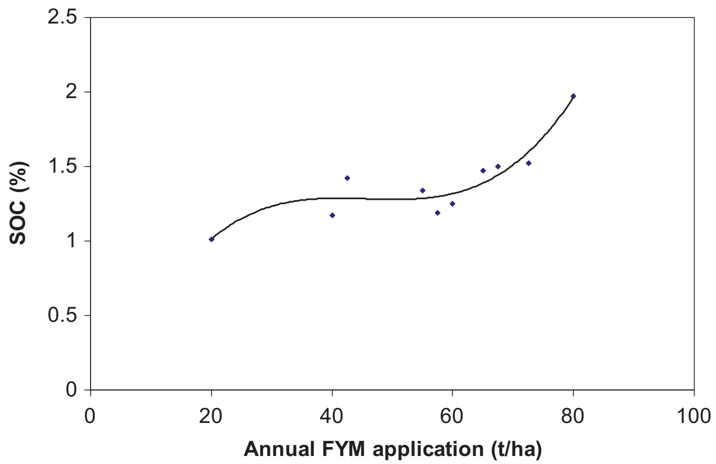

Fig. 22.3 Effect of different rate of annual FYM application for 5 years on SOC (%) content of soil (Rai et al. unpublished)

effect of guinea grass on SOC enrichment. SOC also increased in NPK-treated plots, but statistically it was at par with control. All the FYM-treated plots have significantly higher SOC and TOC content. Rate of SOC build-up showed third-degree polynomial relationship with FYM application (Fig. 22.3). SOC of the soil was related with rate of FYM application as $Y = -0.01 + 0.085X – 0.0019X^2 + 0.0000145\ X^3$ ($R^2 = 0.99$**), where Y = SOC in % and X = rate of FYM application (tons ha^{-1} $year^{-1}$).

The second derivative of the equation showed the rate constant for SOC build-up. The rate constant was 45.9 t ha^{-1} year^{-1} for initial 5 years for 1% increase in SOC content over the initial value of 0.22%. The dry forage yield showed response to different SOC levels and critical SOC level during the initial period was 0.8% (Fig. 22.4).

Interestingly guinea grass-based cropping system and FYM application contributed more SOC in active C pools (Fig. 22.5). However, in NPK fertilizer-treated system passive C pools were higher than the control. This shows the slower rate of

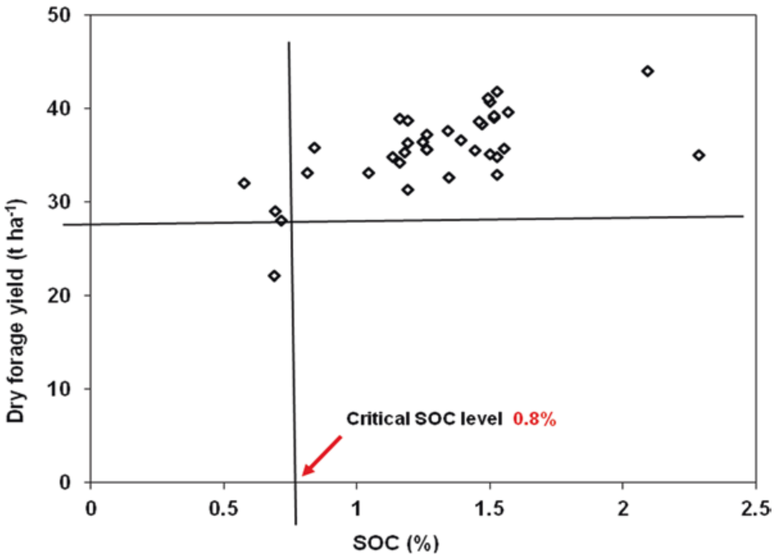

Fig. 22.4 SOC and dry forage yield plot showing critical SOC level for getting response of FYM application (Rai et al. 2013)

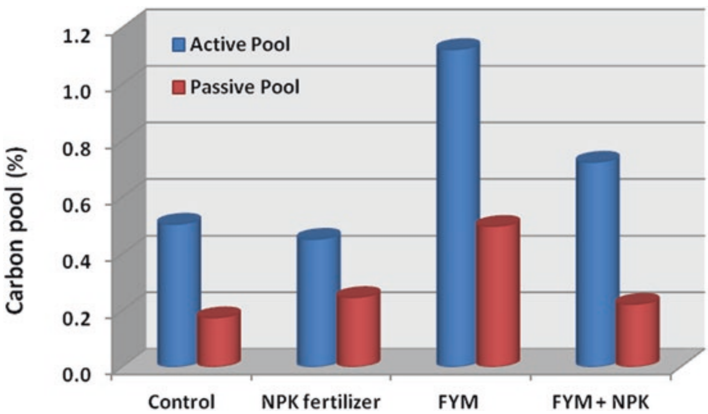

Fig. 22.5 Change in carbon pool of different treatments (Rai et al. 2013)

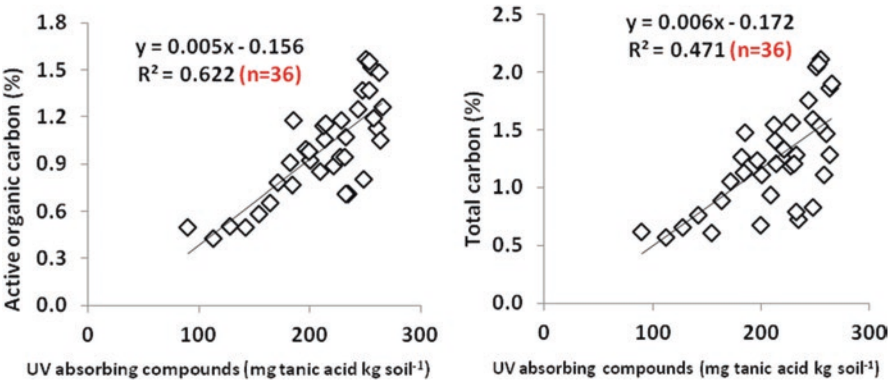

Fig. 22.6 Relation between active organic carbon (AOC), TOC, and 0.5 M K_2 SO_4 extractable UV-absorbing compounds (Rai et al. 2013)

Table 22.4 Effect of nutrient management in sorghum on SOC content (Kumar et al. 2005)

Treatments	TOC (g kg soil^{-1})	TOC build-up rate (g kg^{-1} year^{-1})
Control	4.12	−0.09
Vermicompost (10 Mg ha^{-1})	5.99	0.58
FYM (10 Mg ha^{-1})	5.32	0.31
80 kg N + 40 kg P_2O_5	4.92	0.22
40 kg N + 20 kg P_2O_5 + Vermicompost (5 Mg ha^{-1}) + FYM (5 Mg ha^{-1})	6.12	0.62

decomposition of SOC in fertilizer-treated soils. In contrast, UV-absorbing compounds (UVAC) correlated well with the active organic carbon (AOAC) pool in different soils can be utilized for quick estimation of AOC (Fig. 22.6).

In fodder sorghum-based cropping system, the TOC content declined due to continuous cropping of sorghum for 3 years without any addition of nutrient (Table 22.4). Application of nutrients through fertilizer/manures alone or in combination, however, resulted in a reverse trend. Application of 40 kg N + 20 kg P_2O_5 + Vermicompost (5 Mg ha^{-1}) + FYM (5 Mg ha^{-1}) resulted in highest TOC build-up rate in comparison to other treatments in sorghum-based system. Similarly in hybrid napier, application of nitrogen fertilizer alone or in combination with FYM and cakes resulted in 1.14–1.71 time increase in TOC (Tripathi and Hazra 1986). The regression equation developed between TOC and dry forage yield explains 58.2% variability in TOC of the soil (Fig. 22.7). Phosphorus application in berseem crop resulted in significant increase in dry forage yield and SOC stock of the soil (Fig. 22.8). Berseem–cowpea was the most suitable intercrop followed by sunn hemp and guar. Application of 150 kg N ha^{-1} resulted in 1.13–1.27 times increase in TOC content in soil in 3 year.

Pathak et al. (2011) described about the potential of different forage-based cropping system on SOC concentration, SOC stock, and SOC build-up under inorganic

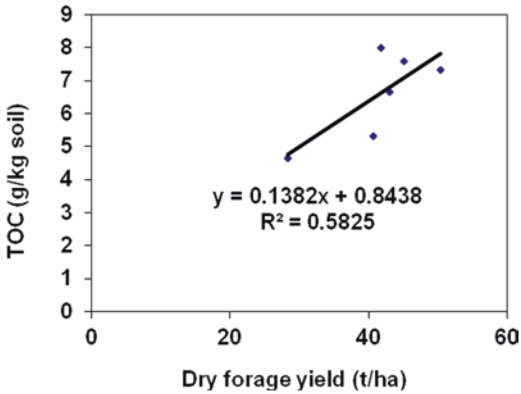

Fig. 22.7 Relation between biomass production and TOC content of soil (Tripathi and Hazra 1986)

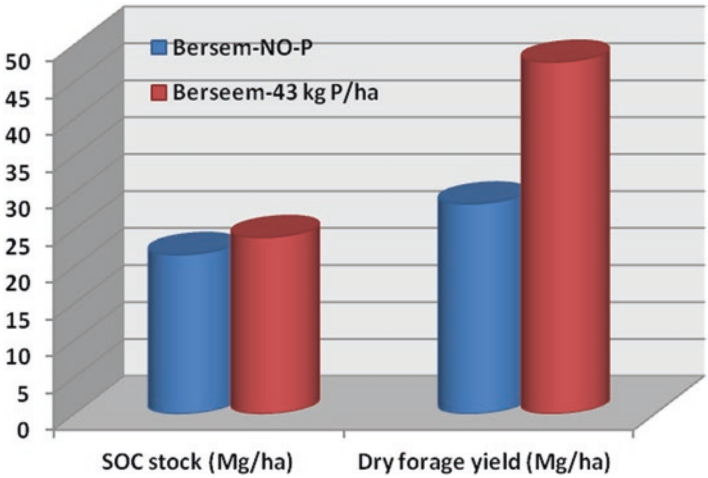

Fig. 22.8 Effect of P fertilization to berseem on SOC storage and dry forage yield. (Hazra and Tripathi 1986)

and integrated nutrient management practices across the country under different soil orders (Table 22.5). The observed database specifies disproportionate rate of build-up of SOC under different cropping systems. NPK fertilization depleted 0.7 and 1.7 g kg^{-1} compared to inherent SOC status in rice (R)–berseem (B) and pearl millet-based cropping system in Eastern and Western India, respectively, whereas integrated nutrient management nearly maintained the status of SOC in R–B system. NPK fertilization maintained the stable amount of SOC in soils both soybean (S)–wheat (W)–maize (M) (F) in Central India and finger millet (FM)–maize (M)–cowpea (C) (F)-based cropping system in Coimbatore of South India.

Table 22.5 Long-term effect of cultivation on SOC status and build-up in different forage-based cropping system across the country (Pathak et al. 2011)

Cropping system/location	BD (Mg ha^{-1})	Initial SOC (g kg^{-1})	Final SOC (g kg^{-1})		Final SOC stock (Mg ha^{-1})		SOC build-up rate (Mg ha^{-1} year^{-1})	
			NPK	NPK + FYM	NPK	NPK + FYM	NPK	NPK + FYM
Rice–berseem (20 years) Kalyani; Inceptisols; subtropical Eastern India	1.2	7.7	7.0	7.9	16.1	18.2	0.04	0.09
Soybean–wheat–maize (F[a]) (28 years); Jabalpur; Vertisols; Central India	1.5	3.2	3.4	5.0	10.0	14.7	0.02	0.12
Finger millet–maize–cowpea (F) (20 years) Coimbatore; Inceptisols; hot dry semiarid climate	1.5	5.7	5.6	6.8	16.2	19.7	0.10	0.10
Pearl millet (20 years); SK Nagar; Entisols; Western India	1.5	4.3	2.0	2.4	6.0	7.2	0.06	0.05

[a]F-fodder crop

Table 22.6 The calculated critical C input (in Mg ha^{-1} year^{-1}) for a zero change in SOC for soils under forage-based cropping system across the country

Cropping system	Predominant agroecology	Critical C input	Recalculated from
Pearl millet–cluster bean–castor	SK Nagar; Entisols; Western India (18 years)	3.3	Srinivasarao et al. (2011)
Rice–fallow–berseem	Kalyani; Inceptisols; subtropical Eastern India (20 year)	3.3	Majumder et al. (2008)
Finger millet–maize–cowpea (F)	Coimbatore; Inceptisols; hot dry semiarid climate (37 year)	4.4	Gupta Choudhury (2010)
Finger millet	Bangalore; Alfisols; Semiarid tropical South India (27 year)	1.1	Srinivasarao et al. (2012a)
Winter sorghum	Solapur; Vertisols; semiarid tropics of Central India (22 year)	1.1	Srinivasarao et al. (2012b)

22.2.3 Critical C Value for Forage-Based System

Organic amendments and crop residues facilitate build-up of C stock in soil. Several attempts have been made by different groups for defining the critical value input of C in different forage-based cropping system (Srinivasarao et al. 2011, 2012a, b; Majumder et al. 2008; Gupta Choudhury 2010). The estimated critical C input values varied widely among the cropping systems, soil orders, and agroecological zones (Table 22.6). Data depicted that for maintaining the zero change of C values, more amount of external C input is required for intensive cropping system [finger millet–maize–cowpea (F), 4.4 Mg ha^{-1}; pearl millet–cluster bean–castor, 3.3 Mg ha^{-1}] compared to less intensive [rice–fallow–berseem, 3.3 Mg ha^{-1}; rice–horse gram, 2.3 Mg ha^{-1}] or monocropping systems [finger millet, 1.1 Mg ha^{-1}; winter sorghum 1.1 Mg ha^{-1}]. Additionally, varying rate of decomposition of organic C in soil under different climatic conditions of temperature, humidity, precipitation, and aridity under different agroecological zone may facilitate this discrimination. So, adoption of suitable cropping system may help to maintain zero change or build-up of C in soil and maintain soil health.

22.3 Conclusion

Forage-based cropping practices are reported to have mixed effects on C storage and stability in farmland soils. Better adaptability, fast growth, high biomass production, and greater belowground biomass addition by grasses and legumes make the fodder-based production system ideal for carbon sequestration in different land-use systems. High-diversity mixtures of perennial grassland stored five to six times more soil C and N than monoculture plots of the same species. Increased biomass productivity of the pastures showed linear association with increase in the TOC content and SOC stock in the surface soils. Choice of crop species plays an important role in maintaining the SOC stock. Among the cropping systems, perennial grass-based land-use system had high SOC stock in comparison to seasonal crops.

The quality and quantity of the residues returned to the soil also impact the stocks and the turnover or the mean residence time in the soil. Productivity and soil fertility of the natural grassland and pastures can be improved by proper nutrient management and introduction of the range legumes such as *Macroptilium lathyroides*, *Siratro*, and *Stylosanthes*. The estimated critical C input values varied widely among the cropping systems, soil orders, and agroecological zones. For maintaining the zero change of C values, more amount of external C input is required for intensive cropping system compared to less intensive or monocropping systems.

