Soil Carbon Sequestration in Crop Production

1

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Abstract

The carbon (C) sequestration potential of global soils are estimated between 0.4 and 1.2 Gt C $year^{-1}$ or 5–15 % (1Pg = 1×10^5 g). The C emission is rising rapidly by 2.3% every year. If the emissions continue to rise, warming could reach the levels that are dangerous for the society, but it looks like global emissions might now be taking a different turn in the last few years. As we know the sustainability of agroecosystem largely depends on its C footprint as the soil organic carbon (SOC) stock; it is an indicator of soil health and quality and plays a key role to soil sustainability. At the same time, continuing unsustainable agricultural approaches under intensive farming have depleted most of the SOC pool of global agricultural lands. Still, the terrestrial ecosystem has enormous potential to store the atmospheric C for a considerable period of time. Therefore, promoting the cultivation of crops sustainably offers multiple advantages, e.g. augmenting crop and soil productivity, adapting climate change resilience, and high turnover of above- and below-ground biomass into the soil system, thus sequestering atmospheric C and dropping concentration of GHGs from the atmosphere. The continuous vegetation on soil surface ensures good soil health and soil C concentration at variable soil depth as per the specific crop. The C sequestration potential and the amount of organic C returned by crop plants rest on specific plant species, depending on the nature of growth, root morphology and physiology, leaf morphology, climatic conditions, soil texture, structure and aggregation, prevailing cropping system, and agronomic interventions during crop

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growth period. The above-ground plant biomass, e.g. plant leaves, branches, stem, foliage, fruits, wood, litter-fall, etc., and below-ground plant biomass, e.g. dead roots, released substances from root exudates, rhizospheric deposition, and plant-promoted microbial biomass C, directly contribute to the SOC buildup. Sustainable crop management practice that ensures the increased nitrogen (N) availability accelerates the C input in the soil ecosystem. Farming practices that improve nitrogen and water use efficiency (NUE and WUE) reduce soil disturbance and erosion, increase plant biomass, and together affect N availability and SOC stock. Conservation tillage together with surface residue retention and legume-based sensible crop rotation reduces soil disturbances, surface runoff, and erosion; increases N availability and SOC sequestration; increases soil sustainability by mixed cropping, intercropping, crop rotation, cover cropping, multiple cropping, and relay cropping; and generates and adds greater amount of qualitative plant biomass into the soil. The N addition, especially from bulky organic manure, green manures, leguminous crops, cover crops, biological N-fixing microbes, and farm and kitchen waste materials, is essential for agricultural productivity and SOC sequestration. The C sequestration benefits from addition of chemical nitrogenous fertilizers are compensated by the release of carbon dioxide (CO_2) and nitrous oxide (N_2O) during manufacturing, transportation, storage, and application of fertilizers. Therefore, approaching integrated nutrient management (INM) encompassing manures and other C-rich resources sustains soil health and increases N availability and SOC sequestration. Moreover, location-specific scientific research is needed to point out the best management practices that enhance NUE, maintain/improve soil health, boost crop production and SOC sequestration, and minimize greenhouse gas (GHG) release in the biosphere. In the view of above, in this chapter, quantifying the C sequestration potential with higher degree of confidence is required in agriculture management. The present book chapter is critically analyses the C sequestration potential of different soil and crop management practices under diverse ecological conditions for sustainable crop productivity.

Keywords
Carbon dioxide · Crop production · Soil C sequestration · Sustainable agriculture

Abbreviations

AFS	Agroforestry system
C	Carbon
$CaCO_3$	Calcium carbonate
CH_4	Methane
cm	Centimetre

CO_2	Carbon dioxide
CO_3^{-2}	Carbonate
FYM	Farmyards manure
g	Grams
GHGs	Greenhouse gases
GPP	Gross primary production
Gt	Gigatons
ha	Hectare
HCO_3^-	Bicarbonate
INM	Integrated nutrient management
IPCC	Intergovernmental Panel on Climate Change
kg	Kilograms
Mg	Megagrams
Mt.	Metric tons
N	Nitrogen
N_2O	Nitrous oxide
NPP	Net primary productivity
NUE	Nitrogen use efficiency
OC	Organic carbon
OM	Organic matter
Pg	Picograms
ppm	Parts per million
RMPs	Recommended management practices
SOC	Soil organic carbon
SOM	Soil organic matter
Tg	Teragrams
WUE	Water use efficiency

1.1 Introduction

Enriching soil organic carbon (SOC) pools in agriculture by encouraging soil C sequestration is an efficient way towards diminishing atmospheric carbon dioxide (CO_2) level and inducing soil health (Lal et al. 1999; Post et al. 2004; Bronick and Lal 2005; Lal 2002, 2011; Ashoka et al. 2017). In soil, the C sequestration is characterized by two types: *first*, organic C sequestration – in the form of organic C – which is considered as boon to agriculturalists and, *second*, inorganic C sequestration, in the form of paedogenic calcium carbonate ($CaCO_3$), often called as bane for farmers (Chaudhury et al. 2016; Meena and Meena 2017). The significance of soil as a terrestrial C regulator has been increasingly documented, especially after the Paris Agreement, December 2015, which appeals for action to store and increase the sink capacity of greenhouse gases (GHGs) (FAO 2016). Even after knowing the significance of world's soil as a potential sink and pool of C (Lal 2011), the knowledge about the existing soil C reserves and its capacity of sequestering C is so far incomplete (FAO 2016). However, scientists are trying to optimize the management skills through sustainable crop cultivation so that soils can function as sinks more effectively for C and pay to CO_2 diminution strategies (Curtin et al. 2000; Yadav et al. 2018b). After oceans (38,000 gigatons/Gt C), the soil is the second largest C pool of the Earth, and a little change in organic C reserve in soil may cause significant alteration in atmospheric CO_2. It is important to understand for the reason that the annual flux of CO_2 between soil and atmosphere is big and depends on man-made alterations (Bakker et al. 2007; Kumar et al. 2017b; Dadhich and Meena 2014). The atmosphere holds about 750 Pg (picograms) of C as CO_2, whereas globally (excluding permafrost) the upper 100 cm soil holds about 1500 Pg C (1 Pg = 1 Gt = 1015 g) (2500 Pg C in top 200 cm) in the form of SOC and 900–1700 Pg as inorganic C, and this soil exchanges 60 Pg C with the atmosphere every year (Eswaran et al. 1993; Lal 2010; Meena et al. 2015d). It was estimated that global soils hold nearly 1.5×10^{12} metric tons of C. In actual, the SOC sequestration potential seems to be between 0.37 and 1.15 Gt C annually (Smith et al. 2008). The rate of soil sequestration in soils under agricultural use varied from 0.1 to 1.0 tons C hectare^{-1} every year (Paustian et al. 2016). Accordingly, there is a huge available gap to reach the potential capacity of soil to sequester C. We should have to manage the billion hectares of land to sequester C so as to touch the annual sequestration rate of 1 Gt C. Moreover, the sequestration level would be comparatively less at the start which would reach at its peak after 20 years and thereafter would decrease gradually (Sommer and Bossio 2014; Yadav et al. 2018a).

The change in organic C content in soil is directly linked with the total amount of Cic substance entered (Buyanovsky and Wagner 2002). The SOC pool is considered as the key indicator of soil fertility and health, and an upmost C pool in terrestrial ecosystem had a very imperative role in global C cycle (Wang et al. 2015). The concentration of SOC in soil is about twice to that of atmosphere and vegetation. So, if the concentration of C is increased, the atmospheric C concentration will get reduced, and it will consequently assuage the problem of global warming and climate change. The soil organic matter (SOM) is linked in a straight line to the SOC; meanwhile, organic C contains 58% of the SOM (Collins et al. 1997). It was projected that 1 ton of SOM is emitted in about 3.667 tons of CO_2 into the atmosphere (Meena et al. 2016a). The SOC is the biggest C pool in the terrestrial biosphere, chiefly greater than double of the C accumulated in the atmosphere and vegetative biomass (Jobbagy and Jackson 2000; Liang et al. 2016; Varma et al. 2017a). In top 30 cm soil profile, the average concentration of SOC ranged from 0.30% to 1.05%. It is around 10% of the SOC stocks (140~170 Pg) in agricultural ecosystem and utmost active fragment of the world's terrestrial soil C pool of farmland ecosystem (Liang et al. 2016; Datta et al. 2017a). The farmland harbours of China hold SOC approximately 25–27 Pg and had an imperative contribution in the global C budget (Qin et al. 2013).

The C capturing capacity of soil can be enhanced and improved via improved farming practices that restore soil fertility and health. Promoting sustainable crop cultivation offers multiple advantages: augmenting crop and soil productivity, adapting climate change resilience, sequestering atmospheric C, and dropping concentration of GHGs from the atmosphere (FAO and ITPS 2015). With the purpose to tap the C sequestration potential of soil, the cultivation of plants having higher biomass production capability needs to be endorsed in the agricultural system (FAO and ITPS 2015). Crop residues are one of the chief sources of C in agricultural soils. Agricultural crops produce a considerable quantity of residues, which in turn favours the accumulation of humus in consequent soil C pool upon incorporation into soil (Hajduk et al. 2015; Meena and Yadav 2015). In this chapter, the emphasis is on the magnitude of the potential impacts of agricultural crops that have a capacity to soil C sequestration.