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Part V

Frontier Science Regulating SOC Storage

23 Developments in Measurement and Modelling of Soil Organic Carbon

D. K. Benbi and Shahida Nisar

Abstract

Soil organic matter (SOM) plays an important role in maintaining soil quality, agriculture productivity, ecosystem functionality, as well as in environment moderation. Besides quantity, the composition of soil organic matter is vital for understanding the mechanism of carbon (C) sequestration in soils. A number of methods, with several variants, have been proposed to measure and characterize SOM. Conventional methods of soil organic carbon (SOC) measurement are not only laborious and time-consuming but also suffer from issues related to spatial variability. In the last few decades, several new methods including in situ techniques have been developed to minimize the uncertainties associated with the conventional procedures. Besides being more sensitive, the in situ techniques provide the possibility of repetitive and sequential measurements for spatial and temporal evaluation of soil C stock on a large scale. However, these methods are still evolving and pose some procedural limitations. Models have been used to overcome some of the problems associated with measurements and to upscale point measurements at different levels of spatial aggregation. Organic matter turnover models have been used to predict C sequestration potential of soils, assess and identify appropriate land-use and best management practices for C sequestration and to predict climate change effects on SOC. However, application of these models is constrained because of the lack of detailed spatial data, leading to the development of protocols for reducing input data requirements. In this chapter, we trace the developments in measurement and modelling organic matter dynamics in soils.

Keywords

Carbon dynamics · Measurements · Modelling · Soil organic carbon · Temperature sensitivity

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23.1 Introduction

Concentration of carbon dioxide (CO_2) in the atmosphere has increased globally from 278 parts per million (ppm) in the pre-industrial era to 409 ppm in 2017 (NOAA 2017) and is currently increasing at an average rate of ~4 Pg C year^{-1} (IPCC 2013). The increasing concentration of CO_2 in the atmosphere causes global warming and depletes the stratospheric ozone. International efforts are underway to develop strategies for mitigating climate change and set goals for limiting global warming. The COP21 or the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change agreed to limit atmospheric increase of temperature to less than 2 °C compared to pre-industrial levels. As compensation for the anthropogenic emission of greenhouse gases a goal of increasing soil organic matter (SOM) stocks by 0.4% per year has been set. To meet this goal, a voluntary action plan to implement farming practices that maintain or increase soil C stocks in agricultural soils is required (Chambers et al. 2016). The soil C pool is estimated to be about 2400–2500 Pg C, which is approximately three times greater than the atmospheric pool (840 Pg C) (IPCC 2013). Historically, soils have lost about 55–78 Pg C, and thus offer a significant sink for C storage (Nieder and Benbi 2008). It is estimated that soils have the potential to offset atmospheric load of CO_2 by ~135 Pg (Lal 2018). Therefore, C sequestration in soil seems a viable option for stabilizing atmospheric abundance of CO_2 till alternative strategies for mitigation are made available. The rate and magnitude of C sequestration in soil besides depending on soil properties, climatic conditions, land-use and management is influenced to a great extent by antecedent C level. Therefore, monitoring of soil organic C level is a prerequisite to evaluating the impact of management and land-use on soil C sequestration.

Besides environment moderation, SOM plays an important role in maintaining soil quality and ecosystem functionality. Land-use and agricultural management practices influence the storage of soil organic carbon (SOC) due to differences in cropping practices, tillage, irrigation, fertilization, etc. Greater C sequestration in soil has co-benefits of restoring soil fertility, improving crop productivity, reducing erosion and loss of nutrients. However, it is not only the quantity but also the composition of organic matter that is important for understanding nutrient fluxes and the mechanism of C sequestration in soils. It is well-recognized that C fluxes in soil may be better understood by isolating active/labile and recalcitrant/non-labile pools of SOM by physical, chemical and biological techniques. A number of methods, with several variants, have been proposed to enumerate SOM sub-pools. However, for comparison of results among different studies and to develop repositories of soil C stocks at different levels of spatial aggregation, it is important to adopt standard protocols. Another problem with the measured SOC is its large variation because of spatial variability, which most often leads to impossible mass balance between sampling times. Increased sampling size, large sampling intervals and modelling can help in overcoming some of these problems (O'Leary et al. 2015). Standards need to be defined for sample collection, preparation and analysis. Past meetings and the proceedings of several symposia and workshops have shown the need for standard procedures to measure different C pools and flux rates, and the need to model and predict agricultural management effects on changes in SOC. There is an additional need to upscale point data to farm, regional, national and global levels with the help of models. Linking measured SOC dynamics with soil C modelling can improve quantification of soil C stocks and in understanding the mechanisms of its stabilization. In this chapter, we trace the developments in measurement and modelling organic matter dynamics in soils.

23.2 Measuring Soil Organic Carbon Stocks

Soil organic C is the result of the balance between C inputs and outputs (Fig. 23.1). Carbon inputs include plant residue, root biomass and exogenous materials and outputs occur through decomposition, leaching of water-soluble components and soil erosion. The decomposition of SOM is influenced by temperature, soil water and clay content. Only a small portion of the organic input is finally converted to the stable form of SOC, known as humus. Management practices or technologies that increase C input to the soil and reduce C loss or both, lead to net C sequestration in soils. To identify best management practices (BMPs) that lead to C sequestration in soils, it is necessary to evaluate the impact of an agricultural management and land-use practice on changes in SOC stocks. Generally, one or more of the following approaches is used for determining C sequestration in soil: (1) repeated measurement of SOC stocks at the same location over a period of time (chronosequence studies), (2) quantification of the differences in SOC stock between the new practices and 'control' treatment or a reference land-use that is assumed to present status quo, (3) mass balance studies in which all inward and outward C fluxes from the soil are quantified over a specified time period, and (4) measurement of changes in some sensitive soil C pool or fraction, which may provide early indications of long-term changes in total C stocks. Chronosequence studies require long-term measurements, at least 5–10 years before significant changes in SOC stock are discernible as the annual C inputs and outputs are relatively small compared to soil C stocks. In the

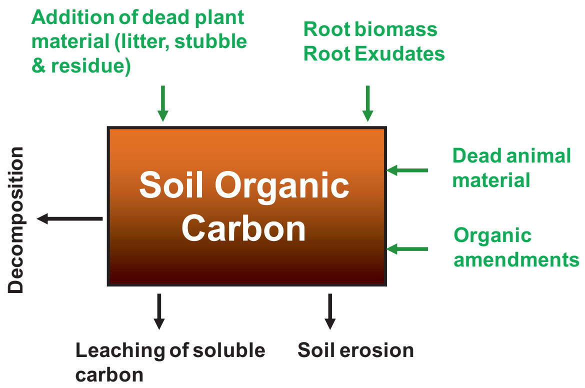

Fig. 23.1 Input and outputs of soil organic carbon

short term, the differences are either not discernible or are too variable to be reliable. Sometimes differences in SOC between two consecutive years can be more than 30 times the mean rate of change (Chan et al. 2011). For short-term (<5 years) monitoring, the mass balance approach and measurement of sensitive soil C pools may be preferable, whereas the chronosequence approach will provide more reliable information in the long term. Mass balance approach has the limitation that some of the fluxes such as root exudates, respiration, etc. are difficult to quantify. Another problem in monitoring SOC for quantifying soil C sequestration is the measurement and definition of the plant material that is returned to the soil. This is a major C input that drives the microbial processes for soil C turnover. Large differences exist between crop residues left on the surface to those that are effectively incorporated into the soil.

Considerable progress has been made in measurements of SOC and a number of methods are available for determining SOM and SOC concentration, each with distinct advantages and disadvantages. The commonly used methods include (1) oxidation of organic matter with hydrogen peroxide, (2) loss on ignition, (3) wet digestion, and (4) dry combustion. While the first two methods provide direct estimates of SOM, the latter two methods are used to determine organic C. The method based on oxidation with hydrogen peroxide is mainly suitable for soils devoid of manganese dioxide and the loss on ignition method is more suitable for high organic carbon soils (>15%). The major limitation in peroxide digestion method is incomplete oxidation of organic matter and loss of volatile organic compounds if samples are air or oven-dried prior to digestion (Santisteban et al. 2004; Cresser et al. 1991). The loss on ignition method, apart from being time-consuming, does not account for loss of water held in soil minerals during heating, thus affecting the weight difference. For soils containing inorganic carbon it is assumed that organic matter is oxidized at lower temperatures than carbonate C. While most carbonates are stable at temperatures up to 500 °C, $MgCO_3$ may decompose at temperatures below 400 °C. Thus, loss on ignition method is not suitable for samples containing carbonates as well as stable SOM compounds.

Wet combustion analysis of soil by chromic acid digestion has long been a standard method for determining total C. The primary limitation associated with this method is inefficiency of dichromate to oxidize recalcitrant C forms such as charcoal, graphite and soot, and trapped C in soil aggregates (Tivet et al. 2012; Hussain and Olson 2000; Nelson and Sommers 1996). The wet digestion method, proposed by Walkley and Black (1934), is commonly used in several laboratories as it needs minimum equipment. The method is based on oxidation of SOC by potassium dichromate ($K_2Cr_2O_7$) in the presence of sulphuric acid (H_2SO_4). The dilution of H_2SO_4 provides heat for the oxidation reaction but only about 75% of SOC reacts with $K_2Cr_2O_7$. In order to estimate total organic C in soil, the SOC determined by the Walkley and Black method is multiplied by a recovery factor of 1.33. Several studies have shown that this conversion factor is not constant and varies (1.4–3.3) depending on soil type, soil depth and management; thus leading to large uncertainties in total organic C estimates (Nelson and Sommers 1996). Modifications to wet digestion method include using salts to reduce interferences and applying external heat to achieve complete oxidation of SOM. However, the time and temperature of heating have to be standardized to ensure complete oxidation of SOM (Benbi 2018). Recently, a simple method involving wet digestion of $K_2Cr_2O_7$-H_2SO_4-soil mixture in a microwave oven followed by spectrophotometric measurement of Cr (III) was found successful in determining total organic carbon in soil and it yielded results similar to the dry combustion method (Benbi 2018). Dry combustion method is based on thermal oxidation of organic C and decomposition of inorganic C to CO_2 at temperature between 1000 and 1600 °C. The method does not differentiate between organic C and inorganic C present in charcoal, coal and other non-humus materials. Carbonates if present in the sample have to be removed, prior to analysis, by acid pre-treatment. However, there is a possibility of losing SOM during acid treatment. Different automated instruments determine total C, N and H in soils in the presence of O_2 and chromium dioxide (CrO_2, as catalyst) at 1700–1800 °C. In this method, soil sample is oxidized in the presence O_2 in a combustion tube. The oxidized C, N and H are carried by He gas carrier into a tube maintained at 650 °C and then brought to constant pressure and volume in a gas mixing chamber where gases are allowed to expand into the analyzer portion of the instrument. The analyzer consists of three thermal conductivity detectors connected in series and separated by two traps to quantify H, C, and N. The automated dry combustion method is most widely used as it is more accurate and it is possible to handle a variety of samples, including solids, liquids, volatile and viscous samples. Dry combustion with automated analyzers can also be used to determine total C or SOC in non-calcareous soils. In addition to wet and dry combustion, several techniques based on spectral properties of the soil are being used under laboratory conditions (Stevens et al. 2006; Bellon-Maurel and McBratney 2011).

The wet and dry combustion methods are based on ex situ measurement of soil C necessitating destructive sample collection and preparation, which is not only laborious and time-consuming but also subject to spatial and temporal variability (Ellert et al. 2001). Further, these methods provide C concentrations (weight percentages) and information on soil bulk density is required to express data on volume or area basis (C stocks) for estimating C sequestration in soil. Measurement of soil bulk density per se presents similar sampling challenges as for soil C sampling. Therefore, development of methods for soil C analysis that minimize the uncertainties associated with conventional methodologies are important for improving estimates of C sequestration in soils. Consequently, in the last two decades, research efforts have focused on developing or standardizing methods for in situ measurement of SOC. A variety of spectroscopic and remote sensing methods such as inelastic neutron scattering (INS) and gamma-ray spectroscopy (Wielopolski et al. 2000; Wielopolski et al. 2003), mid- and near-infrared and diffuse reflectance spectroscopy (MIRS, NIRS, DRIFTS) (Reeves et al. 2006; McCarty et al. 2002), remote sensing imagery (Chen et al. 2000) and laser-induced breakdown spectroscopy (LIBS) (Ebinger et al. 2003; Gehl and Rice 2007) have been proposed for measurement of SOC. Besides high sensitivity, these techniques provide the possibility of repetitive and sequential measurements for spatial and temporal evaluation of soil C stock at a large scale and thus circumvent some of the problems associated with

Table 23.1 Methods for in situ measurement of soil carbon

Technique	Methodology	Advantages	Disadvantages
Infrared and diffuse reflectance spectroscopy (MIRS, NIRS, DRIFTS)	Based on infrared spectroscopy in which diffused radiations by illuminated soil are used to measure inorganic and organic soil C	Rapid, cost-effective and simple in operation, measures different soil C fractions	Particle size, soil moisture and carbonate content affect spectral absorbance in the NIR interpretations
Laser-induced breakdown spectroscopy (LIBS)	Measures total and organic C based on atomic emission spectroscopy	Rapid, efficient, minimum soil disturbance, and can distinguish between total soil C, inorganic and organic C	Interference by presence of fine roots and other biological substances in the sample; spatial variability associated with small point sample
Inelastic neutron scattering (INS) and gamma-ray spectroscopy	Measures total soil C from intensity of gamma rays emitted from inelastic scattering of C neutrons	In situ analysis on a large spatial scale	Instrument and transport costs are high, and requires radiological control licenses and appropriately trained personnel
Remote sensing imagery	Direct measurement of soil C by remote sensing principles	Soil C is measured over a large area; soils from different parent materials can be distinguished based on C content	Complications arise due to dependence of soil color and reflectance on many other soil physical and chemical properties, management practices and presence of vegetation and surface organic residues

MIRS mid infrared spectroscopy, *NIRS* near infrared spectroscopy, *DRIFTS* diffuse reflectance spectroscopy

sampling schemes and collection and preparation of samples. However, these methods are still evolving and present some instrumental and procedural limitations (Table 23.1).

23.3 Characterizing SOM Composition and Turnover: The Pool Approach

Soil organic matter is a heterogeneous mixture of decomposed and partially decomposed substances of organic molecules such as polysaccharides, lignin, aliphatic biopolymers, tannins, lipids, proteins and amino sugars, derived from plant litter, faunal and microbial biomass (Totsche et al. 2010). The traditional approach for characterizing organic matter includes fractionating SOM into humic acid, fulvic acid and humin, primarily based on their solubility at different pH values. Though this approach is useful for understanding soil formation and development yet it has little relevance to SOM turnover and soil functions. In order to characterize SOM in terms of ease (lability) or resistance (recalcitrance) to decomposition several chemical and physical fractionation methods have been proposed. Chemically extractable SOC pools are based on solubility of certain organic compounds in different solvents and the extracting solutions, which range from water and salt solutions to strong acids. Commonly used chemical methods include water-extractable organic C, hot water soluble C, $KMnO_4$-oxidizable C, and organic C fractions of different oxidizability. Though most of these pools are positively related to each other yet the amount extracted by each method differs considerably, suggesting that each method enumerates a different fraction of SOC (Benbi et al. 2015). Water extractable organic carbon (WEOC) comprising a small fraction of SOC includes uncomplexed and readily mineralizable C consisting mainly of carbohydrates derived from plant roots, microorganisms, amino acids, humic substances and rarely from phenol and lignin monomers, proteins and chitin (Cambardella and Elliott 1993). The WEOC is closely related to microbial biomass (Balaria et al. 2009), cellulose, hemicellulose and lignin contents (Klimanek 1997). Hydrolysis with mineral acids (HCl or H_2SO_4) simulates the stability of SOM against hydrolytic decomposition caused by extracellular enzymes of soil microorganisms. Acid hydrolysis distinguishes between hydrolyzable (active) and non-hydrolyzable (resistant) C fractions. The hydrolyzable fraction is comprised of proteins, polysaccharides, and nucleic acids, and some carboxyl C (Schnitzer and Khan 1972; Schnitzer and Preston 1983; Rovira and Vallejo 2007; Preston and Schnitzer 1984), while non-hydrolyzable fractions contain mainly lignin, fats, waxes, resins and suberins (Paul et al. 1997; Rovira and Vallejo 2007). The extractable pools of SOM exhibit variable sensitivity to land-use and management; for instance, in rice-wheat system, water extractable C has been found to be more sensitive to management than the other extractable pools (Benbi et al. 2015). The organic C fractions of different oxidizability and their ratios have been used to discern the effect of land-use on C stabilization in soils (Benbi et al. 2014b). The labile pools not only serve as early indicators of management-induced changes in SOM but are also considered indicators of soil quality.

Organic matter turnover in soil depends not only on the chemical nature of the substrate but also on its proximity to soil microbes and the nature of its association with the soil's mineral components (Christensen 2001). In the last three decades, several physical fractionation schemes according to size and/or density have been proposed for the study of SOM functions and its turnover in soil (Balesdent et al. 1988). These fractions vary in turnover times ranging from months to hundreds of years (Table 23.2). The fractionation schemes are usually based on the degree of physical protection or occlusion within aggregates and formation of organo-mineral complexes (Degryze et al. 2004; Golchin et al. 1994; Sollins et al. 2006). Primarily, SOM is differentiated into two main fractions, viz. particulate organic matter (POM) and organo-mineral complexes. Particulate organic matter may further be differentiated into coarse (>250 μm) and fine (53–250 μm) fractions. Particulate organic matter representing uncomplexed organic matter such as plant residues in various stages of decomposition along with microbial biomass and microbial debris has been shown to be a sensitive indicator of management effects on SOC (Benbi et al. 2012).

Table 23.2 Turnover times of different fractions of soil organic matter (Lal 1997)

Organic matter pool	Turnover time (years)
Microbial biomass	0.1–0.5
Litter and crop residues	1–8
Light fraction	2–15
Particulate	2–20
Inter microaggregate	20–50
Intra macroaggregate	50–1000
Intra microaggregate	1000–3000

The organo-mineral complexes, which include physically and chemically stabilized organic C have low bioavailability and long turnover times and are thus resistant to decomposition (Parton et al. 1987; Six et al. 2002b; Krull and Skjemstad 2003; Benbi et al. 2012). A number of studies have shown that the turnover time of POM is lower than for mineral-associated organic matter. The POM has wider C/N ratio and the ratio narrows down as the SOM fractions degrade into finer particle size, suggesting that the crop and organic amendments derived C is first transferred to POM, which on decomposition is progressively stabilized into silt and clay-sized fractions. Therefore, SOC within the sand fraction is allocated to the active pool and SOC in silt and clay fractions to the intermediate and passive pool (von Lützow et al. 2007).

Some methods combine size and density fractionation to isolate multiple, spatially explicit SOM pools that have distinct functional roles in nutrient cycling and stabilization mechanisms (Jastrow 1996; Six et al. 2002b). Density fractionation of SOM is achieved using liquids of specific gravity 1.6–2.0 g cm^{-3}. A specific gravity of 1.6–1.8 g cm^{-3} is generally preferred to maximize the recovery of plant-like POM and exclude the most of mineral and organic material from the light fraction. However, dispersing soils in high density liquid or in sodium hexametaphosphate could result in losses of organic C during separation. Six et al. (2002a) proposed a physical fractionation scheme that could isolate four SOM pools suitable for inclusion in SOM turnover models. In a first step, coarse non-protected POM, microaggregates, and silt plus clay associated C are isolated from 2 mm air-dried sieved soil. The method involves a complete break-up of macroaggregates without breaking up microaggregates, which are then separated by sieving. In a second step, fine non-protected POM that is collected together with the microaggregates on the sieve is isolated by density flotation. Subsequently, microaggregates are dispersed to isolate microaggregate protected POM versus silt and clay associated C. The silt and clay associated C fractions from both the steps are then hydrolyzed to differentiate the silt plus clay protected C versus biochemically protected carbon. Virto et al. (2010) used combined physical and density fractionation approach to isolate occluded and non-occluded organic matter at the silt-size scale. The fractionation scheme comprises three consecutive steps: (1) dispersion of the whole soil sample and recovery of the completely dispersed sand-size fraction, non-aggregated clays and the silt-size fraction containing slaking-resistant silt-size aggregates, (2) density fractionation of the silt-size fraction to recover slaking resistant aggregates, and (3) dispersion of such aggregates and separation of their constituents. Benbi et al. (2012) employed size and density flotation techniques to study nutrient management effects on organic C distribution among various physical fractions in rice-wheat system. Light fraction POM was most sensitive to management, followed by sand-sized heavy fraction organic matter and silt and clay-sized mineral associated organic matter suggesting that these may be considered to represent active, slow and passive pools, respectively. Short-term soil C mineralization is shown to be positively related to particulate organic C; however, light fraction exhibits a stronger relationship compared with other fractions (Fig. 23.2) suggesting that it could be a better indicator of management-induced changes in SOM (Benbi et al. 2012). A recent inter-laboratories comparison of several SOC fractionation schemes showed that even after 36 years, no method was able to isolate a fraction with more than 76% turnover, which poses a challenge to link the most active plant-derived C pools in models. Therefore, a comprehensive comparison of methods to separate the bulk SOC into fractions with varying turnover rates needs a more systematic approach to confirm these results (Poeplau et al. 2018). In addition to the traditional pool approach, advanced analytical techniques such as pyrolysis (McCarty and Reeves 2001), carbon isotope analysis have been used to estimate composition, retention time and C turnover rates in soils (Paul et al. 2001).

Besides physical accessibility of SOM to decomposers and the nature of its association with the soil's mineral components, SOM turnover depends on microbial and biochemical activity in soil. Based on microbial activity, SOM is divided in different pools according to biological stability, decomposition rate, and turnover time (Table 23.3). Some biological pools such as soil microbial biomass and mineralizable C have been suggested as sensitive indicators of land-management effects

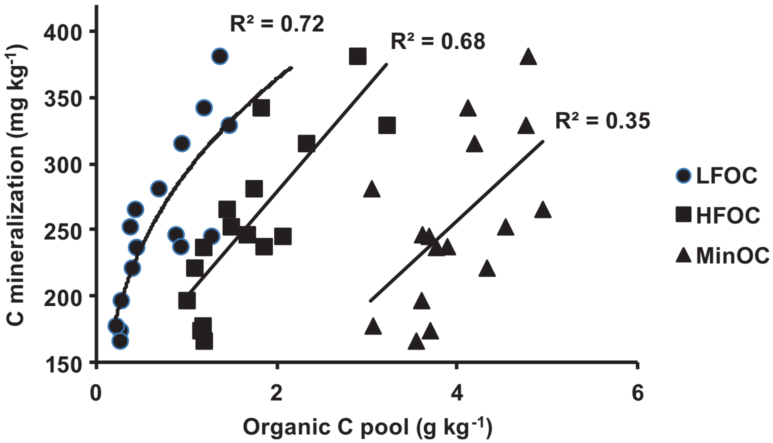

Fig. 23.2 Relationship of C mineralization with light fraction (LFOC), heavy fraction (HFOC) and mineral associated (MinOC) organic carbon in soil (Benbi et al. 2012)

Table 23.3 Classification of SOC pools based on their stability (Baldock 2007)

Stability measure	Pool category		
Biological stability	Labile (active)	Non-labile (stable)	Recalcitrant (passive)
Decomposition rate	Fast	Slow	Inert
Turnover time or mean residence time (MRT)	Days to years	Years to decades	Decades to millennia
Example	Surface plant residue and buried plant residue, root exudates; particulate organic matter	Well-decomposed organic material associated with soil particles (humus)	Charcoal or charred materials resulting from burning of organic matter

on organic matter turnover in soil (Powlson et al. 1987; Haynes 2005). Several direct and indirect methods have been developed for determination of microbial biomass in soils including direct microscopic counts, substrate-induced respiration (SIR) and CO_2 production, fungal estimation, phospholipid fatty acids (PLFA) analysis, ATP analysis, DNA measurements, fluorescence in situ hybridization (FISH), and chloroform fumigation. Soil DNA analysis is considered to be the most important and precise tool for a better understanding of soil microbial functionality and inter-relationships among them. The commonly used chloroform fumigation (Jenkinson and Powlson 1976; Vance et al. 1987) and substrate-induced respiration (Anderson and Domsch 1978) methods measure total soil microbial biomass and do not distinguish between active and inactive components. Active fraction of the microbial biomass largely governs the organic matter decomposition and nutrient transformations in soil, and may serve as a good predictor of early changes in soil health (Nordgren et al. 1988).

Soil organic matter serves as a substrate for microorganisms that foster soil enzyme activities. Burns et al. (2013) labelled extracellular enzymes as proximate agents of organic matter decomposition whose production is coordinated with nutrient and energy supplies and demand. SOM is synthesized as well as degraded by microbial enzyme activities. The balance between these two competing processes determines how much C is sequestered. Decomposition of SOM has been studied by measuring the activities of C cycle enzymes and those representing overall soil microbial activity, including cellulase, β-glucosidase, xylanase, filter paperase, invertase, dehydrogenase and fluorescein diacetate hydrolysis (Stemmer et al. 1999; Allison and Jastrow 2006; Yu et al. 2012). Benbi et al. (2016) developed a regression model involving dehydrogenase, xylanase and cellulase along with microbial biomass C and clay content to predict SOC content in alluvial soils of Indo-Gangetic plains. Evidently, information on soil enzyme activities and microbial community composition, both of which mediate SOM degradation, can help identify and assess the intensity of the processes involved in the decomposition of SOM (Benbi et al. 2014b, 2015).

23.4 Modelling Soil Organic Carbon Dynamics

Carbon dynamics in soil are complex and exhibit strong spatial and temporal variability (Sleutel et al. 2006). The changes in SOC are slow to occur and it takes several years before the effects of land-use and management are measurable. Consequently, modelling has been used for simulating organic matter dynamics and predicting the impact of land-use and management on changes in SOC stocks. A number of models, differing in level of detail and complexity, have been developed and used under different soil, crop and climatic conditions. The models range from simple empirical formulations involving exponential decay functions to complex biogeochemical models that describe soil and plant processes at different spatial and temporal scales (Table 23.4). Though majority of the commonly used models employ compartmentalization approach, yet models with a continuous structure (e.g. Bosatta and Ågren 1985) have been developed presuming that SOM is represented by a changing continuum. In such models, the decomposition is described by a continuous quality equation involving growth rate of decomposers, efficiency of C utilization by decomposers, and a transition probability between different states (Bosatta and Ågren 2003). Despite the obvious advantage of continuum approach, its use is limited because of complex mathematics. The multi-compartment models differentiate organic matter into conceptual or imaginary pools and the decomposition of organic matter in each pool is assumed to follow first-order kinetics. However, emerging models define SOM pools based on specific stabilization mechanism or as analytically measurable fractions to simulate short-term changes (Tipping et al. 2012; Segoli et al. 2013; Benbi and Khosa 2014; Davidson et al. 2014). A key consideration in SOM modelling is the availability of quality data for model development and evaluation. A Global Environment Facility co-financed Soil Organic Carbon (GEFSOC) Project was developed to predict land-use and management effects on changes in SOC at the national and sub-national levels. The GEFSOC involves the use of Century, RothC and the Intergovernmental Panel on Climate Change (IPCC) models (Easter et al. 2007). The system interacts with a SOTER (Soil and Terrain) database and other databases of climate and land-use to simulate SOC dynamics.

Table 23.4 Classification of models (Stockmann et al. 2013)

Model type	Applications
Empirical	Simulate annual changes in C stocks employing regression techniques; more transparent and simpler with reduced uncertainty than process based models
Process-oriented	Simulate C and N turnover in soil by partitioning soil organic matter into conceptual or imaginary pools varying in size, decomposition rate and stabilization mechanisms
Food-web chain or organism based	Simulate C and N flow through food webs and the role of soil biota on C and N mobilization, simulates specific management practices such as 'what options do farmers have for managing populations of organisms?'
Landscape	Simulate the influence of soil moisture dynamics on soil C and N dynamics such as transport of dissolved organic matter caused by erosion

The multi-compartment models sub-divide SOM into labile and resistant or stable pools each with its unique decomposition rate. The models differ considerably in structure particularly with regard to number of pools considered, influencing factors and the processes simulated (Table 23.5). The changes in SOM pools with management practices are predicted, monitored and verified under diverse conditions. Some of the most commonly used process-based models for simulations of soil C dynamics include RothC (Jenkinson 1990), DNDC (Li et al. 1992), C-TOOL (Petersen et al. 2002), EPIC (Williams et al. 1984), CENTURY (Parton 1996) and SOMM (Chertov and Komarov 1996). These models simulate different components and fluxes of C cycle in soil-plant system by incorporating the effect of various biotic and abiotic factors. For instance, RothC simulates the turnover of SOC in non-waterlogged soils by incorporating the effects of soil type, temperature, moisture content and plant cover (Farina et al. 2013). The model has been used to simulate SOC turnover in arable, grassland and forest soils in different regions of the world (Coleman and Jenkinson 1996; Coleman et al. 1997; Xu et al. 2011; Guo et al. 2012). The DeNitrification and DeComposition (DNDC) model estimates C and N biogeochemistry in agro-ecosystems. The model can evaluate SOC dynamics, sequestration potential, and greenhouse gas (GHG) emissions at regional or national scales (Kurbatova et al. 2008; Smith et al. 2004; Zhang et al. 2012; Li et al. 2003; Sleutel et al. 2006). The model also simulates crop growth and partitioning of crop biomass into roots, stems and grain. Limitations to application of DNDC model include requirement of exhaustive data and quantifying the uncertainty resulting from soil heterogeneity (Li et al. 2004, 2013; Qiu et al. 2005). The model C-TOOL (Andrén et al. 2004) simulates medium- to long-term changes in SOC by transporting C from topsoil (0–25 cm) to the corresponding subsoil pool (25–100 cm) using few parameters (Taghizadeh-Toosi et al. 2014). Changes in SOC are driven by type, quantity and application date of organic matter inputs, soil texture (clay content), soil temperature and soil C/N ratio. However, soil water is not taken as factor for SOM turnover though it has a primary role in C turnover. Therefore, the model is not applicable to soils exposed to prolonged dry seasons or water-logging. On the basis of comparative performance of nine SOM models by using long-term datasets from seven locations across a wide range of land-use, soil types and climatic conditions, Smith et al. (1997) categorized the RothC model into a group of six models performing significantly better than another group of three models. However, in semi-arid areas, RothC did not perform well and required unrealistically high C inputs to obtain good simulations (Farina et al. 2013).