1.2 Global Carbon Cycle

It is very important to study the circulation of C on the planet as the C is a major structural component of living organism comprising about 50% of their dry weight, besides its active involvement in the global energy flow and metabolism of natural, human, and industrial systems (Houghton 2003; Dhakal et al. 2015). The C cycle is the biochemical cycle of continuous C exchange among the atmosphere, biosphere, hydrosphere, geosphere, and pedosphere on the planet through the combined process of photosynthesis, respiration, and OM decomposition (Fig. 1.1). The global C cycle is comprised of five major interconnected reservoirs – the atmosphere, terrestrial biosphere, oceans, sediments, and the Earth's interior (David 2010). The C continuously moves through exchange pathways among these reservoirs as a result of numerous physical, chemical, and biological processes (Falkowski et al. 2000; Varma

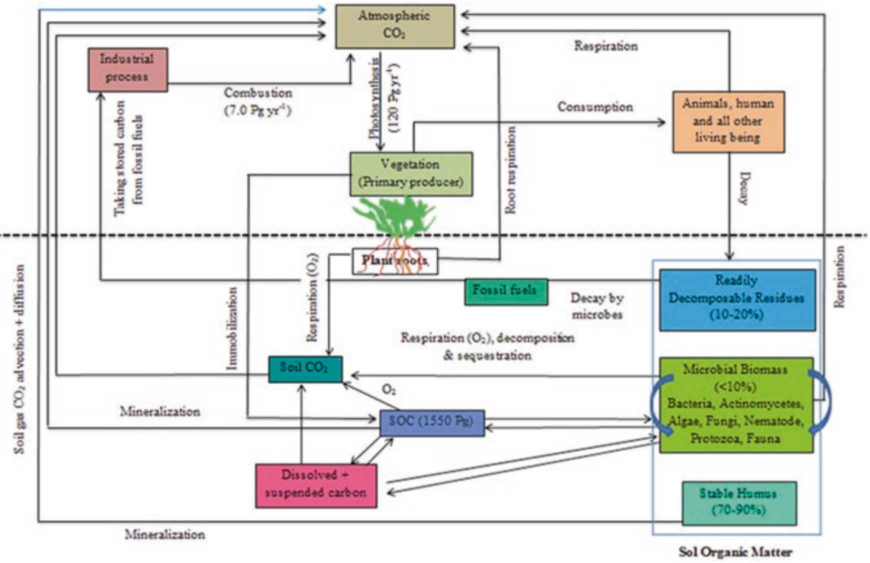

Fig. 1.1 Schematic diagram of global C cycle. (Data adapted from Lal 2008)

et al. 2017b; Meena and Lal 2018). This cycle starts with the biological C fixation – the conversion of atmospheric CO_2 into the living biomass C through the biochemical process of photosynthesis by the more favoured photosynthetic eukaryotes and prokaryotes (Bleam 2012). The photosynthetic process reduces C (+4) in CO_2 to C (+1) in the terminal C in glyceraldehyde-3-phosphate, the feedstock for simple sugars, amino acids, and lipids (Bleam 2012). Here, the gross primary production (GPP) is the measure of quantity of atmospheric CO_2 removed by photosynthesis every year. According to an estimate, photosynthesis captures 120 Pg C year^{-1} from the atmosphere reservoir and is able to accumulate around 610 Pg C within the living plant at any given time. A part of the photosynthesized biomass C retained by the living plant is directly consumed by the herbivores, while the remaining biomass C becomes the soil residue inviting the diverse soil microbes to attack and decompose, which is known as C mineralization (Bleam 2012; Meena and Yadav 2014). This mineralization of SOC into CO_2 occurs through a process called oxidative metabolism in which chemical energy is stored during C-fixation. Respiration (including decomposition of soil biomass) by plant, human, animals, and soil pays back the C into the atmosphere in the form of CO_2 and methane (CH_4) under anaerobic situations. Forest fires also greatly contribute CO_2 and CH_4 emission to the atmosphere on annual timescales, but again it is removed by the terrestrial biosphere if vegetation regrows over the decades (IPCC 2007). The plant respiration alone accounts the 50 % of the CO_2 (60 Pg C year^{-1}) that is returned to the atmosphere in the terrestrial C pool. Similarly, with the decomposition of SOM by the soil microbes, the CO_2 is released at the average rate of around 60 Pg C year^{-1}. The CO_2 released by use of fossil fuel, deforestation, and cement production promoted by human activities accelerates the C exchange chain between atmosphere, terrestrial biosphere, and the oceans. At present, about 5.5×10^{15} g (grams) of anthropogenic C is being added in the atmosphere each year. Of them, about 50 % is retained by the atmosphere, while the second half is moved to the terrestrial and oceanic system. Immediately after entering the CO_2 into the ocean, it reacts with water to form carbonate (CO_3^{-2}) and bicarbonate (HCO_3^-) ions (dissolved inorganic C). The residential time of such type of CO_2 in the ocean is less than a decade. The combustion of fossil fuel is one of the rapid emission fluxes of large amount of C. Currently, it represents a flux to the atmosphere of approximately 6–8 PgC year^{-1} (averagely 7 Pg C).

The C cycle consists of six important steps:

1. Movement of C from atmosphere to plants through photosynthesis
2. C movement from plants to animals through food chain
3. Transformation of C from plants and animals to the ground after the death of animals and plants and their subsequent decompositions
4. Release of C from living organisms to the atmosphere through the respiration by soil, plant, animal, and human being
5. C movement from fossil fuels to the atmosphere when fossils fuels are burned
6. Direct absorption of atmospheric CO_2 by the oceans

1.3 Carbon Dioxide Emission Trend and Present Status in Atmosphere

In 1958, Dave Keeling – an American scientist – took the first measurement of CO_2 at Mauna Loa Observatory in Hawaii and at Scripps Institution of Oceanography and alerted the globe to the possibility of anthropogenic greenhouse gas effect and global warming. He was the first to register the rise of CO_2 in the atmosphere. In 2005, scientists around the world started to keep track of C emissions. Since pre-industrialization time (1750s), the global atmospheric CO_2 concentration is continuing to increase from approximately 280 ppm (part per millions) (IPCC 2007) to 406.99 ppm at the end of August 2018 with annual average growth rate of 0.47 ppm $year^{-1}$, although it was 2.7 ppm $year^{-1}$ for the past 2006–2015.The atmospheric CO_2 reached the record height of 410.31 ppm in the history for the month of April 2018 as per the report from Mauna Loa Observatory, Hawaii. The increase in annual means from 2015 to 2016, 2.63 ppm, is higher than the increase from 2014 to 2015 and 2013 to 2014 (~2.3 and 2.1 ppm $year^{-1}$, respectively) (WMO 2016). The atmospheric CO_2 abundance in 2016 relative to year 1750 was 144.5%. The relative increment from 2015 to 2016 was 0.67%. According to a study, the atmospheric CO_2 concentration is now increasing at the rate of 100 times faster over the rate which was at the end of ice age owing to the uncontrolled population growth, rapid industrialization, intensive cultivation, and continuous deforestation promoted by human. Therefore, the release of CO_2 into the atmosphere as a result of anthropogenic activities is of great concern. In fact, human activities were responsible for about 110% of observed warming (ranging from 72% to 146%), with natural factors in isolation leading to a slight cooling over the past 50 years as pointed out by IPCC's implied best guess by NASA's Dr. Gavin Schmidt (FAO 2016). In the year 2015, the total CO_2 emission from fossil fuel combustion and cement production from industries was 9.9 ± 0.5 Gt C $year^{-1}$, and from land-use pattern mainly deforestation, it was 1.3 ± 0.5 Gt C $year^{-1}$(Le Quéré et al. 2016; WMO 2016). During the last decade (2006–2015), the growth rate of global atmospheric CO_2 level, mean ocean CO_2 sink, and global residual terrestrial CO_2 sink were 4.5 ± 0.1, 2.6 ± 0.5, and 3.1 ± 0.9 Gt C $year^{-1}$, whereas, in 2015, they were 6.3 ± 0.2, 3.0 ± 0.5, and 1.9 ± 0.9, respectively (Le Quéré et al. 2016; Yadav et al. 2017c). The CO_2 emitted from the deforestation and land-use change activities was the prime factor behind increased CO_2 level in the atmosphere above preindustrial levels (Ciais et al. 2013; Verma et al. 2015c).

Over the globe, the total greenhouse gas CO_2 emission in the year 2016 continued to increase at the rate of 0.5 ± 1%, about 53.4 Gt CO_2 equivalent (including those from land use and forestry – 4.1 Gt CO_2 eq.) (Olivier et al. 2017; Meena et al. 2018a). But, if we look forward, we can find that in the recent 3 years, the amount of CO_2 in the atmosphere being released from burning of fossil fuels, gas flaring, and cement manufacturing is consistent. In 2014, the growth in global CO_2 emissions was 1.1% (40.3 Gt CO_2 eq.); in 2015, it did not grow at all and remains almost stable (39.7 Gt CO_2 eq.); and in 2016, they are set to grow very little by just 0.3% (Olivier et al. 2016; Kumar et al. 2018a). This growth in emission trends looks prominently a slowdown over the growth rate of 3.5% in the 2000s and 1.8% in the recent last decade (2006–2015). The main reason behind this slowdown was the change in energy use by the people in China by decreased consumption of coal and fuel and increased use of natural gases and promoting renewable power generation (e.g., wind, solar power, etc.) (Olivier et al. 2017). The leading five emitters China, the United States, India, Russian Federation, and Japan in 2016 covered about 68 % of total global CO_2 emissions (Olivier et al. 2017; Meena et al. 2015c). China is the world's top emitter accounting 10,357 metric tons (Mt) (29%) of global CO_2 emissions, and the United States is the second biggest emitter, responsible for 5414 Mt. CO_2 (15%) of global emissions in 2015. The US emissions since the last decade have been going down because of reduced burning of coal and increased usage of oil and gas; this is why the emissions of the United States fell down by 2.6% in 2015 and also dropped further by 2.0% in 2016 (Olivier et al. 2016, 2017; Yadav et al. 2017b). But it will be a little bit early to say confidently that it has reached its peak as the emissions would increase in the Trump presidency. The emissions across the developing nations are also rising. India is responsible for the 2274 Mt. CO_2 (6.3%) of the global CO_2 emissions which were increased by 4.7% in 2016. Russia and Japan rank fourth and fifth in global emissions, which account 1617 Mt. (4.5%) and 1237 Mt. CO_2 (3.4%), respectively.

C budget is the balance between sink and source of C. The C sources from fossil fuels, industry, and land-use change emissions are balanced by the atmosphere and C sinks on land and in the oceans. The global CO_2 emissions and their segregation among the land, ocean, and atmosphere are in balance:

$$E_{FF} + E_{LUE} = G_R + S_O + S_L$$

where E_{FF} is the emissions from fossil fuels and industry, E_{LUE} emissions from land-use change, G_R rate of growth of CO_2, S_O mean ocean CO_2 sink, and S_L global residual terrestrial CO_2 sink.

The growth rate is usually expressed in terms of ppm year^{-1}, which can be converted to Gt C year^{-1} (Gt of C year^{-1}) using 1 ppm = 2.12 Gt C (Prather et al. 2012; Ballantyne et al. 2012; C. Le Quéré et al. 2016; Dadhich et al. 2015).

However, all CO_2 released do not stay in the atmosphere. It is absorbed either by the vegetation on land or in the oceans, minimizing the warming potential which we experience. In 2015, out of the total global CO_2 emissions, 44% CO_2 remained in the atmosphere (below blue light) and 31% (green) is absorbed by plants and 26% (dark blue) by oceans. The total global CO_2 emissions from industrialization time to by the end of 2016 will total 565 billion tons of C which is 92% of the global C budget. Over the last 10 years, the average CO_2 released from fossil fuels and industry are responsible for 91% of anthropogenic emissions, whereas the remaining 9% comes from change in land-use pattern. In 2015, 9.9 billion tons of C was emitted in the atmosphere from fossil fuels in the form of CO_2, which came from burning of coal (41%), oil (34%), and gas (19%) along with cement production (5.6%) and faring (0.7%) (Meena et al. 2016b; Kumar et al. 2018b).

1.4 Soil Carbon Decline Under Intensive Cropping

The intensive cultivation without caring for sustainability of the system resulted in the common problem of reduced SOC stock since long. Most of the global agricultural soils have already lost organic C by 30–75 % from their antecedent SOC flux because of intensive cultivation. It has been projected that the global cultivated soils have already lost 41–55 Pg C (Paustian et al. 1995). Although Smith et al. (2008) stated that the global soils have been experienced as loss of in excess of 40 Pg C due to its cultivation with an average rate of about 1.6 Pg C $year^{-1}$ to the atmosphere in the course of 1990s (Smith et al. 2008; Verma et al. 2015a). However, Lal (2013) reported that the prolonged intensive cultivation is supposed to decrease the soil C stock at the rate of 0.1–1.0 % $year^{-1}$. The soils of India severely depleted the SOC pool which ranged from <1.0 g kg^{-1} (kilograms) to hardly 10–15 Mg (Megagrams) C ha^{-1} (hectare) in upper 40 cm soil horizons (Lal 2015a). The Chinese soils have also lost equal or greater than 30–50 % of the soil C flux (Lal 2013). And in Sweden, nowadays, the C reserve is declining at the annual rate of 1.0 Tg (teragrams) from the total C stock of 270 Tg C in top 25 cm soil surface under agriculture (Andren et al. 2008). The average rate of soil C depletion in soils of England and Wales has been projected to be 0.6% annually (Bellamy et al. 2005). The extent of C loss ranges from 10 to 30 Mg C ha^{-1}, reliant on the type of soil and historic land-use pattern, which is higher in soils prone to erosion, salinization, and nutrient diminution than the C loss from least or undegraded soils (Lal 2013). The historical C losses from global soil are estimated to be 78 ± 12 Pg (Lal 2004a, b, c; Buragohain et al. 2017).

Intensive agriculture has a strong capacity to reduce the soil C level in a relatively short time period following initial cultivation, though the degree of reduction varies with the ecosystem and management practices like soil cover, climatic and edaphic characteristics, and farming practices (Poeplau et al. 2011; Powers et al. 2011; Cusack et al. 2013; Meena et al. 2015a). The short-lived impacts are in general dramatic, and agricultural ecosystem may have-long term effects on soil C pool that last for several decades after deserting agriculture (Solomon et al. 2007; Kumar et al. 2017a). The C depletion at the initial time was associated with disruption of soil aggregation, accelerated aeration and decomposition, alteration in plant productivity, biomass production and soil biological properties, and induced soil erosion (Culman et al. 2010; Datta et al. 2017b). The deteriorating soil aggregation as a result of soil cultivation can also lead to increased C loss and consecutive decrement in retention of new C addition (Six et al. 2000). The reduced C status over a long time period was associated with the elongated intensive agricultural practices with less C addition (Solomon et al. 2007). Likewise, the C deposition rate can decrease with time with leftover of C content for longer beneath pre-agricultural levels (Su et al. 2009). These changing trends may expound by increased C losses in the course of cultivation or we can say the lack of ability of agricultural soils to retain the C after crop harvest. The C added by crop plants into the soils is probable to be more liable and susceptible to decomposition than that of the C returned by the woody plants that would be present in the field during the crop growing period (Helfrich et al. 2006; Meena et al. 2017a). Along with these factors, the biomass removal and soil disturbance could result in soil C losses for the duration of cultivation. The lack of strong association of SOC with mineral surfaces is also the reason of reduced soil C retention capacity after crop harvest. To maintain the soil C over long period varies C returns with different practices and the approaches those reduce the C emission from soil. The intensive agriculture can change the C chemistry in the soil through altering plant chemistry, C decomposition rate, etc. (Cusack et al. 2013).

The unsustainable agricultural intensification and change in pattern of land use from natural system to intensive agricultural system management is known to deplete the soil C pool (Guo and Gifford 2002; Söderström et al. 2014; Yadav et al. 2017a). Scientific reports suggested the decreased C stock in permanent cropping system transformed from natural forest land, hastily in the initial years and thereafter at slower rate which reaches at equilibrium after 30–50 years (Nieder and Benbi 2008; Benbi and Brar 2009; Sofi et al. 2018). In the same line, the result of meta-analysis carried out by Guo and Gifford (2002) showed the declined soil C concentration after land-use change from native forest to cropland (−42%) and plantation forest (−13%) and also from pasture to cropland (−52%) and plantation (−10%). This depletion was associated with intensified cultivation practices which have high OM exerting rate, mineralization/oxidation, and soil erosion (Söderström et al. 2014; Ram and Meena 2014). Currently, several agricultural strategies are practiced that expose the agricultural soils to soil erosion. In the last 40 years, about 33 % of global arable land has been lost by erosion or pollution. Soil erosion is the prime factor in substantial removal of SOM and emission of CO_2 into the atmosphere. In a experiment on maize diminished SOC level was recorded by 50% in upper 50 cm soil horizons in temperate region at the end of 35 years of intensive cultivation (Arrouays and Pelissier 1994). Liu et al. (2003) also displayed a substantial drop of gross SOC content during the initial 5 years of cultivation with an average annual loss of 2300 kg C ha^{-1} in 0–17 cm soil profile. After 5 years of cultivation till 14 years, the SOC losses also occurred but with decreasing trend with an average annual loss of 950 kg C ha^{-1}, and the same decreasing trend still exists between 14 and 50 years of cultivation with a mean loss value of 290 kg C ha^{-1}. The overall losses of total SOC in upper 0–43 cm soil profile (0–17 + 18–32 + 33–43 cm) were 17, 28, and 55% after 5, 14, and 50 years, respectively, of intensive cultivation in mollisols of China. The soils of Southern and Central Asia and of sub-Saharan Africa have higher degree of SOC loss. The SOC content in most of South Asian soils ranged from 0.1% to 0.5%. In different regions of India, the SOC concentration significantly decreased after the 1960s (a period of intensive cultivation) as compared to the uncultivated soils prior to the 1960s in top 20 cm soil horizon (Lal 2013). In this line, Jenny and Raychaudhuri (1960) summarized the data of different provinces of India and found the considerable depletion in SOC level (0–20 cm soil) after intensive farming practices. The SOC level in southeastern coast, western coast (per humid), western coast (humid), and Nagpur region of India were decreased from 0.76% to 0.30%, 2.46% to 1.36%, 1.86% to 0.92%, and 1.09% to 0.55%, respectively, when soils were under cultivation. Cusack et al. (2013) examined the potential impact of 200 years of intensive agriculture on soil C level and their chemistry in Hawaii by comparing the reference soil under modem management with intensified pre-European-contact agricultural field system. They reported the declined trend in soil C stocks in Hawaiian agricultural fields (6.1 ± 0.6%) rather than the fallow reference soils (9.3 ± 1.2%). Therefore, the average soil C stock in soil under pre-contact agriculture was reduced by 26 ± 12% relative to the soils of reference sites after intensive 200 years of cultivation.

Globally, the declining C status in soils under agricultural ecosystem is a matter of considerable discussion. As a region of 12 per cent of the total soil C pool is still exists present in cultivated soil (Andren et al. 2008), and the soil under agriculture reside in 35 per cent of the global land surface (Söderström et al. 2014). The technical potential of C sequestration in world soils is 1.2–3.1 Pg $year^{-1}$ for 25–50 years (Lal 2013). By considering the above facts, there is urgent demand of time to rethink about the adoption of sustainable agricultural practices in the twenty-first century. The SOM is not only an indicator of C presence but is also an imperative sink of C sequestration. The SOC represents the largest C pool in terrestrial ecosystems, and is a key factor in deciding the soil quality and input use efficiency (Wiesmeier et al. 2016; Meena et al. 2017b). But the long-term exhaustive farming practices deplete the SOC concentration and result in deterioration of soil structure and consequently the soil productivity (Liu et al. 2013b, c). So, it is a need to improve the critical level of C about 1.1% in the rhizospheric zones (Lal 2013). At present, the intensive agriculture is not sustainable, so the sustainable intensification is a good tactic to save the SOC loss. By changing the land-use pattern following sustainable ways such as through introducing higher biomass-producing crops, shrubs, and tree species in the existing system, the annual C sequestration rate could be increased by 20–75 g C m^{-2} and SOC may reach a new equilibrium in the interior several years (Liu et al. 2013b, c; Kakraliya et al. 2018).