Despite the development of a number of process-based models, upscaling of results from these models is constrained because of the lack of detailed spatial data particularly on soil properties. Therefore, meta-modelling, which is a statistical procedure to derive simple relationships from processes-based models, has been suggested to simplify and reduce input and increase their use at a higher spatial resolution (Kleijnen and van Groenendaal 1992). Meta-models comprise functional relationships that link the output from process-based simulation models to primary drivers with calibrated parameters. Meta-models are used for understanding critical relationships within simulation models and validating and reducing the size of

Table 23.5 Main characteristics of the process-based models (Stockmann et al. 2013)

Model	Characteristics	Applications	References
CENTURY	The SOM is divided into five pools, viz. metabolic and structural SOM (litter), active SOM, slow SOM and passive SOM	Simulates long-term SOM dynamics, plant growth and N, P and S cycling	Parton (1996)
	Soil texture (clay content) determines separation of C from AOM pool into CO_2 or slow pool	Developed for grassland, cropping systems, forests and savannas	
RothC	C turnover is simulated by assuming C flows among five pools, viz. DPM, RPM, microbial biomass, humified OM and IOM.	Applicable to arable, forest and temperate grasslands	Jenkinson (1990)
	Decomposition rate and ratio between humus, microbial biomass and CO_2 evolution depend on soil clay content	Simulates SOC dynamics under a wide range of soil and climatic conditions and agricultural management practices	
DNDC	Couples denitrification and decomposition processes both at site-specific and regional scales.	Evaluates SOC dynamics, trace gas fluxes, C/N balance, SOC sequestration potential, global warming potentials incurred by greenhouse gas emissions	Li et al. (1992)
	Divides SOM into labile and resistant microbial biomass, and labile, resistant and passive humads		
SOMM	Rate of SOM turnover depends on temperature, moisture and chemical composition of the material; SOM assumed to exist as undecomposed litter, partially decomposed litter and soil humus	Developed for forest systems to simulate SOM mineralization, humification and N release for a wide range of environmental conditions, tundra to tropical rain forest; simulates influence of soil fauna on C flux, models C accumulation in soil organic horizons	Chertov and Komarov (1996)
C-TOOL	Considers three conceptual pools: C in FOM, HUM and ROM.	Simulates medium- to long-term changes through vertical transport of SOC from topsoil (0–25 cm) to the corresponding subsoil pool (25–100 cm) using few parameters	Petersen et al. (2002)
EPIC	Pools defined are metabolic and structural litter, active humus, slow humus, and passive humus with turnover time of days to hundreds of years	Simulates methane and other greenhouse gas emissions; evaluates the impact of different cultivation practices on climate change	Williams et al. (1984)

(continued)

Table 23.5 (continued)

Model	Characteristics	Applications	References
ICBM	Divides SOM in two pools, young and old soil carbon. The model properties can be mathematically analyzed and can be run in an ordinary spreadsheet programme	Equations for steady-state conditions, i.e. when the pools are constant and the input and output balance out	Andrén and Kätterer (1997)
ITE	Developed for grassland environments; assumes decomposition rates as function of microbial biomass	Simulates N cycling in a grazed soil-plant system, and SOM dynamics are simulated by a sub-model that responds to faeces, urine and decaying plant residues	Thornley and Cannell (1992)
Socrates	Considers five pools of soil C, viz. DPM, RPM, unprotected and protected microbial biomass and humus; SOM turnover governed by soil CEC and soil microbial biomass	Estimates changes in topsoil SOC	Grace et al. (2006)
		Diversity in land-use and soil type, and wide range of datasets enables the model to assess potential C stores under agricultural (cropped and grassland) and forested ecosystems	
Struc-C	Updated and modified version of the Roth-C model	Enables link between SOC dynamics with soil structure, thus crucial to determining soil quality	Malamoud et al. (2009)
	The model comprises six pools of C, viz. DPM, RPM, mineral, microaggregates and macroaggregates associated C, and NCOC	Simulates formation of organo-mineral associations and aggregates	
Verbene	Divides SOM into DPM, SOM, RPM, microbial biomass, protected, biomass, non-protected biomass, protected, SOM, non-protected SOM, stabilized OM. Decomposition rate is modified by temperature and soil moisture, but not influenced by microbial activity and biomass	Developed for grasslands	Verbene et al. (1990)
		Simulates N dynamics and influence of clay on protection of microorganisms and soil organic components	
CANDY	Modular system combined with database system for model parameters, uses proportion of soil particles to separate active, stable and inert organic matter	Simulates soil N, temperature and water to predict N uptake, leaching, water quality	Franko (1996)
		Simulates litter decomposition, and IOM component (<6 μm)	

DPM decomposable plant material, *RPM* resistant plant material, *AOM* active organic matter, *MB* microbial biomass, *FOM* fresh organic matter, *HUM* humified organic matter, *ROM* resistant organic matter, *NCOC* Non-complexed organic C, *CEC* cation exchange capacity, *IOM* inert organic matter, *OM* organic matter simulation models (Ruben and van Ruijven 2001). Florin et al. (2011) derived an inverse meta-model from the agricultural production simulator (APSIM) to estimate soil available water capacity from available yield data in South Australia. Similarly, a RothC derived meta-model involving current SOC level, mean annual temperature, precipitation, and soil clay content was used to estimate critical C input required for maintaining SOC level in wheat producing regions of the world (Wang et al. 2016).

23.5 Modelling Decomposition Temperature Sensitivity of Soil Organic Matter

Soil respiration represents the second largest flux between ecosystems and the atmosphere and a small change in soil respiration could markedly impact atmospheric abundance of CO_2. Therefore, understanding the temperature sensitivity of SOM decomposition is important in determining the role of soils in future climate change. Generally, it is hypothesized that warming will enhance the decomposition of SOM and consequently increase the flux of CO_2 to the atmosphere (Davidson et al. 2000). Simulations with RothC model showed that the increase in global temperature will result in enhanced soil respiration rates and hence decreased soil C stocks (Niklaus and Falloon 2006). The SOC loss per degree warming may increase by 8–9% in regions with temperatures of 10–15 °C and by only 2% at 35 °C (Benbi et al. 2014a). The composition of SOM is the main factor that could influence the temperature response of organic matter decomposition. The effect of SOM composition is generally expressed in terms of decomposition temperature sensitivity of labile and stable SOC pools (Powlson 2005; Kirschbaum 2006; von Lützow and Kögel-Knabner 2009). However, the reports on the decomposition temperature sensitivity of SOC pools differ; some suggesting slow pools to be more sensitive (Knorr et al. 2005), others propose labile pools to be more sensitive (Benbi et al. 2014a), while others postulate similar responses of labile and stable SOM pools to temperature (Reichstein et al. 2005). The conflicting results from different studies may partly be due to the range of methods used to estimate decomposition temperature sensitivity of SOM, and the inability to consistently define and quantify labile and stable SOM. A variety of models including van't Hoff, Arrehenius, Lloyd and Taylor, and Gaussian have been used to describe the effect of temperature on decomposition of organic matter (Table 23.6). The most commonly used approach to incorporate temperature into first-order decay models is the Arrhenius equation, which describes an exponential increase in respiration with increasing temperature (Ellert and Bettany 1992). While the Arrhenius equation assumes the activation energy for the process to be constant, the Lloyd and Taylor model assumes the energy of activation to vary as the reciprocal of temperature. A comparison of different models (Benbi et al. 2014a) revealed that though van't Hoff's, Arrhenius, the Lloyd and Taylor and the Gaussian models provided a good

Table 23.6 Models to describe effect of temperature (T) on decomposition rate (k)

Model	Formulation	Model coefficients
Q_{10}	$Q_{10} = \left(\frac{k_2}{k_1}\right)^{10/(T_2-T_1)}$	k_1 and k_2 respiration rates at temperatures T_1 and T_2
van't Hoff's	$k = ae^{bT}$	'a' and 'b' fitted parameters
Arrhenius	$k = Ae^{-E_a/RT}$	'A' is frequency or pre-exponential factor, E_a is required activation energy, R is gas constant (8.314 J K^{-1} mol^{-1}) and T is temperature in Kelvin
Lloyd and Taylor	$k = ae^{-E_0/(T-T_0)}$	'a' is an overall rate term; E_0 does not denote the activation energy as in Arrhenius equation; T is temperature in Kelvin; T_0 is some temperature used as a reference temperature
Gaussian	$k = ae^{bT+cT^2}$	'a' represents absolute rate of the process and b and c represent its temperature dependence. All are fitted parameters

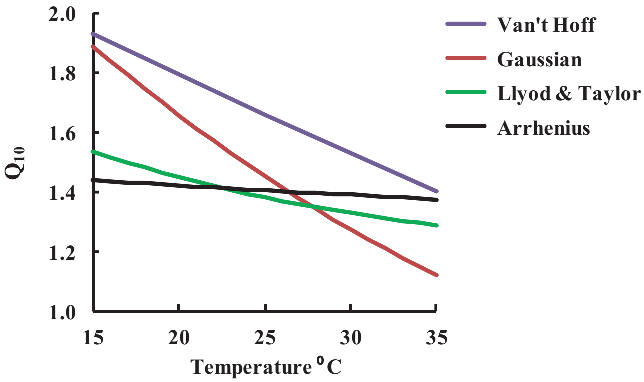

Fig. 23.3 Decomposition temperature response (Q_{10}) of soil organic matter estimated from van't Hoff's, Arrhenius, Lloyd and Taylor and Gaussian models (Benbi et al. 2014a)

fit to the temperature response of C mineralization of isolated SOM fractions and whole soils in laboratory incubation experiments, the models differed greatly in predicting the magnitude of response (Fig. 23.3). However, irrespective of the model used highest Q_{10} values were observed at a temperature of 15 °C which gradually declined as the reference temperature increased to 35 °C, suggesting that temperature sensitivity of organic matter decomposition depends on reference temperature (Kirschbaum 1995).

23.6 Model Applications

Organic matter turnover models have been used to upscale experimental results, predict C sequestration potential of soils, assess and identify appropriate land-use and BMPs for C sequestration and GHG mitigation, and predict climate change effects on SOC and explore the synergies between soil C sequestration and productivity in agricultural systems (Meyer et al. 2015). Models have been used to evaluate the potential effect of abiotic factors (temperature, moisture, soil properties such as texture) on turnover rates of organic C in soil. Depending on the underlying concepts and the purpose for which the model was developed, the models are applicable at different scales (Table 23.7). Models developed at one scale may not be applicable at another scale because of the underlying relationship used. Models developed at ecosystem scale have been used to estimate minimum C input required to maintain existing or reference levels of SOC. In global wheat systems, an average input of 2.0 ± 1.6 Mg C ha^{-1} $year^{-1}$ was predicted by RothC model (Wang et al. 2016). The amount of C input required was greater in soils with higher current soil C stocks such as in the United States and Western Europe. For India, critical C inputs estimated were 1.0 ± 0.9 Mg ha^{-1} to maintain existing SOC stock of 37 Mg ha^{-1}. However, these estimates differ greatly from those computed from results of long-term experiments in the country (Benbi 2015). The estimated critical C input for maintenance of SOC in Indian agroecosystems ranges between 0.31 and 11.8 Mg ha^{-1}. Such variations are not unexpected because of varying rate of organic matter decomposition in soils under different climatic conditions of temperature, humidity, precipitation, aridity, etc. prevailing at experimental sites. Apart from the

Table 23.7 Application and limitations of SOM models at three different scales (Campbell and Paustian 2015)

Scale	Model formulation	Applications	Limitations	Examples
Microsite	Mechanistic relationships at the small scale	Predict short-term and small-scale changes, predict dynamics of measurable soil C fractions	Dependent on soil fractionation method, difficult to extrapolate to larger scales	EnzModel, NICA, INDISIM
Ecosystem	Mechanistic or empirical relationships	Predict impact of site-specific changes, simulate site and regional scenario	Require site-level data to drive and evaluate model, cannot always represent mechanistic relationships important at smaller scales	RothC, DNDC, Ecosys, DAYCENT
Global	Hypothesis for large-scale dynamics	Predict climate change with dynamic soil feedback, simulate global scenario	Require global level data to drive and evaluate model, model complexity determined by computational capacity	CLM, IBIS, TEM

climatic conditions, the reference or targeted SOC level for zero change as well as the prevalent cropping system influence the estimated C input. The critical C input could be effectively estimated using an empirical model driven by current SOC level, mean annual temperature, precipitation, and soil clay content (Wang et al. 2016). Modelling has been used extensively to estimate C sequestration at regional, national and global scales (Gilhespy et al. 2014). RothC model has been used to study SOC dynamics across the main global cereals systems (Wang et al. 2017). The model simulations showed the positive influence of crop residue retention on C sequestration in soils. The model simulations suggested that on a global average, the cropland SOC density increased at an annual rate of 0.22–0.69 Mg C ha^{-1} $year^{-1}$ as the crop residue retention rates increased from 30 to 90%. During the past decade, DNDC model has been used widely in C sequestration and GHG emission studies (Smith et al. 1997; Butterbach-Bahl et al. 2001; Pathak et al. 2005; Babu et al. 2006). Muñoz-Rojas et al. (2013) used CarboSOIL, an empirical model, to predict short-, medium- and long-term trends of SOC dynamics and sequestration under projected future scenarios of climate change in Spain. Results revealed a trend towards decreasing SOC stocks in the upper soil and an increasing trend in the deeper soil layers. Such information can help decision-making in climate adaptation strategies.

Since SOM models can provide quantitative evaluation of organic C and ecosystem dynamics these can be applied in decision-making (van Ittersum et al. 2008). SOM models are now increasingly being examined for linking to policy and are used as a component of decision support systems such as for evaluating C sequestration in soil as a climate change mitigation strategy. There is extensive application of SOM models in predictive methods for the GHG assessment and mitigation (Stockmann et al. 2013).

23.7 Conclusion

The complex nature of soil C dynamics exhibits strong spatial and temporal variability. Conventional methods developed for monitoring and measurement of SOC are laborious and time-consuming. Standard protocols or new methods have been developed to minimize the associated uncertainties. The in situ techniques developed for measuring SOC are not only sensitive but also provide the possibility of repetitive and sequential measurements for spatial and temporal evaluation of soil C stock at a large scale. This circumvents some of the problems associated with sampling schemes and collection and preparation of samples. However, these methods are still evolving and present some instrumental and procedural limitations. The methods that exhibit variable sensitivity to land-use and management have been used to discern the effect of land-use on C stabilization in soils. These methods serve as early indicators of soil quality and management-induced changes in SOM. Modelling has been developed and used under different soil, crop and climatic conditions to describe soil and plant processes at different spatial and temporal scales for simulating organic matter dynamics and predicting the impact of land-use and management on changes in SOC stocks. Linking measured SOC dynamics with soil C modelling can improve quantification of soil C stocks and in understanding the mechanisms of its stabilization. Despite the development of number of models, upscaling of results from these models is constrained because of the lack of detailed spatial data. Therefore, meta-modelling has been suggested to simplify and reduce input and increase their use at regional, national and global scales. Organic matter turnover models have been used to upscale experimental results, predict C sequestration potential of soils, assess and identify appropriate land-use and best management practices for C sequestration and GHG mitigation, and predict climate change effects on SOC and explore the synergies between soil C sequestration and productivity in agricultural systems. Use of SOM models has been examined for linking to policy and are used as a component of decision support systems such as for evaluating C sequestration in soil as a climate change mitigation strategy. There is extensive application of SOM models in predictive methods for the GHG assessment and mitigation.

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Nanotechnology for Improved Carbon Management in Soil

24

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Abstract

Agriculture today is at crossroads facing challenge of efficient food production due to a growing population burden and a shrinking arable land base and water resources. Current important challenges of agriculture include, but not limited to, food security, sustainability of natural resources, improving nutrient use efficiency, production of nutrient-enriched agriculture for maintaining human health and healthy life, and climate change. In the era of climate change, nanotechnology could be useful in mitigating climate change by trapping C in terrestrial pools. The nanomaterials due to their unique properties at nanoscale are reported to enhance carbon stabilization and its possible sequestration in soil. However, contradictory reports on the potential impact of nanomaterials on soil microorganisms are one of the major reasons to limit the adoption of this technology at large scale for mitigating climate change. Nevertheless, continuous efforts are needed to explore the possibility of nanotechnology in C sequestration without compromising ecosystem productivity for developing a climate smart agriculture. This chapter aimed at highlighting the potential of nanomaterials for improved C management in soil and the future research prospects in nanotechnology research pertaining to soil carbon study.