1.5 Principles of Soil Carbon Sequestration

Kane (2015) established four pillars for managing soil C dynamics:

1. Reducing soil disturbance through tillage to ensure the physical shelter of C in soil aggregates
2. Enhancing the quantity and quality of plant and animal biomass input in to the soil strata
3. Improving the diversity, abundance and functionaries of beneficial soil microbes
4. Maintaining continuous vegetative cover on soil surface

The capture of atmospheric CO_2 and their subsequent storage in the terrestrial ecosystem by a sustainable management of soil and vegetation comprises several agronomic interactions as follows:

- Elimination of mechanical soil disturbance by adopting zero tillage or drastically reduced tillage system (Shaver et al. 2002)

- Continuous surface cover either with living vegetation or crop residue in the form of mulch round the year (Lal 2004a, b, c; 2010; 2016)
- Adoption of agronomic and mechanical measures together to reduce the surface runoff and soil and water erosion by obstructing the velocity of wind and water (Lal 2016)

Accelerating soil health and fertility through practicing INM inclosing organic nutrition sources, biological N fixers/legumes in rotation, mycorrhizae, and organic home wastes promotes in situ OM buildup, potential activities, and diversity of soil bio-organisms and maintains sustainability of soil ecosystem (Liu et al. 2013b, c; Han et al. 2016; Dhakal et al. 2016):

- Maintain adequate soil moisture in crop root zone to increase green water content by improving WUE through introducing drip-cum-fertigation technique and by eliminating or minimizing water loss through evaporation (grey water) and runoff (blue water) (Kumari and Nema 2015).
- Improvements in quality and dietary practices of animal feed to reduce the formation and emission of CH_4 through enteric fermentation.
- Follow the system approach rather than an individual crop including livestock and agroforestry along with multiple viable crops in the farming system for efficient resource utilization and biodiversity conservation and to work within the natural ecosystem (Rotenberg and Yakir 2010; Wang et al. 2010, 2015).

1.6 Carbon Sequestration Potential of Crop Land

Soil is the major reservoir and a very important sink of C in the terrestrial C cycle because of its capacity to withhold C for relatively a long period of time (Swift 2001). The global soils contain double the amount of C to that of stored in atmosphere plus living vegetation. The C sequestration potential of a soil depends on its capacity to maintain the stock of resistant plant materials to biological decomposition, chemical makeup of SOM, and accumulate the humic fractions more. The amount of C that a soil can sequester rely on the vegetation it supports, soil depth, its drainage capacity, mineral composition, soil temperature, and the relative proportion of soil water and air (Swift 2001). The improved land-use change regulates the budget and transfers of C in terrestrial ecosystem (Lal et al. 2003; Layek et al. 2018). The judicious management of croplands, grasslands, forest, and restored lands are crucial for enhancing the C sequestration potential of soil (Lal 2002), i.e. transforming croplands to grasslands proved in increased soil C. This conversion can be made over the entire field or in confined spots like for shelterbelts, grassed waterway, or field borders. The replacement of conventional agricultural practices by improved land management practices such as introduction of zero tillage or drastically reduced tillage that reduces soil disturbance and incorporation of crop residue into the soil ecosystem has potential to capture the atmospheric C and store in soil as long as these are practiced. The SOC sequestration rate of 570 ± 140 kg C ha^{-1} $year^{-1}$ upon conversion of intensive/plow tillage to zero tillage system after

Table 1.1 Conversion of conventional unscientific farming practices to improved sustainable practices

S. No.	Conventional practices	Improved sustainable practices
1.	Intensive tillage and clean cultivation	Conservation tillage/no-till/drastically reduced tillage
2.	Crop residue burning and removal	Residue retention on soil surface/mulch farming
3.	Summer fallow	Raising cover crops
4.	Synthetic fertilizer use	Site specific nutrient management with compost, biosolids and nutrient cycling
5.	Low input subsistence farming	Judicious use of organic and inorganic nutrient sources
6.	Uncontrolled water use	Water/irrigation conservation/management, water table management
7.	Fence-to-fence cultivation	Marginal agricultural land transformation in to natural conservation/grasslands
8.	Continuous monoculture	Intercropping, mixed cropping, integrated farming system including legumes in rotation
9.	Land use along poverty lines and political boundaries	Integrated watershed management
10.	Draining of wetland	Restoration of wetlands
11.	Deforestation	Afforestation
12.	Naked/barren soil	Soil cover including terrace, vegetative barriers, shelterbelts
13.	Unscientific pasture management	Improved pasture with perennial legume, improved grasses and legume shrubs
14.	Indiscriminate use of pesticides	Integrated pest management

analysis of 67 long-term experiments in diverse agroecological situations of globe. This figure of SOC pool may reach at new heights in 40–60 years. This conversion of intensive tillage to zero tillage farming on 1500 million ha of cultivated lands besides best recommended management practices (RMPs) could result in sequestration of 0.5–1.0 Pg C year^{-1} by 2050. The conversion of summer fallow by growing of leguminous cover crop permanently is a vital strategy to curtail the depletion in SOC flux. Therefore, the changes in existing land-use pattern towards more ruminative and improved land-use pattern and management practices reduce the soil C depletion, at least partially, and enhance the C sequestration potential of agricultural soils (Table 1.1).

The current rate of C loss due to land-use change (deforestation) and related land-change processes (erosion, tillage operations, biomass burning, excessive fertilizers, residue removal, and drainage of peat lands) is between 0.7 and 2.1 Gt C year^{-1} (World Bank 2012). Presently, the terrestrial sink capacity is increasing at the rate of 1.4 ± 0.7 Pg C annually. Accordingly, terrestrial sink grips nearly 2–4 Pg C year^{-1} whose sink potential could reach at the digit of 5.0 Pg C year^{-1} by 2050 owing to CO_2 fertilization effect, sustainable land-use conversion. and viable agronomic management practices. The various improved land conservation practices and their mean soil C sequestration rates across the globe are presented in Table 1.2.

The C sequestration potential of global soil is estimated between 0.4 and 1.2 Gt C year^{-1} or 5–15 % (1Pg = 1 × 10^5 g) (Lal 2004a, b, c). Similarly, the SOC sequestration

Table 1.2 Land-use changes and mean soil C sequestration rates (kg C ha^{-1} year^{-1}) (World Bank 2012)

Land-use change	Africa	Asia	Latin America
Crop-to-forest	1163	932	528
Crop-to-plantation	–	878	893
Crop-to-grassland	–	302	–
Crop-to-pasture	–	–	1116
Pasture-to-forest	–	–	362
Pasture-to-plantation	–	–	1169
Pasture improvement	799	–	1687
Grassland-to-plantation	–	–	−406
Annual-to-perennial	–	1004	526
Restoration of wetlands	–	471	–
Intensive vegetables and specialty crops	–	2580	–
Exclusion or reduction in grazing	–	502	172

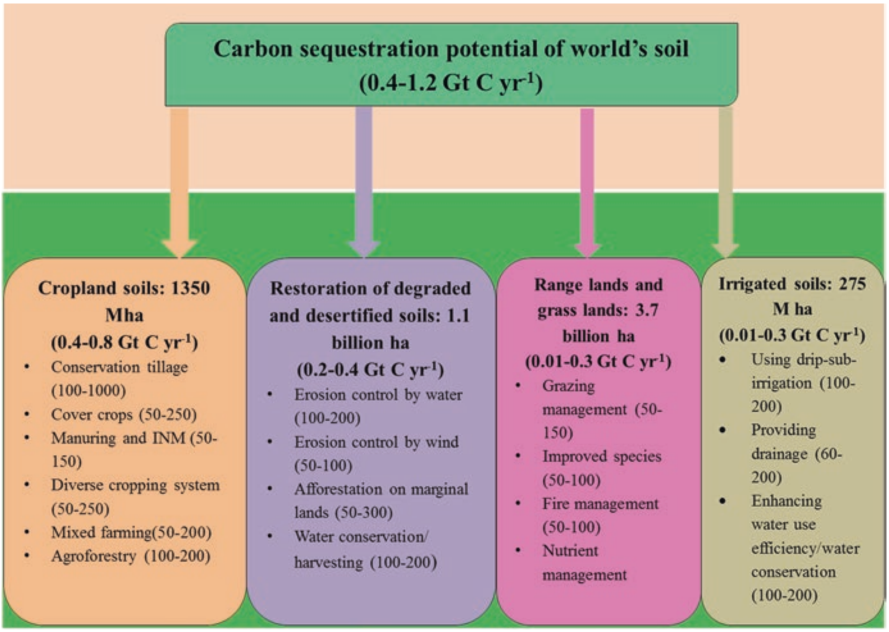

Fig. 1.2 Carbon sequestration potential of world's soil. (Data adapted from Lal 2004a, b, c)

range of croplands (1350 M ha) varies from 0.4 to 0.8 Gt C year^{-1} in forest and degraded lands (1.1 billion ha) from 0.2 to 0.4 Gt C year^{-1} and 0.01 to 0.3 Gt C year^{-1} in each of rangelands and grasslands (3.7 billion ha), and irrigated soils (275 M ha), respectively (Fig. 1.2).Globally, nearly about 750 million ha of soils is degraded in the tropics with a huge potential of afforestation and soil C restoration. The C sequestration potential of these degraded soils is about 0.5 Mg ha^{-1} $year^{-1}$ as SOC besides additional biomass accumulation rate of 1.0 Mg ha^{-1} $year^{-1}$. Therefore, these soils have the potential to store approximately 1.1 Pg C ha^{-1} $year^{-1}$. According to an estimate (Lal 2002), desertification control in arid and semi-arid regions has the SOC sequestration potential of 0.4–0.7 Pg C $year^{-1}$. According to the Intergovernmental Panel on Climate Change (IPCC) Assessment Report, the global agricultural soils could sequester 400–800 Tg C $year^{-1}$ with the finite capacity saturating after 50–100 years (Verma et al. 2015b). The croplands of Europe have the biological C sequestration potential of 90–120 Tg C annually with best crop and soil management practices when the soil is not disturbed (no/reduced tillage) and efficient utilization of organic amendments. Similarly, the rate of SOC sequestration potential of Chinese soils with improved crop and soil management was estimated to be 2–2.5 Pg C by the 2050s (Sun et al. 2010). Crop and soil management approaches that promote the soil C sequestration take account of the following.