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Keywords
Carbon nanotubes · Carbon sequestration · Greenhouse gases · Nanoparticles · Soil structure

24.1 Introduction

The technology that deals with the matter at nanoscale dimensions (1–100 nm) is known as nanotechnology. This is one of the rapidly emerging technologies having numerous applications in the field of electronics, pharmaceuticals, civil engineering, energy, health, and agricultural sectors. The applications of nanotechnology in agriculture and allied sector include nano-fertilizers, nano-pesticides, and herbicides; nanosensors for precision farming; veterinary medicines; fisheries and nutrition, etc. (NAAS 2013). The importance of nanotechnology and its application in agriculture and allied sector have been recognized in recent years, although research on nanotechnology was initiated about half a century back (Mukhopadhyay 2014). Presently, nanotechnology is considered as a smart solution for addressing challenges in agriculture and allied sector. It is imperative to mention that nanotechnology has the potentiality of developing a climate-resilient agriculture for efficient food production (Kashyap et al. 2017).

Climate change has been an important threat to agriculture. Increase in extreme weather events such as floods, droughts, and heat waves due to climate change adversely affect agricultural productivity. Therefore, accelerated increase in the concentration of greenhouse gases (GHGs) in the atmosphere vis-à-vis climate change is a cause of concern. Among the GHGs, carbon dioxide (CO_2) constitutes a major share in the atmosphere. The increase in atmospheric CO_2 concentration at the rate of 2 ppm per annum is one of the important global issues (Lal 2009). Strategies to address the issue involve enhancing the terrestrial C pool. Agricultural management decisions have a profound influence on whether soils are net source or sink of CO_2. Appropriate management of soil resources with special emphasis on soil carbon management and its sequestration in recalcitrant pool would serve a pivotal role in checking CO_2 concentration in the atmosphere.

Nanotechnology has high potential in enhancing terrestrial C pool for improved soil health and better environment. The nanomaterials due to their unique properties at nanoscale have been reported to enhance carbon stabilization and its possible sequestration in soil (Monreal et al. 2010; Calabi-Floody et al. 2011). Carbon sequestration in soil is governed by various edaphic, environmental, and management factors; soil aggregation and structure are important among them (Singh et al. 2017). Therefore, good understanding on the role of soil structure in carbon sequestration is of immense importance in identifying potential nanomaterials for enhancing carbon storage through improved soil aggregation.

24.2 Strategies for Reducing CO_2 Emissions from Soil: Implication of Nanotechnology

Reduction in CO_2 emissions from soil into the atmosphere is possible, if soil resources act as potential sink of C. The soil resources may act as a sink of atmospheric carbon depending on land use, management practices, and environmental conditions. It has been reported that with the adoption of recommended management practices, global agricultural soils have the capacity to sequester approximately 50–66% of the total C lost from soil (Lal 2004). Important management strategies to reduce CO_2 emissions from soil into the atmosphere involve enhancing soil aggregation and structure for better retention of soil organic carbon and increasing terrestrial C pool through carbon sequestration. As far as the management of soil resources is concerned, these strategies have direct role in ensuring soil as a potential sink of C. Besides, capture and storage of atmospheric CO_2 are also useful in checking CO_2 concentration in the atmosphere.

24.2.1 Nanomaterials for Improved Soil Structure

Soil aggregation and structure are the important soil factors to ensure improved carbon management in soil–atmosphere continuum. The importance of soil structure and aggregates on carbon storage in soil has been studied extensively by various researchers (Elliott 1986; Gupta and Germida 1988; Tisdall and Oades 1982). Significant contributions have been made in studying the effect of various management practices on carbon storage in soil as affected by varying soil aggregation and vice versa (Spaccini et al. 2002; Bhattacharyya et al. 2009, 2012). The management practices include crop rotation, zero tillage or conservation tillage, proper fertilization and nutrient management, and addition of humic substances in soil. Such research efforts have revealed that carbon storage in soil could be enhanced through enhancing soil aggregation and improving the stability of soil aggregates by adopting proper management practices. The research efforts that relate the usefulness of nanotechnology in carbon storage through improved soil aggregation are still at infancy. Some attempts have been made to improve soil structure and associated properties using nanomaterials (Table 24.1). Most of these studies have explored the usefulness of nanomaterials in improving soil structure vis-à-vis mechanical soil properties for engineering purposes. Very few studies have attempted to assess the impact of nanomaterials on soil structure in relation to soil aggregation and carbon storage in soil (Aminiyan et al. 2015; Raliya et al. 2014; Tarafdar et al. 2012; Mahawar et al. 2012). In these studies, the positive effects of nano-zeolite, nano-ZnO particles, and nano-Fe on soil aggregation and carbon build-up in agricultural soil have been documented. Nano-zeolite application in soil was reported to increase the mean weight diameter (MWD) of water-stable aggregates and organic carbon content in each aggregate size fraction of MWD. The high MWD of soil as a result of nano-zeolite application was ascribed to the high calcium (Ca) content of zeolite mineral. Formation of cation bridges between organic matter and clay crystals in the presence of Ca^{2+} ion has been reported to form more stable

Table 24.1 Nanomaterials for improving soil structure and associated properties

Nanomaterial used	Affected soil physical properties	Reference
Nano-silica, nano-zeolite	Soil moisture content, shear strength, swelling characteristics, dry density, Atterberg limits	Hareesh and Vinothkumar (2016)
Nano-copper, nanoclay, nano-magnesium	Soil compaction characteristics and strength, Atterberg limits	Majeed et al. (2014)
Nano-lime	Soil strength	Govindasamy et al. (2017)
Carbon nanotube, carbon nanofibers, nanocarbon made of coconut shell	Soil moisture content, dry density, hydraulic conductivity, Atterberg limits, interparticle spacing, available soil water content	Alsharef et al. (2016); Correia et al. (2015); Zhou and Chen (2017)
Nano-titanium dioxide and nano fly ash	Load-bearing capacity of soil, shear strength, dry density	Babu and Joseph (2016)
Nano-Fe_3O_4, nano-MgO	Bulk density of soil, tensile strength of soil aggregates	Bayat et al. (2017)
Nano-alumina (Al_2O_3)	Swell–shrink behaviour of soil, hydraulic conductivity	Taha and Taha (2012)
Graphene oxide nanosheet	Tensile and shear strength of soil	Naseri et al. (2016)

aggregates to provide structural stability to soil microaggregates (Six et al. 2004), which in turn provides protection to organic carbon from microbial and enzymatic attacks. Other than nano-zeolite, nano-ZnO and Fe particles are also effective in enhancing soil aggregation. Nano-ZnO and Fe have been reported to induce the secretion of extracellular polysaccharide from *Bacillus subtilis* (JCT1), *Bacillus subtilis* (JCT6), *Aspergillus terreus* (JF681300), and *Aspergillus flavus* (JF681301) (Raliya et al. 2014; Tarafdar et al. 2012; Mahawar et al. 2012), which have impacted on increased soil aggregation (62–82%), moisture retention (10.7–14.2%), and organic carbon content (up to 63%) (Raliya et al. 2014; Mahawar et al. 2012).

24.2.2 Nanomaterials for Carbon Sequestration in Soil

Carbon sequestration in soil has long been considered as a win–win strategy for improving soil functions as well as ensuring steady CO_2 concentration in the atmosphere. It implies capturing carbon into a more stable form, which would otherwise be emitted into the atmosphere. Sequestration of organic carbon in soil can be enhanced through (i) increasing chemical recalcitrance of SOC (chemical protection to SOC), (ii) facilitating organo-mineral interaction (physicochemical protection to SOC), and (iii) providing protection to SOC from microbes and microbial decomposition (biological protection to SOC) (Barré et al. 2014). The widely followed recommended management practices (RMPs) for facilitating the above mechanisms in order to enhance the sequestration of SOC are mulching, conservation agriculture, agroforestry, adoption of diversified cropping systems, integrated nutrient management, improved grazing, and forest management (Lal 2004). Nevertheless, there have been increasing interests in research and development on demonstrating the usefulness of nanotechnology in sequestering carbon in soil.

Natural nanoparticles, for example, nanoclays, hydrous Fe oxides, or oxyhydroxides at nanoscale have been documented for their plausible effects on carbon stabilization in soil (Calabi-Floody et al. 2011; Calabi-Floody et al. 2015; Filimonova et al. 2016). The uniqueness of nanoparticles in respect of their electronic, magnetic, kinetic, and optical properties has been attributed to enhance carbon stabilization in soil (Monreal et al. 2010). Natural nanoclay, for example, allophane, a non-crystalline aluminosilicate, occurs at nanoscale in Andisols. The percent contribution of nanoclay to the total clay fraction in Andisols ranges from 22% to 28% (Calabi-Floody et al. 2015). Allophane nanoclay has been reported to retain a significant amount (11.8%) of carbon against intensive peroxide treatment (Calabi-Floody et al. 2011). This suggests the possible potential role of allophane in SOC stabilization and further sequestration for long term. High accumulation of SOC in allophanic soils has also been reported by Calabi-Floody et al. (2015) and Chevallier et al. (2010) which may be attributed to physical, chemical, and biological protection of SOC owing to the spatial arrangement of SOC and minerals within interspherular spaces of allophane aggregates (Filimonova et al. 2016). The nanoclay in Andisols consists of spherical aggregates of allophane having a diameter of about 100 nm. The peculiar microporous structure (fractal pore) of allophane aggregates with a large specific surface area provides the stability to organic carbon in Andisols, since the SOC trapped in the fractal pore structure is less available to the microbes and degrading enzymes. Besides, dominance of nanoparticulate Fe oxyhydroxides (ferrihydrite) in the allophane structure is ascribed to the formation of stable organo-mineral complex for long-term sequestration of SOC.

24.2.3 Nanomaterials for Capture and Storage of CO_2

Carbon dioxide, being one of the major GHGs, maintaining its concentration in the atmosphere has become a challenge. High CO_2 emission and concentration in the atmosphere often lead to urban smog, acid rain, and health problem. Therefore, CO_2 removal for maintaining its concentration in the atmosphere is of prime importance. According to Aaron and Tsouris (2005), adsorption of CO_2 using solid adsorbents is one of the potential technologies for CO_2 capture. Adsorbents such as active carbon (Siriwardane et al. 2001), zeolites (Prezepiórski et al. 2004), and mesoporous silica (Zhu et al. 2013) have been documented for their effectiveness in adsorbing CO_2. However, the adsorption technology has a limitation of low retention of CO_2 by the adsorbents. We need adsorbent materials with better physical characteristics than the conventional materials for improved retention of CO_2. Nanotechnology is useful in developing nano-adsorbents with high specific surface area for high retention of CO_2. In recent times, researchers have used nanomaterials for CO_2 removal and storage. Carbon nanotubes (CNTs) and nanotubes functionalized with amines by physical adsorption processes can be used for removal of CO_2 (Smart et al. 2006). Single-walled carbon nanotubes (SWNTs) and multiwalled carbon nanotubes (MWNTs) have been reported to show high capacity of adsorbing CO_2 due to activated carbon. CaO derived from nano-sized $CaCO_3$ was reported as a potential CO_2 absorber (Yang et al. 2009). Comparison of these nanomaterials with commercial adsorbents such as active carbon and zeolite suggests that nanocompounds are better CO_2 absorber (Smart et al. 2006), which may be attributed to their higher reactive sorption capacity, fast reaction rate, and high durability of the adsorbent (Wu and Zhu 2010; Wu et al. 2008; Florin and Harris 2009; Wu and Lan 2012; Biswas et al. 2011; Mishra and Ramaprabhu 2011). Such nanomaterials can be divided into four categories, namely, nanoporous materials, nano-hollow structured materials, nanocomposite materials, and nanocrystalline particles (Table 24.2).

Table 24.2 Nanomaterials for CO_2 capture

Nanomaterials	Nanosorbents	Advantages	Reference
Nanoporous	Nanoporous MCM-41 "molecular basket"	A synergetic effect on the adsorption of CO_2 by polyethylenimine (PEI)	Xu et al. (2002)
		CO_2 condensed in a pore channel like a "basket" form	
	Mesoporous MgO	Selective to CO_2 gas	Bhagiyalakshmi et al. (2010)
		Thermally stable	
		Regenerable	
	CuO nanoparticle-load porous carbons	Higher CO_2 capture capacity	Kim et al. (2010)
Nano-hollow structured	Multiwalled CNT	Have higher capture capacity with the same surface area with activated carbon or zeolite	Hsu et al. (2010)
	Single-walled CNT	Have higher capture capacity with the same surface area with activated carbon or zeolite	Hsu et al. (2010)
	CaO nanopods	Higher CO_2 capture capacity retaining > 50 CO_2 absorption capacity after 50 CO_2 capture-and-release cycles	Yang et al. (2009)
	Nano-sized CaO derived from $CaCO_3$	Higher CO_2 capture capacity	Florin and Harris (2009)
Nanocomposite	Amine-functionalized mesoporous capsules base	Higher CO_2 capture selective to CO_2 gas	Wang et al. (2011)
	Nano-magnetic decorated multiwalled CNT	Improved CO_2 adsorption	Mishra and Ramaprabhu (2011)
	Aminosilane-functionalized cellulosic polymer	Improved CO_2 sorption	Pacheco et al. (2011)
Nanocrystalline	Spinel-stabilized CaO-$MgAl_2O_4$ nanoparticles	Reduce decay problem of CaO	Li et al. (2010)
		Improved durability for high-temperature CO_2 capture	
	Nanocrystalline Li_2ZrO_3 particles	Improved capture of CO_2 in a wide temperature range and improved kinetics of the regeneration	Ochoa-Fernández et al. (2006)
	Nano CaO/Al_2O_3	Improved adsorption capacity	Wu et al. (2008)
	Lithium silicate nanoparticle	Improved CO_2 capture	Khomane et al. (2006)
		Thermally stable	

24.3 Nanomaterial and Soil Microbial Activity: Implication on Soil Microbial Biomass Carbon

The nanomaterials may have an impact on soil microorganisms via (i) a direct effect (toxicity), (ii) changes in the bioavailability of toxins or nutrients, (iii) indirect effects resulting from their interaction with natural organic compounds, and (iv) interaction with toxic organic compounds which would amplify or alleviate their toxicity (Simonet and Valcárcel 2009). There are two schools of thought on the effect of these nanomaterials on soil microorganisms. One group suggests that there is no toxic effect, but the other group firmly raises their serious concern over the toxicity effect of such nanomaterials on the microorganisms that promote plant growth and nutrient cycling in soils. There are reports that plant growth-promoting rhizobacteria (PGPR) like *P. aeruginosa*, *P. putida*, *P. fluorescens*, *B. subtilis*, and bacteria involved in soil N cycle, namely, nitrifying bacteria and denitrifying bacteria, have shown varying degrees of inhibition when exposed to nanomaterials in pure culture conditions or aqueous suspensions (Mishra and Kumar 2009). On the contrary, Raliya and Tarafdar (2013) reported the improvement in microbial population in *Cyamopsis tetragonoloba* rhizosphere due to application of zinc nanoparticles. The issue of the potential impact of nanomaterials on soil microbial communities is highly relevant as far as the microbial biomass carbon (MBC) content of soil is concerned. It is imperative to mention that the higher the MBC in soil, the higher the potentiality of soil to sequester carbon in non-labile pool. The effects of nanomaterials on soil microorganisms as revealed from various studies are summarized below (Table 24.3).