1.7 Soil Carbon Pools Improve Sustainability

Sustainability of an agricultural ecosystem strongly hinge on its C footmark. So, the SOC flux is a vital indicator of soil quality and an important driver of agricultural sustainability (Lal 2015b). The changes in land-use system or adaptation of prolonged unsustainable management strategies have already lost the concentration of SOC. The soil C pool is considered as key indicator of soil quality and sustainability of soil ecosystem as a consequence of its influence on soil physical, biological, chemical, and ecological properties (Reeves 1997). Recently, United Kingdom's 'Sustainable Farming and Food Strategy' selected the SOM as the momentous indicator for soil health and quality in the United Kingdom (Anon 2006). The function and significance of SOM is basically associated with its dynamic nature, being constantly synthesized, mineralized, and reorganized (Grego and Lagomarsino 2008). Several researchers documented the improvement in soil physical, biological, chemical, and ecological parameters only because the enrichment of soil by OC is basically based on anecdotal evidence (Bhogal et al. 2009; Meena et al. 2018c). The arable land has been extensively concerned in the worsening of soil health, functionality, and quality through the diminution of soil C stock associated with oxidation next to cultivation. The SOM has long been known as a crucial element in soil quality. The OM has direct effects on the soil available water and indirectly the soil pore distribution. The SOC enhances the stability of soil aggregates and structure because SOM remains physically protected in the core of soil aggregates. The stability of soil aggregation decides the soil water contents, gaseous exchange between soil and atmosphere, soil microbial communities, and nutrient cycling (Sexstone et al. 1985). The soil structure is comprised of primary soil particles and macro- and micro-aggregates acting as physical units of aggregates. The turnover of plant residue in soil is the base of soil aggregation which ensures the availability of C to the soil microbial community as a source of metabolic energy, leading to improvement in soil biological diversity and stimulating biodegradation of harmful soil contaminants (Grego and Lagomarsino 2008; Meena et al. 2015e). These soil microscopic populations and plant-derived carbohydrates are responsible for the creation of soil aggregates by acting as binding force (Six et al. 2000). The turnover rate of SOM influences the biogeochemical transformation of nutrients and associated biochemical processes and thus the agronomic productivity sustainably (Lal 2015b). The increasing SOC stock improves the soil fertility while decreasing the vulnerability of soil to degradation. The plant nutrition is largely owed to the active and water-soluble portions. The dissolved organic fraction has a direct encouraging influence on root growth and nutrient uptake by them (Grego and Lagomarsino 2008). The SOC acts as a buffer counter to immediate change in soil pH filtering agrochemicals and promoting their biodegradation (Grego and Lagomarsino 2008). (Lal 2015a). No doubt, the SOC flux is the utmost reliable pointer of regulating soil degradation, more importantly that caused by androgenic erosions (Rajan et al. 2010). As we know the SOC is a long-lasting component of global C cycle whose concentration in soil is about twice to that of atmosphere and vegetation. So, if the concentration of C is increased, the atmospheric C concentration will get reduced and consequently assuage the problem of global warming and climate change.

1.8 Soil Carbon Restoration Options

The SOC sequestration rate ranges between negative to nil in arid and hot climatic regions and 1000 kg C ha^{-1} year^{-1} in temperate and humid regions (Lal 2004a, b, c). But the general mean SOC sequestration rate of agricultural soils ranges between 200 and 250 kg C ha^{1} year^{-1} (Lal 2008). The re-carbonization of the exhausted C flux has need of steady Cic biomass addition which is essential for several functions (Lal 2015a). By looking forward the population explosion and economical emergencies, especially in India, China, Mexico, and Brazil, the significance of innovative agricultural approaches and their impacts on soil and ecological dimensions need to be considered more now than in the ancient. But still, it is needed to critically analyse the biophysical constraints, stabilization mechanisms, relevant economics, and policies with the intension of stabilization of SOC sequestration (Lal 2008). Therefore, implementation of sustainable and viable management practices at ground level in agricultural and forest soils is a vital strategy for soil C sequestration (Lal et al. 2003; Meena et al. 2015b).The practice that can improve the agricultural production in unit area along with a considerable improvement of SOC turnover must be preferred. While, care should be taken when selecting the appropriate farming practice as some approaches are able to accelerate the economical production, but still are C exhaustive in nature, and so increases CO_2 emission from soil into the atmosphere. The land improvement practices that accelerate C addition through increasing net primary productivity (NPP) should be enhance to the C sequestration close to their potential mark. However, it is assumed that by the implementation of sustainable management practices only 50–66% of their capacity is attainable.

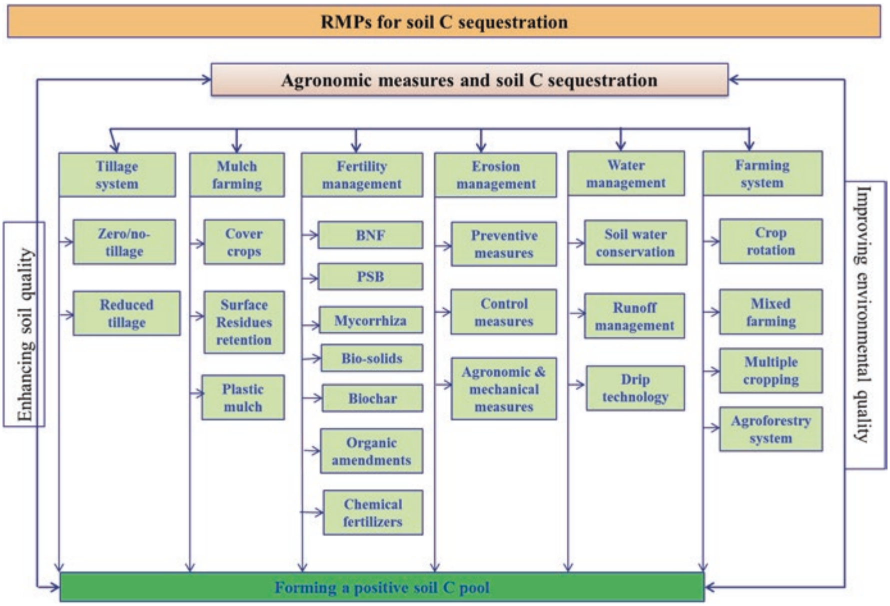

Fig. 1.3 Recommended management practices (RMPs) for soil carbon sequestration. (Modified Lal 2004a, b, c)

In agricultural ecosystem, the rate of soil C sequestration can be regulated through change in existing land-use pattern, farming system, tillage, soil fertility maintenance, and pest management methods. Practically, there are numerous improved sustainable agricultural practices to be followed instead of non-scientific traditional approaches in C-depleted soils for ensuring good soil C build-up (Fig. 1.3). The sustainable management practices improve the soil, need based nutrient to sustain the soil health, and efficient water management to improve water use efficiency, sustainable pest management with minimal possible use of agro-chemicals, conservation tillage, surface residue retention, mulching, crop rotation, mixed farming, intercropping, cover cropping, strip cropping, and vegetative barriers enlarges C accumulation in soil. Besides this, agricultural strategies also include rescheduling of farm management practices such as irrigation and nutrient application to better match critical growth stages and introducing and implementing efficient technologies that conserve water and soil. Appropriate land uses through intensifying the prime agricultural lands, multiple cropping, improved pasture with low stocking rate, and restoring wetlands and by converting marginal agricultural land to grassland are more desirable options for soil C enrichment. The improved farming practices via adapting ecologically sustained strategy with high diversity, mixed farming, sensible crop rotation while inclosing legume, agroforestry system (AFS), and adding of shrubs in silvipastoral system are found to be good in terms of sustainable soil C sequestration. Reduced or no-tillage reduces the C losses by reducing fossil fuel usages and by adding extra C in the soil system and also the surface stubble retention increases C turnover into the soil.

The implementation of these technologies offers the greatest potential of increasing SOM (Tables 1.3 and 1.4). The amount of C stored in plant biomass ranges from 3.0 Gt in croplands to 212 Gt in tropical forests (World Bank 2012). The trend of C sequestration rate of RMPs are as follows: crop rotation (~0.2 t C ha^{-1} $year^{-1}$), zero/reduced till (~0.3 t C ha^{-1} $year^{-1}$), residue incorporation (~0.35 t C ha^{-1} $year^{-1}$), organic amendments (~0.5 t C ha^{-1} $year^{-1}$), conversion to pasture (~0.5 t C ha^{-1} $year^{-1}$), and afforestation (~0.6 t C ha^{-1} $year^{-1}$) (Minasny et al. 2017). In the United States, it was estimated that the adoption of RMPs may results in sequestration of 144–432 (~288) Tg C $year^{-1}$ [1 MMT = 1 Tg] (Lal et al. 2003). In Australia, introduction of legumes and pastures a rotation in a ley farming systems were reported to store the C at the annual rate of 0.26 t C ha^{-1}, when applied with zero/no-till and stubble retention (Chan et al. 2011). A 40-year study found that surface residue retention with balanced fertilizer application under zero till was recognized as a good management practice for optimum crop yield and SOC sequestration in semi-arid tropics of Australia (Dalal et al. 2011; Meena et al. 2014). The rate of C sequestration is faster during the initial stage/years of implementation of RMPs

Table 1.3 Soil carbon sequestration rates under USDA Natural Resources Conservation Service (NRCS) conservation practices for cropland (Lal et al. 1998; Swan et al. 2015; Chambers et al. 2016)