24.4 Fate of Nanomaterials in Soil

Adequate information on the interaction between soil organic matter (organic humic substances), natural colloids, and nanomaterials of different types is not available. It is reported that due to adsorption by soil organic matter (SOM), the mobility of nanomaterials in soil is reduced, and their influence on the microbial populations is drastically declined (Dinesh et al. 2012). Nanomaterials can be strongly sorbed to soil surfaces and SOM making them less mobile or small enough to be trapped in the interspaces of soil particles. The strength of sorption in soil, however, depends on the size of particles, chemistry, aggregation behaviour, and conditions under which it is applied (United States Environmental Protection Agency 2007). In fact, whether a nanoparticle can be risky in soil depends not only on its concentration, but also on the likelihood of it ever coming into contact with microbial cells. It may also be noted that natural colloids and nanomaterials in the soil environment can interact with one another and also with other larger particles (Simonet and Valcárcel 2009). The SOM have the ability to modify the nanomaterials and control its activity by surface coating, which in turn inhibits the aggregation of nanoparticles in soil (Shah and Belozerova 2009). The SOM (in presence of humic acid) can also affect the aggregation and deposition behaviour of nanomaterials by adsorption due to

Table 24.3 Effects of nanomaterials on soil microorganisms and microbial biomass carbon

Nanoparticle	Effects	Nature of study	Source
Nano-CeO_2 and Nano-ZnO	Nano-CeO_2 did not affect soil bacterial communities in unplanted soils, but 0.1 g kg^{-1} nano-CeO_2 altered soil bacterial communities in soybean-planted soils. Nano-ZnO at 0.5 g kg^{-1} significantly increased *Rhizobium* and *Sphingomonas* but decreased *Ensifer*, Rhodospirillaceae, *Clostridium*, and *Azotobacter*	*Mesocosm* study	Ge et al. (2014)
FeO nanoparticles	Positive effects on soil microbial metabolic activity (at 1 and 10 mg/kg soil) and soil nitrification potential (at 0.1 and 1 mg/kg soil)	Field study	He et al. (2016)
Nano-CuO and ZnO	Total bacterial count was higher with the application of CuO (9.45 log CFU/g of soil) and ZnO (9.46 log CFU/g of soil) at their lower doses than higher doses	Field study	Maity et al. (2018)
	Total bacterial count and MBC in soil increased up to 100 ppm of nano-CuO over control. Total biomass carbon, dehydrogenase, and MBC increased in nano-ZnO treatments	In vitro	Srinivasan et al. (2017)
Silicon nanoparticles	Enhanced soil microbial population, soil dehydrogenase, acid phosphatase, and alkaline phosphatase activities	In vitro	Kaur (2016)
Nano-lime and nano-dolomite	Increased the population of bacteria, fungi, and actinomycetes	In vitro	Reddy and Subramanian (2017)
Nano-Zn and Fe	Soil enzyme (dehydrogenase, esterase, acid phosphatase, alkaline phosphatase, arylsulphatase, nitrate reductase, cellulase, hemicellulase, lignase) activities in the rhizosphere increased between 18% and 283%	Field study	Tarafdar (2017)
Multiwalled carbon nanotubes (MWCNT)/ carbon nanotubes	MWCNTs at 750 μg/mL and above lowered the microbial (*Mesorhizobium* sp. and *Nitrosomonas stercoris*) biomass	In vitro	Keita et al. (2018)
	A slight shift in bacterial DNA as a result of carbon nanotube, indicating a minor change in the community structure	Incubation study	Tong et al. (2007)
	Multiwalled CNT significantly inhibited the activities of 1,4-β-glucosidase, hydrolase, xylosidase, 1,4-β-N-acetylglucosaminidase, phosphatase, and microbial biomass C and N in soils	Incubation study	Chung et al. (2011)

steric repulsion induced by the humic acid macromolecules adsorbed on to the nanomaterials surfaces (Chen and Elimelech 2007). These findings indicate that SOM could significantly mitigate the potential impacts of nanomaterials on soil microorganisms. Besides, the microbial communities in soil have an inherent ability to resist disturbances from heavy metals such as silver (Ag) nanomaterials and the capacity to recover from these (Throbäck et al. 2007). Further, the nanomaterials could also react with ions in the soil and form complex salts that are not toxic to the microorganisms (Shah and Belozerova 2009). The formation of larger agglomerates of nanomaterials by high-molecular-weight nano-organic matter (NOM) compounds is likely to decrease the bioavailability and toxicity of nanomaterials in soil. In contrast, solubilization by natural surfactants such as lower-molecular-weight NOM compounds is likely to increase the bioavailability and toxicity of nanomaterials in soil (Navarro et al. 2008). It is obvious that interactions of nanomaterials with SOM and their fates in soil which finally determine the fate of nanomaterials in soil have not been thoroughly investigated.

24.5 Challenges and Future Prospects

Studies on the usefulness of nanomaterial and nanotechnology in SOC sequestration with special emphasis on soil aggregation are scarce. Further research efforts are needed to establish the intense potentiality of natural as well as engineered nanoparticles in SOC stabilization and sequestration for long term, so that "adoption of nanotechnology" can be included in the recommended management practices (RMPs) for SOC sequestration. There is a lack of information on the transformation of nanomaterials and their fates in soil, which is highly crucial before inclusion of any technology in RMPs. Besides, the solution chemistry of metallic nanomaterials is quite limited, and thermodynamic data such as solubility and reaction constants of these materials are unavailable. Limited information is also available on the physicochemical interactions between nanomaterials and bacterial cell surfaces.

Further studies are required to standardize the optimum dosage of nanoparticle application in soil in order to avoid potential damage to terrestrial ecosystem. Economic evaluation and cost-effectiveness of natural as well as engineered nanoparticles for their possible application at large scale need to be addressed in future studies.

24.6 Conclusion

Carbon storage and sequestration in soil depends on the degree of physical, chemical, and biological protection offered to carbon in terrestrial ecosystem. Soil aggregation plays an important role in protecting SOC and its stabilization. With the advancement of science and technology, the applicability of nanomaterials for SOC stabilization and sequestration has come into existence. Understanding of mechanisms of nanoparticle-driven SOC stabilization from various studies indicates that these nanoparticles facilitate aggregate formation and provide better protection to SOC in soil due to their unique properties. Further, our existing knowledge based on a very limited number of studies suggests that soil is a potential source of natural nanoparticles having the capacity to sequester SOC for long term. The potentiality of such natural nanoparticles could be harnessed for the development of green technology for SOC sequestration. The contradictory findings on the potential impact of nanomaterials on soil microorganisms pave the way to further research in this direction. The challenge also lies in the assessment of potential risks due to application of nanomaterials in terrestrial ecosystem.

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Potentials and Limitations of Soil Carbon Modelling: Implications in Indian Conditions

25

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Abstract

Soil is the largest reservoir of C in terrestrial ecosystem and any change in soil organic carbon (SOC) stocks is reflected in the soil–atmosphere CO_2 exchange. Soil organic carbon is an integral component of soil organic matter (SOM) that plays an important role in maintaining and sustaining ecosystem functions and soil productivity. Understanding the dynamics of SOC is important to maintain SOC stocks in soil and to sustain crop yield. An accurate estimate of the change in SOC dynamics is also essential in the wake of fast-changing climate and global warming. The direct impact of climate change is on net primary productivity which is a key driver in SOC dynamics. This change in net primary productivity and soil management would alter SOC dynamics. Several researchers have attempted to simulate the SOC dynamics through building process-based SOC models at different scales like microsites, regional and global. Modelling the dynamics of SOC in the soil is complicated by the fact of numerous controls on SOC mineralization. The challenge lies in calibrating and validating these SOC models for Indian condition which has different soil types, vegetation, and climate. This chapter is aimed to discuss the potentials and limitations of using different SOC models in India with a brief on the importance of SOC and their controls.

Keywords

Soil carbon turnover · Soil carbon modelling · Mean residence time

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25.1 Introduction

Understanding and predicting the fate of soil organic carbon (SOC) in soils is a key focus to understand the magnitude of current and future global changes. The edaphic pool (soil) stores three times more carbon (C) than the atmospheric or terrestrial vegetation pool. Moreover, soil C storage is one of the most important ecosystem processes as it plays a critical role in supporting key ecosystem services such as climate regulation, soil fertility, and food production. According to India's Second National Communication to the UNFCC, the rise in annual mean surface air temperature by the end of the century ranges from 3.5 °C to 4.3 °C. The increase in temperature and consequently evapotranspiration will have a profound influence on the net primary productivity, SOC storage, and dynamics across India. An accurate estimate of the change in SOC dynamics is also essential in the wake of fast-changing climate and global warming. Direct measurements of SOC can be expensive and time consuming to assess spatial heterogeneity. We need to follow more efficient and systematic sampling and measurement protocol to calculate total SOC changes at regional and national level. Further, the differences in methodology for SOC estimation in laboratory to determine chemical, physical, and biological SOC pools does account for true complex nature of SOC. Several researchers have attempted to simulate the SOC dynamics through building process-based SOC models at different scales like microsites, regional, and global. These models vary with respect to structure, parameterization, and data set needed for parameterization such as soil, climate, net primary productivity, and land use. Modelling the dynamics of SOC in the soil is complicated by the fact of numerous controls on SOC mineralization. Many factors control dynamics of SOC, namely abiotic (temperature, moisture), soil properties, vegetation, land use, and biotic factors. Therefore, direct measurements of SOC content alone do not easily support these types of efforts at a regional scale. Simulation models along with direct measurements provide a more realistic estimate of SOC dynamics, capacity for numeric evaluation of changes, including comparison of predicted impacts on SOC. Considering the potential decision-making implications of SOC model applications, there is an immediate need to better connect advances in SOC understanding with SOC modelling. In the following sections of this chapter, we reviewed the importance of SOC, controls of SOC mineralization, modelling SOC dynamics using simulation models, SOC pools in different SOC models, and potentials and limitation of using SOC models.

25.2 Soil Organic Carbon

Soil organic carbon is the carbon stored in soil organic matter (SOM). Organic C enters the soil through the decomposition of plant and animal residues, root exudates, living and dead microorganisms, and soil biota. In fact, SOM is the organic fraction of soil exclusive of un-decomposed plant and animal residues. Nevertheless, most analytical methods do not distinguish between decomposed and undecomposed residues. Soil organic carbon is a measurable component of SOM (Brady and Weil 2002). SOM contains approximately 58% C; therefore, a factor of 1.72 can be used to convert SOC to SOM. SOC is not a homogeneous pool (Banger et al. 2010; Koarashi et al. 2009) but comprises of a continuum of thousands of different C compounds from simple sugars to complex humified molecules, with mean residence times (MRT) ranging from hours to millennia. Soil organic matter is composed of <10% fresh organic residue which is mostly leaf litter or mulch in an agricultural setting, <5% living organisms within the soil, 33–50% humus which is plant material that has transformed from one organic compound to another and is considered stabilized organic matter, and 33–50% decomposing organic matter (active fraction of SOM) (Brady and Weil 2002). The majority of SOC is plant derived (Brady and Weil 2002). Soil organic carbon may be broken down into three distinct fractions: active, intermediate, and passive (Parton et al. 1988; Trumbore 1997). There is a general agreement that SOC contains at least three identifiable C pools: root exudates and rapidly decomposed components of fresh plant litter ("active" pool), stabilized organic matter that persists in soils over several thousands of years ("passive" pool), and a poorly defined "intermediate" or "slow" C pool that has turnover times in the range of years to centuries (Trumbore 1997).

25.3 Importance of SOC

Organic matter makes up just 2–10% of the soil mass but has a critical role in the physical, chemical, and biological function of agricultural soils. Soil organic carbon is critical for soil and ecosystem function. As a manageable property, SOC contributes to ecosystem services through its effect on multiple soil processes and functions. Soil organic carbon affects nutrient cycling and soil fertility status (Lenka et al. 2017). Mineralization of SOC releases nutrients, including nitrogen (N) into the soil (Havlin et al. 1990; Six and Jastrow 2002; Hoyle et al. 2011; Murphy 2015). Maintaining SOC is essential for sustainable use of agricultural soils and improving environment quality (Lal 2004). Thus, a soil with a higher SOC concentration results in a greater release of organic N to the soil than a soil with a lower SOC concentration (Aggarwal et al. 1997; Kusumo et al. 2011; Murphy 2015). In addition, SOC affects many soil physical properties. An increase in SOC concentration decreases bulk density (Tranter et al. 2007), usually increases soil water holding capacity (Vereecken et al. 1989; Wosten et al. 1999; Saxton and Rawls 2006), and has variable effect on hydraulic conductivity (Saxton and Rawls 2006; Weynants et al. 2009). Many agricultural soils have been significantly depleted of SOC stocks (Lal 2004). Therefore, there is considerable interest in increasing SOC concentrations in agroecosystems globally to both sequester carbon for climate change mitigation and improve soil quality to enhance productivity and agroecosystem sustainability (Lal 2004; Smith et al. 2008).

25.4 Controls of SOC Mineralization

Mineralization of soil organic carbon is an important biochemical process directly related to the release and supply of nutrient elements, formation of greenhouse gases, and maintenance of soil quality. The soil organic carbon mineralization process is conducted with microorganism involvements (Rousk et al. 2016; Marañón-Jiménez et al. 2017) and is influenced by many factors, including temperature (Raich and Potter 1995; Davidson et al. 1998), moisture condition, quality and quantity of organic carbon input, vegetation (Raich and Tufekciogul 2000), soil properties such as C/N ratio (Parton et al. 1988), soil aggregation, soil aeration, texture, soil water content (Grant and Rochette 1994; Boone et al. 1998; Pregitzer et al. 1998), etc. One of the most important factors affecting soil carbon mineralization is soil temperature, which can improve mineralization rates by enhancing microbe activity and by increasing microorganism quantity (Rey et al. 2005; Sagliker 2009). Significant variance under different temperatures was found by Bai et al. (2011). Soil organic carbon mineralization generally increases with an increase in soil moisture under the same temperature conditions (Wang et al. 2010). Organic C mineralization is faster in climates that are warm and humid and slower in cool, dry climates. Organic matter also decomposes faster when soil is well aerated (higher O_2 levels) and much slower on saturated wet soils. Organic matter input will affect the balance between carbon mineralization and stabilization, carbon mineralization is affected by significant differences in chemical composition of crop residues (Zhang et al. 2009), and mixed residues could promote the cumulated carbon mineralization at the end of incubation (Wang et al. 2012). Soil organic carbon mineralization is also dependent on SOC content of soil and soil inorganic carbon (Aryal et al. 2017). Soil health and long-term soil respiration improves with increased SOC.

Management practices can either increase or decrease SOC (Six and Jastrow 2002; Lenka et al. 2014). Leaving crop residues on the soil surface, use of no till, use of cover crops, or other practices that add organic matter will increase soil respiration and SOC mineralization (Al-Kaisi and Yin 2005). Crop residues with lower carbon to nitrogen (C:N) ratio (e.g. soybean residue) decompose faster than residues with a higher C:N ratio (e.g. wheat straw) (Parton et al. 1988). High residue–producing crops coupled with added N (from any source) increase decomposition and accrual of SOC (Campbell et al. 1991). Surface-placed residues decomposed more slowly, and C and N mineralization was higher when residues were buried (Lynch et al. 2016). Managing soil pH and salt content (salinity) is important because they regulate crop growth and nutrient availability and distribution which impact soil organisms responsible for SOC mineralization and other processes contributing to soil respiration (McCauley et al. 2009). Fertilizers stimulate root growth and nourish microbes; however, at high concentrations, some fertilizers can become harmful to microbes responsible for soil respiration because of increases in pH or salinity.