Conservation practices	C sequestration rate in soil (Mg C ha^{-1} $year^{-1}$)
Conservation agriculture	0.10–0.40
Conservation cover – retiring marginal soils	0.42–0.94
Crop rotation	0.15–0.17
Forage-based rotation	0.05–0.20
Elimination of summer fallow	0.05–0.20
Cover crop	0.15–0.22
Residue management cum zero till	0.15–0.27
Residue management cum reduced till	0.02–0.15
Mulch till	0.07–0.18
Strip till	0.07–0.17
Strip cropping	0.02–0.17
Filter strips	0.42–0.95
Contour buffer strips	0.42–0.94
Field border	0.42–0.94
Vegetative wind barriers	0.42–0.95
Vegetative barriers	0.42–0.94
Grassed waterways	0.42–0.96
Organic amendments	0.20–0.30
Water table management/irrigation	0.05–0.10
Use of improved varieties	0.05–0.10
Soil fertility management	0.05–0.10
Lawns and turfs	0.50–1.00
Mined soil reclamation	0.50–1.00

Table 1.4 Effect of land-use change RMPs on soil carbon sequestration potential of drylands (Lal et al. 1998)

Practice	C sequestration potential (t C ha^{-1} $year^{-1}$)
Water management and conservation	0.10–0.30
Conservation agriculture	0.15–0.30
Conservation tillage	0.10–0.20
Compost (20 mg ha^{-1} $year^{-1}$)	0.10–0.20
Integrated nutrient management	0.10–0.20
Restoration of eroded soils	0.10–0.20
Agricultural intensification	0.10–0.20
Mulching or cover cropping (4–6 mg ha^{-1} $year^{-1}$)	0.05–0.10
Elimination of summer fallow	0.05–0.10
Restoration of salt-affected soils	0.05–0.10
Afforestation	0.05–0.10
Grassland and pastures	0.05–0.10

which declines with time as soil attains equilibrium (Minasny et al. 2017). The actual/net quantity of C sequestered in the different soil horizons with the different soil management or farming practices highly varies with the countries, climatic situations, ecosystem, soil texture, and initial C level of that site.

1.8.1 Conservation Tillage

The increase in SOC flux is one of the key objects of sustainable soil resource management (Lal and Kimble 1997). Conventional tillage may negatively affect the soil C pool due to increased soil erosion and breakdown of soil structure. Conservation tillage is a basic term that encompasses all the tillage practices that reduce surface runoff and soil and water erosion over the conventional practices and provide protection from the falling raindrop impacts. As the soil under zero tillage system remains without interruption, soil aggregates remain intact, physically protecting C. Soil management and conservation tillage practices also endorse the availability of N and SOC sequestration. The enhancement of soil micro-aggregation, deeper placement of SOC in lower horizons, and reversal of soil-degrading processes are the prime tools of C sequestration with conservation tillage system (Lal and Kimble 1997) (Fig. 1.4). Consequently, soil can uphold the C content upon replacing the conventional intensive tillage by zero or drastically reduced or conservation tillage instead by way of decreasing fallow period, plummeting soil disturbance, and incorporation of crop residue in soil strata in the rotation cycle (Fig. 1.5). Avoiding summer fallowing in dry ecosystems and implementing zero till system with surface residue retention as mulch improve the soil structure, infiltration rate, and C accumulation and thus lower the bulk density (Shaver et al. 2002; Meena et al. 2018b). According to Han et al. (2010), zero till + straw returning and rotary tillage + straw

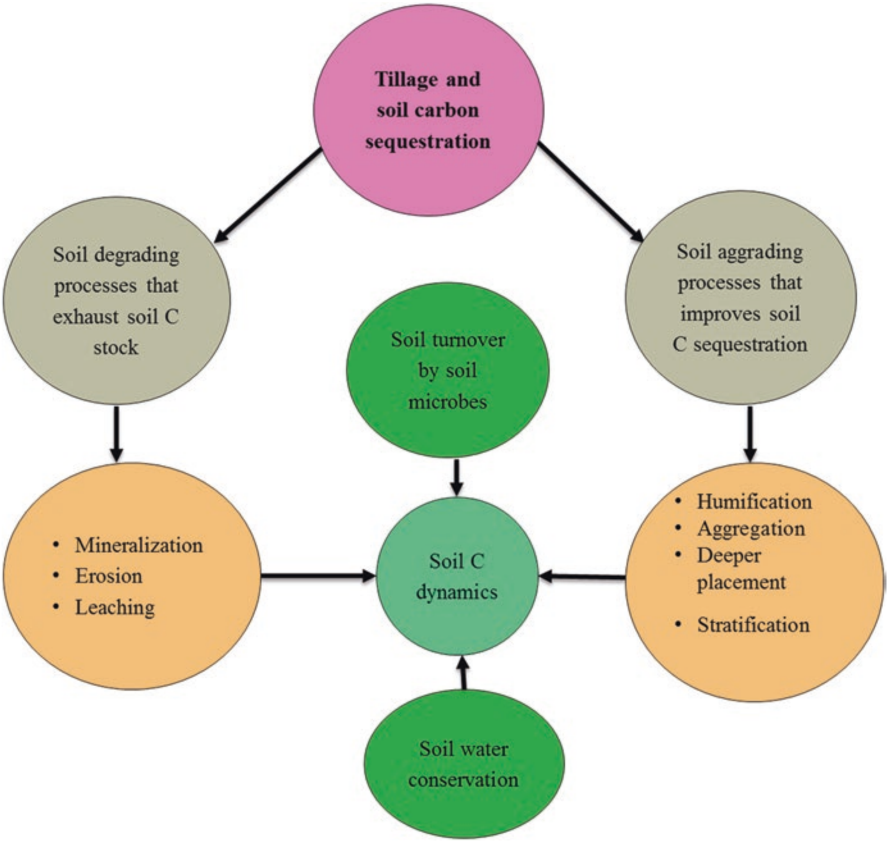

Fig. 1.4 Tillage and soil carbon dynamics. (Adapted from Lal and Kimble 1997)

returning increased the SOC accumulation by 18.0 and 17.6% in top 5.0 cm surface soil over the conventional tillage practice. The mean soil C sequestration rate with adaptation of zero tillage, crop residue management, mulch farming, and cover cropping in Asia, Africa, and Latin America is presented in Fig. 1.5 (World Bank 2012). The adoption of conservation tillage has a great potential to sequester about 43 Tg C in wider Europe including Soviet Union or 23 Tg C in European Union annually (Smith et al. 1998). By 2020, conversing conventional tillage to conservation tillage may cause to a global C sequestration of 1.5×10^{15} to 4.9×10^{15} g C (Lal 1997). According to Lee et al. (1993), transforming the corn and soybean farms in the corn belt of the United States from conventional tillage to no-tillage could sequester 3.3 × 106 tons C $year^{-1}$ over the next 100 years. Besides, as soil is not manipulated and pulverized in conservation tillage, it reduces the rapid microbial breakdown of SOM and plant residues and can therefore reduce the CO_2 evaluation in the biosphere. The tillage and C sequestration rates under diverse cropping system of world are presented in Table 1.5.

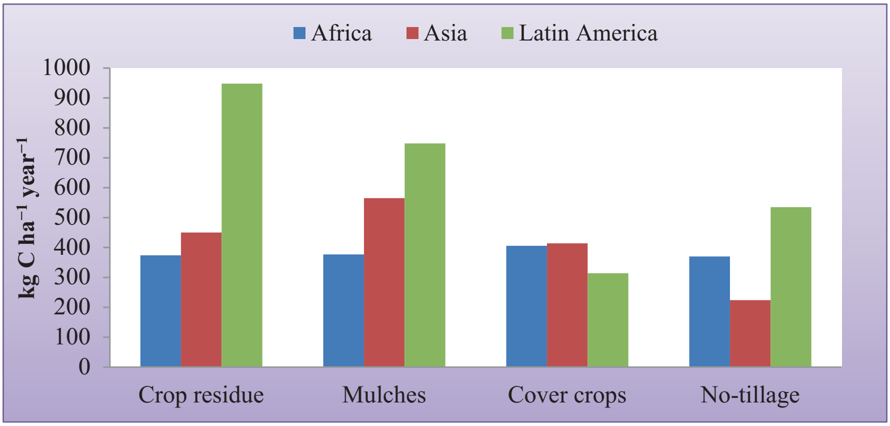

Fig. 1.5 Tillage, crop residue management, and mean soil carbon sequestration rates (World Bank 2012)

Table 1.5 Tillage and carbon sequestration rate under diverse cropping systems of world

Cropping system	Location	Tillage system	C sequestration (Mg C ha^{-1} $year^{-1}$)	Reference
Wheat-corn (6)	Gto, Mexico	Conventional tillage	1.05	Follett et al. (2005)
Wheat-corn (6)	Gto, Mexico	Zero tillage	−0.03	Follett et al. (2005)
Wheat-fallow (27)	Nebraska, USA	Zero tillage	0.18	Kettler et al. (2000)
Wheat-fallow (27)	Nebraska, USA	Conventional tillage	−0.007	Kettler et al. (2000)
Various crops (6)	Georgia, USA	Conventional tillage, zero tillage, minimum tillage	0.02	Sainju et al. (2002)
Rye-corn (20)	Kentucky, USA	Zero tillage	0.37	Ismail et al. (1994)
Rye-corn (20)	Kentucky, USA	Conventional tillage	0.15	Ismail et al. (1994)

1.8.2 Cropping System

The field experiments suggested the increased SOC content by increasing cropping intensity over the monoculture owing to higher biomass and residue production in diverse cropping system (Wang et al. 2010, 2015). The deposition of organic C largely depends on the cumulative input of crop residue on soil surface and their subsequent incorporation in soil strata (Kuo and Jellum 2002). Hence, it is important to increase the total crop biomass input in soil to upsurge the SOC concentration. The biomass addition in soil can be enhanced by eliminating the summer fallow and by increasing the cropping intensity via intercropping, mixed cropping, multiple cropping, companion cropping, etc. (Wang et al. 2010; Sihag et al. 2015). Intercropping system endorses the crop biomass production by improving the light utilization efficiency by optimizing the spatial configuration of crop architecture. According to the spatial disturbance of individual crops and purpose of cultivation, the intercropping is categorized into strip intercropping, row intercropping, relay intercropping, and mixed cropping. Soybean in the intercropping system provides the supplement of (N) uptake to the maize, whereas maize itself acts as windbreaker to protect the soybean from high wind speed. Besides, strip intercropping reduces the insect-pest infestation in the component crops, i.e. sorghum-pigeon pea intercropping. The mixed cropping suppresses the weed and insect infestation; increases resilience to climate risks like hot, cold, dry, and wet climatic events; and optimizes the input-output balance of nutrients (Hirst 2009). These mutual benefits overall improve the total biomass production of overall system and show a potential for biomass return and SOC sequestration. Wang et al. (2010) showed the improved soil C in intercropping depending upon the component crops. The accelerated nutrient removal in intercropping system over the natural ecosystem is the critical logic for enhanced C sequestration. The SOC accumulation rate ranged with a modest value of about 1.0 Mg C ha^{-1} (Nair et al. 2009; Mitran et al. 2018).