25.5 Modelling SOC Dynamics

The dynamic nature of SOC requires frequent monitoring and accurate estimation of SOC at regular interval. Understanding SOC dynamics is also important for maintaining C stocks to sustain and improve crop yields. Although there are various traditional methods for estimating SOC content in soil, they are expensive and time consuming. The SOC dynamics at site, regional and global scale, can be functionally described using soil carbon simulation models that explicitly consider pools differing in residence times. A model-based soil C monitoring system consists of a model of soil carbon, input data to the model, and results on soil C calculated. This is the basic structure, which is similar between systems although details may vary (e.g. Liski et al. 2002, 2006; Ogle and Paustian 2005). Input of C to soil over time is estimated based on biomass information. Cycling of C in soil is simulated using the soil carbon model. As a result of simulation, estimates are obtained for the components of the soil C budget, such as (i) the C pool of soil, (ii) changes in the C pool of soil over time, and (iii) CO_2 emissions from soil as a result of decomposition of organic C compounds in soil (heterotrophic soil respiration).

The soil carbon models used in model-based soil carbon monitoring systems are usually dynamic rather than static models. The major difference between these model types is that dynamic models account for the element of time, unlike static models. The dynamic models are considered as more suitable for simulating carbon cycling in soil, because the C pool of soil consists of different age classes, and these classes may respond to changes in conditions in different ways. Consequently, changes in the soil C pool do not depend only on conditions at a particular moment but also on conditions in the past. Dynamic models are able to account for this behaviour, whereas static models are not. It is worth pointing out that the simplest IPCC Tier 1 and 2 methods, commonly applied when there is only limited information available, are based on static models (emissions factors or soil C contents by land-use category, etc.), whereas application of a dynamic model belongs to a more advanced Tier 3 methodology in the current IPCC classification. There are established dynamic soil C models available which can be used and have been used as parts of model-based soil C monitoring systems, such as CENTURY (Parton et al. 1987), RothC (Coleman and Jenkinson 1996), SOILN (Eckersten and Beier 1998), ROMUL (Chertov et al. 2001), and Yasso or Yasso07 (Liski et al. 2006; Tuomi et al. 2009, 2011). From the user's point of view, these models differ from each other in complexity and input information requirements (Peltoniemi et al. 2007). The complex models require more complicated and more detailed input information than the simple models. Yasso07 and RothC (Coleman and Jenkinson 1996) are examples of simple soil carbon models requiring only basic input data, whereas CENTURY and ROMUL represent more complicated soil carbon models with more demanding input data requirements. The input data used by the soil C models consist of the most important variables affecting C cycling in soil. These variables are commonly (i) litter production of vegetation representing the quantity and quality of C input to soil, (ii) temperature and moisture affecting the decomposition rate of SOM, and (iii) soil characteristics, such as texture, affecting stabilization of SOM and controlling soil moisture conditions. In addition, land-use change is an important factor affecting soil C; therefore it is essential to account for land-use change effects in a model-based soil C monitoring system.

In practice, choosing a soil C model to be used in a model-based soil C monitoring system, it is generally necessary to make compromise between complexity of the soil C model and availability of input data (Peltoniemi et al. 2007). Wherever the input data required by the complex models may not be available, it may be necessary to use a simpler model. Further, the simple model must account for the heterogeneity of conditions in the region of application adequately and be able to describe the effects of the most important factors affecting soil C. Only then can the results of the model-based soil C monitoring system be reliable and the system able to capture the basic variability of soil C pools and the main trends of change in C pools. An important step in applying a model-based soil C monitoring system is an evaluation of the reliability of the results. Information on reliability can be obtained by comparing the results of the system with measured data. Useful measurements to be used in such a reliability evaluation (including systematic and random error) include data on soil C pools, soil C changes, and decomposition rate of litter or soil C. If it appears that the results of the model-based soil C monitoring system deviate from the measurements, the measurements can be used to improve the monitoring system. The data can be used to recalibrate the system and/or even to modify the structure of the system to make it more suitable for the particular application. The reliability of results obtained using a model-based soil C monitoring system can be estimated in a statistical sense at the scale of the application (landscape, country) provided that uncertainty about the input data to the soil C model and the parameter values of the soil C model are known. Unfortunately, little attention has been paid to statistical uncertainty about the parameter values of soil C models when these models have been developed. Consequently, statistical uncertainty estimates are not available for the parameter values of most soil C models. In the absence of the statistical uncertainty estimates, it is still possible to analyse the sensitivity of the results of a soil carbon model to changes in the parameter values. However, it is then not possible to estimate the reliability of the results in a statistical way. When statistical uncertainty estimates are available for the parameter values of a soil C model, it is possible to give statistical uncertainty estimates for the model results, provided that reliable uncertainty estimates are also available for the input data to this model.

25.5.1 Concepts of SOC Pools Used in SOC Models

As dead organic matter is fragmented and decomposed, it is transformed into SOM. Soil organic matter consists of wide variety of materials that differ greatly in their residence time in soil. Some of this material is composed of labile compounds that are easily decomposed by microorganisms, returning C to atmosphere. Some of the SOC, however, is converted into recalcitrant compounds (e.g. organic mineral complexes) which are very slowly decomposed and thus are retained in the soil for decades to centuries or more. Following fires, small amounts of the so-called "black carbon" are produced, which constitute a nearly inert C fraction with turnover times that may span millennia.

Most models are based on several conceptual SOC pools with different turnover rates. These pools can be ascribed to different organic constituents such as plant inputs, decomposers of the incoming organic material, and storage in various forms of SOC. Typically, the latter is divided into pools that differ from each other by decomposition rates and characteristic stabilization mechanisms, which are linked to rate modifiers. Changes in environmental conditions have different impacts on these pools. But even when stocks are at equilibrium, SOC is in a continual state of flux; new inputs cycle – via the process of decomposition – into and through organic matter pools of various qualities and replace materials that are either transferred to other pools or mineralized. For the functioning of a soil ecosystem, this "turnover" of SOC is probably more significant than the sizes of SOC stocks (Paul 1984). An understanding of SOC turnover is crucial for quantifying C and nutrient cycles and for determining the quantitative and temporal responses of local, regional, or global C and nutrient budgets to perturbations caused by human activities or climate change (Trumbore 1993). The turnover of an element (e.g. C, N, P) in a pool is usually determined by the balance between inputs (I) and outputs (O) of the element to and from the pool. Turnover is mostly quantified as the element's mean residence time (MRT) or its half-life ($T_{1/2}$). The MRT of an element in a pool is defined as (i) the average time the element resides in the pool at steady state or (ii) the average time required to completely renew the content of the pool at steady state. The term half-life is adopted from radioisotope work, where it is defined as the time required for half of a population of elements to disintegrate. Thus, the half-life of SOC is the time required for half of the currently existing stock to decompose. The most common model used to describe the dynamic behaviour or turnover of SOC is the first-order model, which assumes constant zero-order input with constant proportional mass loss per unit time (Olson 1963; Jenny 1980):

$$\frac{\mathrm{d}s}{\mathrm{d}t} = I - \mathrm{kS} \tag{25.1}$$

where S is the SOC stock, t is the time, k is the decomposition rate, and kS is equivalent to output O. Assuming equilibrium ($I = 0$), the MRT can then be calculated as

$$\mathrm{MRT} = 1/k \tag{25.2}$$

and MRT and $T_{1/2}$ can be calculated interchangeably with the formula

$$\mathrm{MRT} = T_{1/2} / \ln 2 \tag{25.3}$$

Equations 25.1 and 25.2 form the basis for estimates of SOC turnover derived from first-order modelling; the unknown k is calculated as $k = \frac{I}{S}$ by assuming a steady-state $\frac{\mathrm{d}s}{\mathrm{d}t} = 0$.

This approach requires estimates of annual C input rates, which can be assumed to be continuous or discrete (Olson 1963). The input can also be written as

$$I = hA$$

where A is the annual C addition as fresh residue and h (the isohumification coefficient) represents the fraction that, after a rapid initial decomposition of A, remains as the actual annual input to S. An estimate of h is then necessary. A value of 0.3 is commonly used for agricultural crops, but the value can be higher for other materials such as grasses or peat (Buyanovsky et al. 1987; Jenkinson 1990).

One feature most SOC models share is that they involve one to two labile and/or dynamic pools, two to three physically and chemically protected pools, and one passive or even inert pool (Christensen 1996). Stabilized SOC is of special importance with respect to long-term C sequestration because it accounts for most of the SOC. Mean residence time of “stable” or “long-lived” SOC varies from 250 to 1900 years (Stevenson 1994). For C to be sequestered in the soil, it needs to be protected from microbial degradation within stable microaggregates (<250 mm), adsorbed on the inner surfaces of clays, or be chemically protected in organo-mineral complexes (Lal 1997). Mean residence time of SOC is affected by the type of clay, in which 1:1 clays like kaolinite have a shorter turnover time than 2:1 clays like smectite (Wattel-Koekkoek et al. 2003). Mean residence time also tends to increase with depth in the soil profile (Paul et al. 2001).

Two most important SOC models followed universally are CENTURY SOC model and RothC model. The two models RothC and CENTURY SOC model differ with respect to the definition and slight deviation of SOC pools which is given in Figs. 25.1 and 25.2.

25.5.2 An Overview of SOC Models

Models of SOM dynamics reflect the complexity of interactions existing within the soil environment and help to evaluate the effects of environmental and management changes at local, regional and global scales on rates of turnover. Most models conceptualize that C resides in soils in several discrete pools showing varying rates of turnover and loss. It is commonly assumed that soil organic matter can be fractionated into a smaller labile pool and one or larger recalcitrant pools, each decaying according to first order kinetics. Using such approaches, several soil organic matter models have been developed, such as SOMM, ITE, Verberne, CENTURY, RothC, CANDY, and DNDC. RothC and CENTURY are two of the most widely used and tested SOC models. These largely empirical models have usually provided good predictions of C loss in diverse environments over longer time periods, in general. Despite limitations of less reliable short-term predictions and uncertainty of pool homogeneity and uniqueness, these models are helpful in organizing soil C information. When SOM models are integrated within whole ecosystem simulations, ecosystem responses to environmental changes can be better evaluated. Thus, it is possible to identify the strategies optimizing C sequestration through specific soil

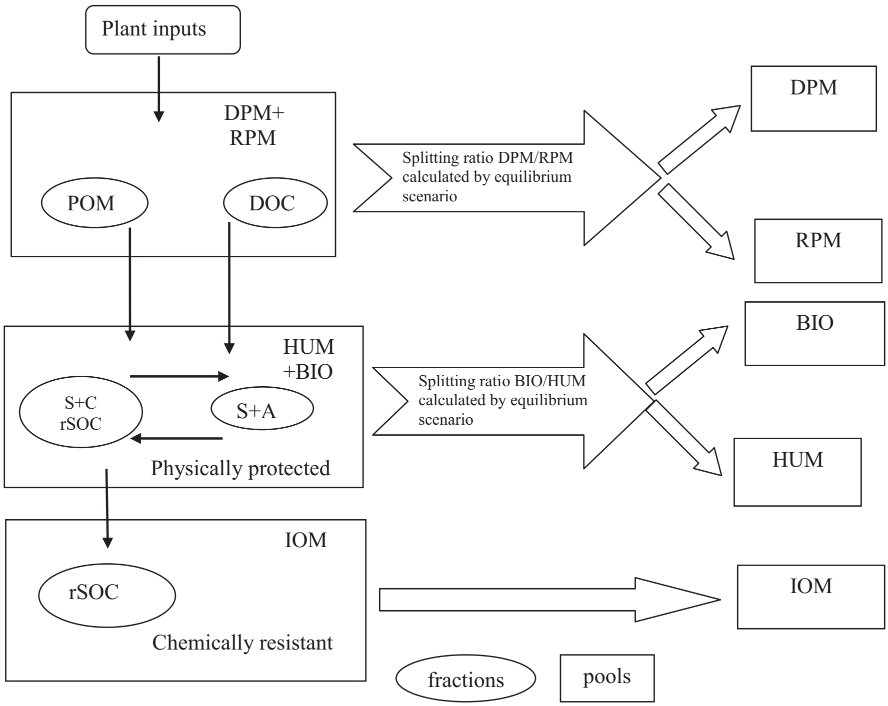

Fig. 25.1 Partitioning of SOC into fractions in RothC model. (Zimmermann et al. 2007) Where *RPM* resistant plant material, *DPM* decomposable plant material, *BIO* microbial biomass, *HUM* humified OM, *IOM* inert organic matter, *rSOC* resistant SOC, *DOC* dissolved organic carbon

and vegetation management. Several workers have used different SOC models all over the world to study the effect of change in management practices on dynamics and turnover of soil organic carbon. The user manual of DNDC, RothC, and CENTURY model is available free for downloading. Interested users can download it from their respective websites. Table 25.1 enlists the parameters required by different SOC models of initialization.

Some few important SOC models widely used are described below.

25.5.2.1 Denitrification–Decomposition (DNDC)

DNDC is a computer simulation model of C and N biogeochemistry in agroecosystems. The model can be used for predicting crop growth, soil temperature and moisture regime, soil carbon dynamics, nitrogen leaching, and emissions of trace gases including nitrous oxide (N_2O), nitric oxide (NO), ammonia (NH_3), methane (CH_4), and carbon dioxide (CO_2). The DNDC model is 1-D process-based biogeochemical model and consists principally of two components. The first component includes the sub-models for soil, climate, decomposition, and plant growth. Based on daily climate data, soil physical properties, and by considering plant and microbial turnover

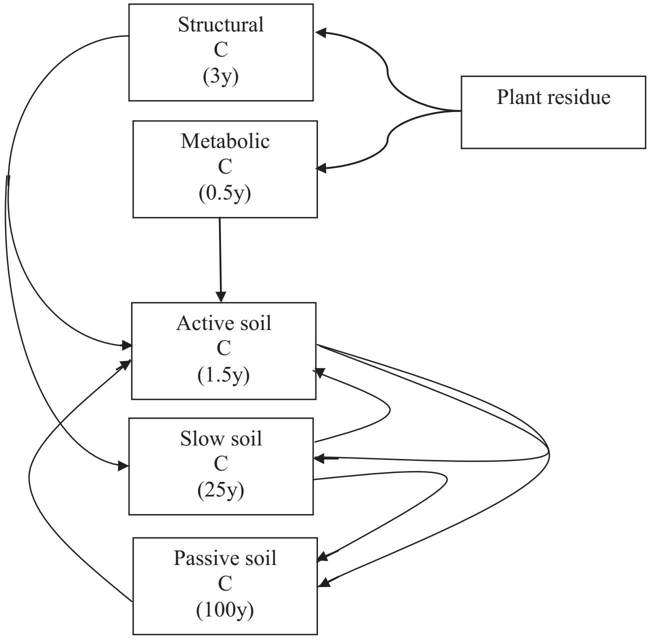

Fig. 25.2 Flow diagram of carbon flow model in CENTURY C model. (Parton et al. 1988)

Table 25.1 Minimum data set requirement in different SOC models

RothC model	CENTURY model	DNDC model
Monthly rainfall (mm) Monthly open pan evaporation (mm) Average monthly mean air temperature (°C) Clay content of the soil (as a percentage) Soil covers – is the soil bare or vegetated in a particular month? Monthly input of plant residues (Mg C ha^{-1}) Monthly input of farmyard manure (FYM) (mg C ha^{-1}), if any Depth of soil layer sampled (cm).	Monthly average maximum and minimum air temperature Monthly precipitation Soil texture Plant N, P, and S content Lignin content of plant material Atmospheric and soil nitrogen inputs Initial soil carbon, nitrogen (phosphorus and sulfur optional)	Maximum and minimum daily air temperature Daily precipitation Daily average wind speed Soil texture, B.D, pH, clay content Soil moisture constants at field capacity and permanent wilting point Soil organic carbon content at surface (0–5 cm) Crop physiological and phenology parameters Types of the crops consecutively planted in a year Planting and harvest dates Maximum biomass production Fraction of aboveground crop residue left in the field after harvest

processes of C, N, and water, the soil–climate sub-model calculates temperature, moisture, and oxygen profiles derived from one-dimensional thermal–hydraulic flow and gas diffusion equations. The respective plant growth sub-model (PnET, DNDC crop model) simulates plant growth driven by solar radiation, temperature, water, and nitrogen stress and passes the litter production, water and N demands, and root respiration to the soil climate or the decomposition sub-model. The decomposition sub-model quantifies the decomposition of organic matter resulting in substrate concentrations of dissolved organic carbon (DOC), NH_4, and CO_2. The second component includes the sub-models for nitrification and denitrification. The concentrations and fluxes of NO_3, N_2O, NO, and N_2 are calculated based on simulated soil microbial activities, which depend on simulated soil environmental conditions and a series of biochemical and geochemical reactions determining the transport and transformation of C and N components. To allow simultaneous occurrence of nitrification and denitrification in aerobic or anaerobic microsites, the scheme of a dynamic "anaerobic balloon" is applied, which is based on the availability of O_2 in the respective soil layer and allocates substrates such as DOC, NH_4, and NO_3 into aerobic and anaerobic soil compartments. DNDC models have been developed for site application but are also used in combination with GIS for quantification of atmosphere–biosphere–hydrosphere matter exchange on regional, national, and global scales.