1.8.3 Legume-Based Crop Rotation

The SOC can be enriched by the use of apposite crop rotations (Lal 2010). Crop rotation can improve biomass production and thereafter the soil C sequestration, principally the rotations of legumes with non-legumes. This was because of the higher conversation efficiency from residue C to soil C by legumes in rotation over the monoculture wheat crop. The legume-based rotations are more efficient in converting biomass C in to SOC in compression to the grass-based rotation. Inclusion of legumes in rotation has the potential of guaranteeing the in situ availability of N which in turn played a vital role in generating higher biomass C. It also promotes the release of C via root exudation in to the rhizospheric zone (Hajduk et al. 2015). N fixed by the root nodules of legumes also accelerates the C sequestration potential of succeeding crop in the rotation, more likely because of the improved microbial functionaries and biomass production by successive crop. The provided by the legumes enhances the NUE and produces more root biomass and thus C inputs in soil. Lal (2010) in their research advocated that the legumes based rotation endorsed the accumulation of liable C pool in soil ecosystem considerably greater than C returned from the contentious wheat and uncultivated fallow period. The effect of leguminous crop species on SOC sequestration is more pronounced for green manure, cover crops, and forage which give back a large quantity of C and N in soil system. The GHG abatements of crop rotation were 0.7–1.5 t CO_2 equivalent ha^{-1} $year^{-1}$ (World Bank 2012).

1.8.4 Cover Crops

Inclusion of the cover crops in the cropping system is a promising way of C sequestration in cultivated soils. Raising leguminous crops enriches biological diversity, the crop residue quality, and soil C flux (Lal 2004a, b, c). The higher the biodiversity of an ecosystem, the more will be the capturing and sequestration capacity over the system exhibiting low biodiversity. The unique advantage of cover crops over the other management options is that they not only enhance the SOC stock but also reduce the C loss, unlike organic manures. The prime object of soil C sequestration through cover crops, and its coming back to the soil ecosystem in such a way that some of the biomass C is not escape back into the biosphere. The improved biomass C below and above the soil surface due to cover cropping can build a C-rich zone through offsetting mineralization and plummeting losses by erosion (Lal 2016), because the soil erosion alone is responsible for the loss of 1.1 Pg C year^{-1} in paedologic pool. Since the entry of cover crops in the cropping system, the change in SOC stock ($R^2 = 0.19$) was tracked for a period of 54 years in a meta-analysis by Poeplau and Don (2015) and reported the annual change rate of 0.32 ± 0.08 Mg ha^{-1} year^{-1} in mean 22 cm soil depth. The predicted new steady state was reached after 155 years of cover crop cultivation with a total mean SOC stock accumulation of 16.7 ± 1.5 Mg ha^{-1}year^{-1}for a soil depth of 22 cm. The cover cropping generated the abatement rates of 1.7–2.4 t CO_2 equivalent ha^{-1} year^{-1} (World Bank 2012). Legume-based cropping systems improve SOC (Sainju et al. 2002) and decrease the C and N evaluation (Drinkwater et al. 1998). Hence, cover cropping improves the soil quality by enriching SOC through their biomass and they also promote soil aggregation, and protect the surface soil from runoff and erosion. The biomass production and the subsequent turnover rate of organic materials in soil depend on the growing environments of cover crop. Therefore, the rate of C sequestration hinge on selection of suitable cover crop, agronomic management practices, climatic zone, and soil texture (Lal 2016).

1.8.5 Integrated Nutrient Management

The C sequestration potential of agricultural soil is being reduced continuously in the presence of imbalanced nutrient management. The balanced application of organic and inorganic fertilizer in agricultural soils for crop production is crucial for soil C sequestration. Several scientific studies advocated that judicious and balanced application of synthetic fertilizers and organic manure for long term can enhance the soil productivity and SOC pool (Johnston et al. 2009; Nayak et al. 2012; Liu et al. 2013b, c; Han et al. 2016). The plots treated with higher rate of N exhibits improved rate of C sequestration with a mean value of 1.0–1.4 Mg C ha^{-1} over the non-fertilized plots. The influence of fertilization on rate of SOC sequestration will be greater when the soil is deficient in nutrient. In such conditions, the practices which improve N use efficiency are critical for SOC accumulation (Fig. 1.6). These should be based on the principle of 5Rs (right time, right method,

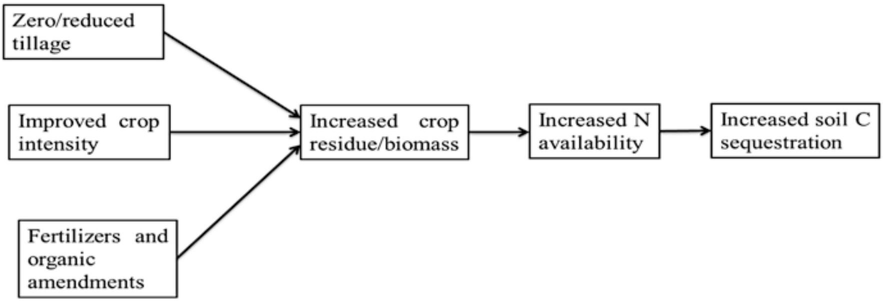

Fig. 1.6 RMPs that increase N availability and soil carbon sequestration

right source, right amount, right place). The sequestration rate can be increased either by increasing the content of crop biomass C or by reducing the CO_2 emission from the soil or by both. The fertilizer management strategies in cultivated soils, e.g. synthetic fertilizers, organic manures (e.g., farm yard manure (FYM), compost, vermicompost, biosolids, and biochar), surface residue retention, and green manuring, have been documented as promising way to enhance SOC accumulation and to reduce CO_2 evaluation from the soil. Adequate availability of nutrient elements from these sources improves the crop yield, biomass-C generation, and, so, crop residue and root input in soil (Kätterer et al. 2011).

In general, the supply of same amount of nutrient through organic manures and compost in soil considerably enhanced the accumulation of SOC, particulate OC, microbial biomass, and, thus, the rate of C sequestration as compared to the inorganic fertilizers. Organic amendments and surface stubble retention are recognized as prominent practices for bringing the change in SOC levels (Maillard and Angers 2014). Their effect on soil C sequestration becomes worthier when it is adapted with conservation tillage and organic farming (Han et al. 2016). A field trial with application of FYM increased SOC concentration by 200% over a period of 100 years at Rothamsted, UK (Johnston et al. 2009). The continuous straw retention of surface soil improved the soil C sequestration in Ultuna, Sweden, at the end of 54 years of experiment (Kätterer et al. 2011; Meena et al. 2017c). It describes the importance of long-term application of organic amendments in building the C reserve in soil strata. Han et al. (2016) carried out a metal-analysis on relation of different nutrient management practices on change in rate of SOC content over a wide range of climatic and ecological regions. The outcome of this analysis was the increased level of SOC by 3.2–3.8 (~3.5 or 36.2%), 1.9–2.2 (~2.0 or 19.5%), 1.2–2.3 (~1.7 or 15.4%), and 0.7–1.0 g kg^{-1} (~0.9 or 10.0%) at 95% confidence interval in topsoil with application of synthetic fertilizer + organic manure (FM), synthetic fertilizer + straw (FS), balanced synthetic fertilizer (BF), and unbalanced synthetic fertilizers (UF), respectively. This estimation of C sequestration under FM and FS was over duration of 26–117 and 28–73 years, respectively, over highly variable ecological conditions. Table 1.6 clearly shows the effects of increasing N availability on soil C sequestration rate in different regions by adapting INM strategy under irrigated and rain-fed conditions.

Table 1.6 Effect of N availability increasing RMPs on soil carbon sequestration rate (kg C ha^{-1} year^{-1}) and potential (Tg C year^{-1}) in the United States, Canada, and Mexico

	Dryland (irrigated)						Humid cropland (non-irrigated)					
Agroecosystem	Canada		United States		Mexico		Canada		United States		Mexico	
Fertilizer	50–150	0.04–0.12	30–390	0.7–9	105–117	0.7	70–680	4–35	20–1690	3–260	50–150	1–3
Fertilizer + manure	50–150	0.04–0.12	111–1545	2–34	50–150	0.3–0.9	50–150	3–8	719–927	111–143	50–150	1–3
Fertilizer + legume as cover crop	100–300	0.08–0.2	500–900	11–20	30–320	0.2–2.0	61–132	3–7	18–224	3–35	100–300	2–6
Fertilizer + manure + legume as cover crop	100–300	0.08–0.2	557	12	100–300	0.6–2	100–300	5–15	656	101	100–300	2–6

Adapted from Christopher and Lal (2007)

1.8.6 Irrigation Management

The application of irrigation water has a large potential to enhance the rate of soil C sequestration. As a result, judicious application of irrigation water in arid and semi-arid ecosystem accelerates the biomass production, improves the above- and below-ground plant parts returned to the soil, and therefore increases the SOC stock. Besides, appropriate water table management, including drip/sprinkler irrigation methods, and effective water recycling are required for SOC sequestration. The experimental results showed the annual C sequestration range of 0.05–0.15 t C ha^{-1} SOC (Conant et al. 2001) and 0.05–0.10 t C ha^{-1} SIC (Nordt et al. 2000) in soil.