25.5.2.2 CENTURY Model

The CENTURY model is a generalized plant–soil ecosystem model that simulates plant production, soil C dynamics, soil nutrient dynamics, and soil water and temperature. The model has been used to simulate ecosystem dynamics for all major ecosystems in the world and has been used for the dominant cropland and agroecosystems. The model results have been compared to observed plant production, soil C, and soil nutrient data for the most common global natural and managed ecosystems. This model has been used to simulate the response of these ecosystems to changes in environmental variables (i.e. maximum and minimum air temperature, precipitation, and atmospheric CO_2 levels) and changes in the management practices (grazing intensity, forest clearing practices, frequency of burning, fertilizer doses, crop cultivation practices, etc.) for grasslands, crop, forest, and savanna ecosystems. The CENTURY model (Parton et al. 1987, 1993) is one of the more widely used ecosystem carbon models. Several applications have been done in Europe using data from long-term experiments in Sweden (Paustian et al. 1992), Italy (Lugato et al. 2007) and in Germany, UK and, Czech Republic (Kelly et al. 1997), also in comparison with other SOC models (Smith et al. 1997).

25.5.2.3 RothC Model

RothC is a soil organic carbon model that accounts for the effect of soil type, temperature, moisture content, and plant cover on the turnover of organic carbon in soils. It is originally developed and parameterized to model the turnover of organic carbon in arable top soils from the Rothamsted long-term field experiments and is basically concerned with soil processes. It uses a monthly time step to calculate total organic carbon (t ha^{-1}), microbial biomass C (t ha^{-1}), and $\Delta^{14}C$ (from which the equivalent radiocarbon age of the soil can be calculated) on a "years to centuries" timescale (Jenkinson et al. 1987; Jenkinson et al. 1992; Jenkinson and Coleman 1994). RothC is designed to run in two modes: "forward" in which known inputs are used to calculate changes in soil organic matter and "inverse" when inputs are calculated from known changes in soil organic matter. SOC is split into four active compartments, namely, decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM), and a small amount of inert organic matter (IOM). Each compartment decomposes by a first-order process with its own characteristic rate. The IOM compartment is resistant to decomposition. The structure of the model is shown in Fig. 25.1. Incoming plant carbon is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming plant material. For most agricultural crops and improved grasslands, the model uses a DPM/RPM ratio of 1.44, that is, 59% of the plant material is DPM and 41% is RPM. For unimproved grassland and scrub (including Savanna), a ratio of 0.67 is used. For deciduous or tropical woodland, a DPM/RPM ratio of 0.25 is used, so 20% is DPM and 80% is RPM. All incoming plant material passes through these two compartments only once. DPM and RPM both decompose to form CO_2, BIO, and HUM. The part that goes to CO_2 and to BIO + HUM is determined by the soil clay content. The BIO + HUM is then split into 46% BIO and 54% HUM. BIO and HUM both decompose to produce more CO_2, BIO, and HUM. RothC-26.3 is tested in long-term experiments on a range of soils and climatic conditions in Western and Central Europe. This model was tested on long-term experimental sites with detailed descriptions of the sites conditions and treatments in majority of cases (Coleman et al. 1997; Smith et al. 1997; Falloon and Smith 2002; Barancikova 2007; Ludwig et al. 2007). Because of its simplicity and the generally good availability of the input data required, this model is used also for the estimation of the SOC stock on agricultural land.

25.6 Review on Validation of Different SOC Models in Tropical Ecosystem

25.6.1 CENTURY

CENTURY soil carbon model has been successfully used in tropical ecosystems. The simulation results obtained in several studies after some model modifications, made to improve the effects of the main parameters that affect the SOM in areas of study, often underestimate or overestimate (Bhattacharyya et al. 2010; Bonan et al. 2013; Plant and Ii 2017) compared to the measured data. Some researchers describe from 30 to 70% of underestimate carbon stocks in an agricultural system (Gupta and Kumar 2017) and forest systems (Alamgir et al. 2016; Sierra et al. 2007). In contrast the other group (Alamgir et al. 2016; Chaplin-Kramer et al. 2015; Gupta and Kumar

2017; Ngo and Lum 2018; Sierra et al. 2007) studying forest soils reported a CENTURY overestimate carbon stocks in tropical forest. Bhattacharyya et al. (2010) evaluated CENTURY SOC model to assess the performance of the CENTURY ecosystem model in long-term fertilizer experiments in contrasting regions of India, namely, humid and semiarid. At the humid site modelled data simulated measured data reasonably well for all treatments whereas at the semiarid site CENTURY performed well for the early years but lower during the end of the experiment. Further, the model simulates only the top 20 cm and does not separate the humified portion of the litter from mineral soils. For this reason CENTURY does not describe the variation on SOM among the soil horizons and the water content dynamics across the deep layers.

25.6.2 RothC

Diels et al. (2004) reported that RothC model overestimated the topsoil SOC (0–12 cm) in a 16-year continuously cropped agroforestry experiment in Ibadan, southwestern Nigeria. They doubled all decomposition rate constants in the model to simulate the measured contrasts in SOC contents between the alley cropping systems and the no-tree to reflect the faster SOC mineralization of the region. The discrepancy between the modelled and observed SOC is possibly because the model doesn't take into account the following factors: (1) SOC loss by soil erosion, (2) activity of termites and other soil macro-organism SOC decomposition, and (3) rhizodeposition and mineral fertilizer. In black soil regions of India, representing humid and semiarid conditions, RothC model simulated the effect of inorganic and organic fertilizer on SOC of surface layer in four long-term experiments (Bhattacharyya et al. 2011).

25.6.3 Global Environment Facility Co-financed Soil Organic Carbon (GEFSOC) Model

The GEFSOC soil carbon modelling system was built to simulate changes in SOC stock at regional and national scale. This helps in modelling of SOC change in response to land use and management at regional and national scale (Easter et al. 2007). This system conducts analysis integrating the output from three models CENTURY, ROTHC, and IPCC computational method. The GEFSOC modelling output was compared with stocks generated using mapping approaches based on soil survey data in different tropical ecosystems globally, namely, the rice–wheat system of the Indo-Gangetic Plains of India (Bhattacharyya et al. 2007) and the tropical rainforest Brazilian Amazon (Kamoni et al. 2007). They reported SOC stock estimated using the GEFSOC Modelling System was higher than the stock estimated using the mapping approach. This is due to the fact that the GEFSOC system accounts for crop input data (crop management) variation, while the soil mapping approach only considers regional variation in soil texture and wetness.

25.6.4 DAYCENT Model

The DAYCENT model was used to simulate SOC sequestration potential under different N management and mitigation options applied at two rice sites in Bangladesh. In this study, all model parameters, except for the plant growth, were set to default values based on previous literature (Cheng et al. 2014). There was a significant agreement between measured and simulated SOC at both sites under single nutrient management practices. A systematic underestimation of SOC was observed at Site 1 (combination of manure and N treatments), which could be attributed to a reduction of plant inputs, suggesting that less N application through manure was limiting plant production (Cheng et al. 2014).

25.7 Practical Application of a Model-Based Soil Carbon Monitoring System

In order to apply a model-based soil carbon monitoring system in practice on a national or regional (subnational) scale, it is first necessary to form an overall picture of the task. This involves (i) gathering general information about the region in relevant aspects like vegetation, climate, natural disturbances, and management of ecosystems; (ii) finding out the availability of input information to the model-based soil C monitoring system; (iii) deciding upon the time period that the calculations will cover; and (iv) finding out the information availability to test the system validity. After an overall picture has been obtained, application of the model-based soil C monitoring system can be divided into the following practical steps: (1) choice of the soil C model to be used and (2) reliability control, that is, evaluation and possible improvement of the soil C model to be used in the application. Steps 1 and 2 result in a suitable soil C model for the application (3) spatial (geographic) calculation units, (4) litter input data (both quantity and quality), (5) climate data, and (6) land-use change data. Steps 3 to 6 result in input data by the spatial (geographic) calculation unit of the application, (7) determination of initial soil C pools to be used in the calculations, and (8) simulation of soil C cycling in the region of the application over the study period. Steps 7 and 8 represent the actual soil C calculations and give results of the soil C budget, namely, the soil C pool, changes in soil C pool over time, and CO_2 emissions from the soil.

Criteria for comparing models include:

1. Degree of field testing and validation
2. Documentation of computer code
3. Ability to use the model for regional and national scales
4. Ability to respond to dominant agricultural management practices
5. Compatibility of the model to available national-level databases

25.7.1 Soil Carbon Models: Potentials and Limitations

Potentials

A priority research area is how SOC monitoring may be improved in the future. Direct sampling and measurement are often used, but this requires vast financial and labour resources to cover large areas and timescales. Indirect sensing and modelling approaches hold greater potential for widespread application, yet there are issues of accuracy to be resolved. Credible, certifiable reporting of SOC stocks is essential if SOC sequestration is to become a significant part of global mitigation efforts.

SOC dynamics have become an increasingly important consideration in many areas of sustainability research and policy (Manlay et al. 2007). These areas range from small-scale projects to preserve or improve soil health to large-scale climate change mitigation strategies (Paustian et al. 1997; Lal 2004). Direct SOC measurements alone do not easily support these types of efforts. Simulation models of SOC, however, provide the capacity for numeric evaluation of changes, including comparison of predicted impacts on SOC. This has led to an expanding use of SOC models in "applied" settings, specifically to predict SOC dynamics in order to apply policy or to make decisions for how land is used (e.g. Taghizadeh-Toosi et al. 2014). Considering the potential economic and policy implications of these model applications (e.g. carbon credits or payments for changing land management practices), there is an immediate need to better connect advances in SOC understanding with SOC model development and these rapidly expanding applications where SOC models are being used in decision-making.

Limitations

Various factors such as vegetation type and productivity (Lenka and Lal 2013), temperature (Davidson and Janssens 2006), soil moisture (Ryan and Law 2005), soil properties and nutrient (Tian et al. 2010), and disturbance regimes such as land-use change (Post and Kwon 2000) and fire (Harden et al. 2000) can affect the SOC pool size (Fig. 25.1). Mediated by soil microbes, heterotrophic respiration (Rh) is the dominant pathway of SOC loss. In contrast to the assumptions of conventional first-order decomposition models (Parton et al. 1987), decomposition rates of SOC should depend not only on the SOC stock size but also on the size and composition of the decomposer microbial pool (Schimel and Weintraub 2003) as well as C–mineral interactions (Six and Jastrow 2002). In addition, various biophysical and physiochemical factors also can influence Rh, which makes it even more difficult to realistically quantify the decomposition of SOC (Davidson and Janssens 2006). Therefore, the magnitude and dynamics of SOC stocks and Rh across the globe are still far from certain. In the Coupled Model Intercomparison Project (CMIP5) involving 11 coupled carbon-climate models (Earth System Models (ESMs)), Todd-Brown et al. (2013) reported that SOC varied sixfold between ESMs, from 510 to 3040 Pg C during 1995–2005. In their study, only 6 out of 11 model estimates were within the range of the Harmonized World Soil Database (HWSD) estimate of 1260

Pg C (with a 95% confidence interval of 890–1660 Pg C), and spatial correlation coefficients between modelled and empirical SOC estimates at 1° resolution were < 0.4, indicating that variations in the spatial distribution of SOC are not well represented by ESMs (Todd-Brown et al. 2013).

Uncertainties in the modelled SOC estimates may arise from model structure, parameterization, and driving data sets such as climate, soil properties, and land use. One of the major uncertainties in model structure is the representation of the below-ground C processes that vary significantly in different models (Johnston et al. 2004). In addition, nutrient limitation (nitrogen and phosphorus) of net primary production and microbial activities is another structural uncertainty but being ignored or poorly represented by most models (Zaehle et al. 2005; Thornton et al. 2009; Goll et al. 2012). Some uncertainties come from the errors in the observations/measurements used for the parameterization and/or from scale mismatch between measured processes and the scale of global models (Zaehle et al. 2005). Another uncertainty is derived from the climate sensitivity of soil respiration, which has been extensively studied through field experiments, laboratory incubations, and ecosystem modelling (Davidson and Janssens 2006; Giardina and Ryan 2000). How changes in soil microclimate could alter SOC decomposition is still under debate. First, climate conditions can affect enzyme activity with respect to activation energy but can also influence plant primary productivity, C entering the soil pool, substrate quality and accessibility, and nitrogen mineralization (Davidson and Janssens 2006). Second, temperature and precipitation covary with other environmental constraints (e.g. soil aeration, soil properties, and vegetation types), which influence the litter quality and the ratio of labile and recalcitrant SOC components. Therefore, modelled climate sensitivities of SOC decomposition are highly dependent on model structure and assumptions, which may, in part, reflect complex biogeochemical processes in the real world and be able to explain different model behaviours in simulating SOC stock change.

25.8 Conclusion

In conclusion, the model-based soil carbon monitoring provides a feasible and practicable means to monitor soil carbon. Consequently, model-based systems provide a viable alternative or complement for surveys to monitor soil carbon. The potential of soil to act as sink for atmospheric carbon has emphasized the importance of soil carbon accumulation, sequestration, and monitoring. Soil organic carbon is essential and imperative for all essential soil functions and processes (physical, chemical, and biological). The turnover of soil organic matter and its dynamics plays a pivotal role in soil carbon sequestration and stabilization. Management of agricultural land is an integral part of global terrestrial carbon pool including carbon cycle. Several management practices (e.g. agroforestry, soil management, biochar, and reduce land clearing) including land-use change and forestry have been shown to increase soil carbon. This whole soil ecosystem along with soil organic matter is very complex process to understand. Soil organic matter models help studying the effect of management practices on soil organic matter turnover and dynamics. Models are important tools to understand any complex biological process in a simplified and easy way. The review also indicates that soil organic matter models, namely, CENTURY and RothC, are widely used model to simulate the management effects in the different bioclimatic systems in terms of predicting SOC change. SOC models also help in developing inventory of soil carbon at regional and national level which could serve as ready reckoned in calculating the carbon credits. Thus SOC models could serve as promising tools in prediction of soil organic carbon stock as a consequence of climatic changes and rapid changes in the land use and land management in the future. However, to remove the uncertainties in the modelled SOC estimates, other driving data sets, namely, belowground soil C processes, soil microbial and enzyme activities, may be included in the model structure.

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