Crop production and quantity of organic residues returned in soil is the function of availability of irrigation water for the crop plants. Soil moisture has substantial impacts on soil-atmosphere C exchange mechanisms and SOM decomposition by microbes. Availability of moisture in soil governs vegetative growth and NPP and thus affects C addition to the soil ecosystem (Yuste et al. 2007). Irrigation to the cropland has both positive and negative impacts on SOC accumulation in soils over long time. The improved water supply promotes plant biomass production and increase C input to the soil in the forms of root exudates, rhizo-deposition, dead roots and other vegetative parts (Kochsiek et al. 2009). In contrast, irrigation endorses the soil moisture build-up and associated microbial activities. This results in increased SOM decomposition and CO_2 emanations into the free atmosphere (Trost et al. 2013; Gogoi et al. 2018). This may lead to reduction in SOC reservoir. Lack of adequate soil moisture in drought-prone areas can inhibit the performance of soil fauna and flora and can therefore cut the SOM decomposition which results in decreases in loss in soil C (Lai et al. 2013). Trost et al. (2013) in their investigation in different dryland ecosystems reported an increase in 90% to more than 500% of SOC owing to application of irrigation in cultivated desert soils. Irrigation increases SOC concentration by 11–35% in semi-arid regions but not in humid regions. Although this relationship between irrigation and SOC build-up is not independent, this also depends on other factors like fertilizer, tillage, etc. This process is simplified by a diagrammatic representation in Fig. 1.7. At last we can conclude that irrigation application leads to upsurge SOC concentration in arid and desert cultivated soils as compared to the non-irrigated soils. Whereas in humid and in soils already rich in SOC content, irrigation has no considerable effects on SOC build-up. In dryland ecosystem, life-saving irrigation and water harvesting minimize the risk in crop production and sequester the atmospheric C in to the soil (Table 1.7). The improved irrigation produced low to medium moderately high abatement rates of 0.2–3.4 t CO_2 equivalent ha^{-1} $year^{-1}$ (World Bank 2012).

1.8.7 Agroforestry System

Agroforestry system (AF) consists of mixture of trees, agricultural crops, and livestock to exploit the economic and ecological benefits of agroecosystem. It is a crucial leader of terrestrial C sequestration containing about 12% of the global terrestrial

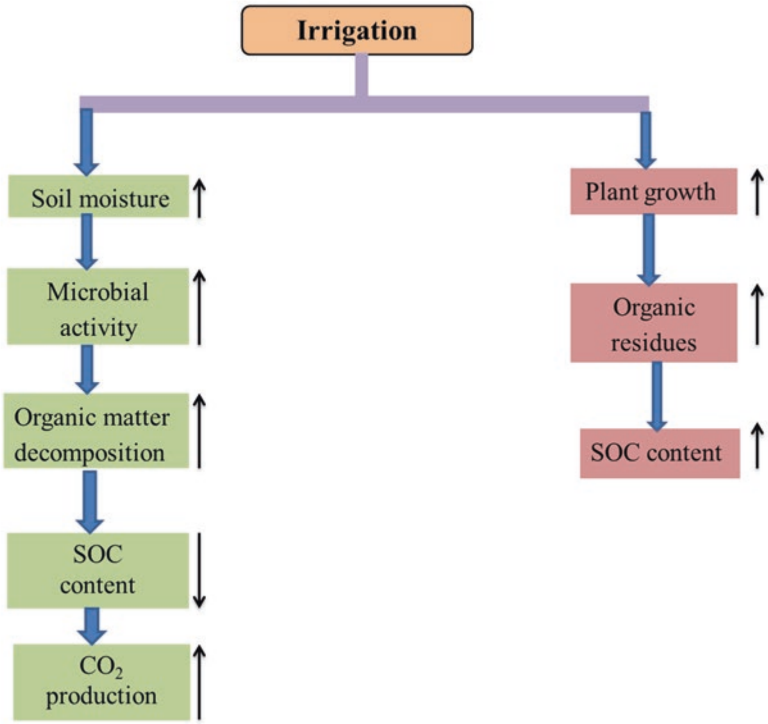

Fig. 1.7 Diagrammatic representation of basic effects of irrigation on SOC (Trost et al. 2013)

Table 1.7 Water management and mean soil carbon sequestration rates (kg C ha^{-1} $year^{-1}$) (World Bank 2012)

Practice	Africa	Asia	Latin America
Rainwater harvesting	839	1086	–
Improved irrigation	–	1428	571
Cross-slope barriers	1193	–	–

C (Dixon 1995). The trees capture and store C by tumbling respiration rate and by growing rapidly by exploring the benefits of favourable temperature at early growth stage (Rotenberg and Yakir 2010). The roots of forest tress and perennial crops penetrate deeper subsurface horizons, thus placing SOC at deeper horizons far away from the range of tillage implements (Lorenz and Lal 2014). Therefore, the SOC pool do not remains for a longer time as a permanent C pool. The acts as mulch and covers the land surface of cultivated field that decompose with passage of time and form the part of SOC pool. Besides, this obstructs the speed of blowing wind and flowing water and reduces soil runoff which is a crucial process of soil C dynamics. It also moderates the soil moisture loss from soil surface as evaporation. Thereby, the increased C content in AFS ensures the better agricultural productivity

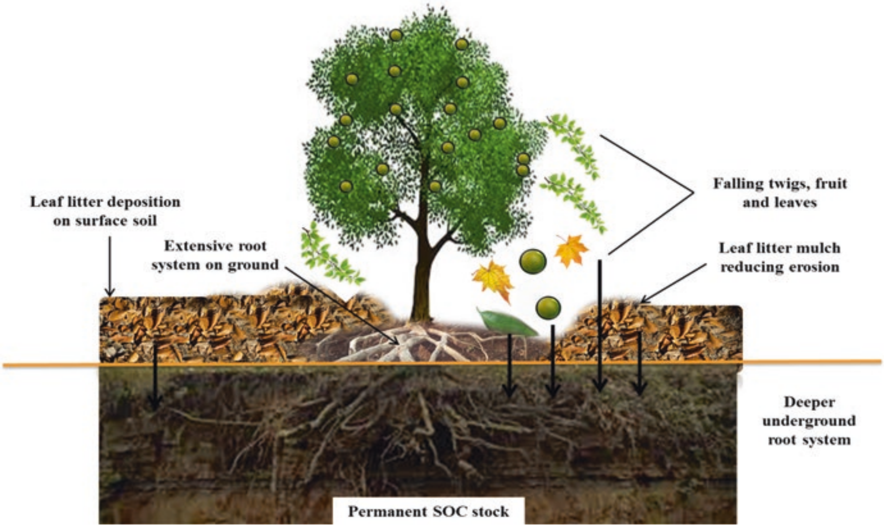

Fig. 1.8 Carbon sequestration mechanisms of an agroforestry system

and sustainability of the agroecosystem. The complete picture of the C sequestration material with AFS is presented in Fig. 1.8.

The estimation of C sequestration potential of AFS under varied ecological and management environment ranged from 0.29 to 15.21 Mg ha^{-1} year^{-1} in above-ground plant biomass and 30–300 Mg ha^{-1} year^{-1} in below-ground plant parts up to a depth of 1.0 m (Nair et al. 2010). Above-ground biomass is a direct measure of C sequestration, assuming that 50% of the biomass is made up by C (Nair et al. 2010). The cumulative C sequestrat

ion including above- and below ground parts under AFS is considerably greater as compared to the treeless croplands in the same ecological and management conditions. Some of the agroforestry practices are silvipastoral, ally cropping, forest farming, windbreakers, home gardens, riparian buffers, woodlots, etc.

The annual accumulation rate of C in soil is expected to increase at the rate of 1.3 Mg ha^{-1} in the next two decades; after that it would decelerate by 0.20 Mg ha^{-1} year^{-1} in the next eight decades (Silver et al. 2000). So, it is very crucial to highlight the significance of AFS in capturing and storing C in soil for the duration of first 2–5 decades. Along with the food, feed, fibre, fuel, and fodder, AFS are also important in relation to the soil fertility and soil C sequestration (Abberton 2010) (Fig. 1.9). It was found that the forest system is supposed to capture equal to 3 Pg Cs yearly (Ibrahim et al. 2010) and also estimated that the global forest system contributes on behalf of about 90% of annual C pool between soil and atmospheric C (Wani and Qaisar 2014). Agroforestry has been recognized as having the greatest potential for C sequestration of all the land-use system (Minasny et al. 2017).Their

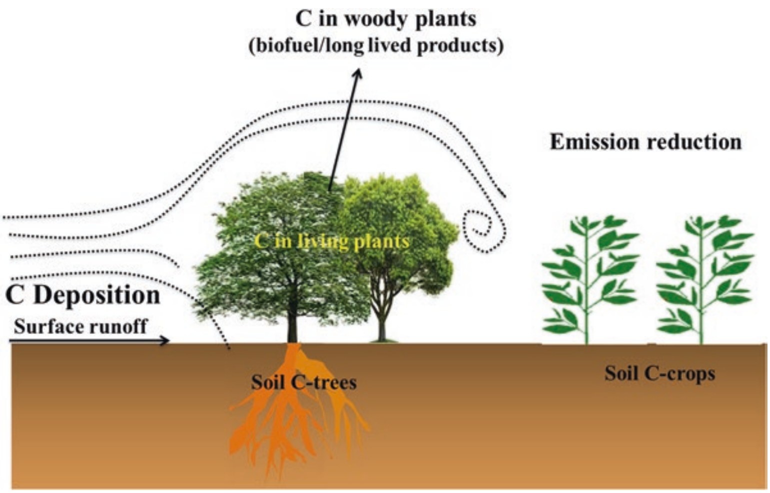

Fig. 1.9 Agroforestry for reducing wind velocity, surface water runoff, and soil C loss

sequestration potential depends on the CO_2 capturing capacity from atmosphere or photosynthetic rate and transformation of CO_2 into long-lived C material as such. Up to 2.2 Pg C (1 Pg C = 1 picogram of C – 10^{15}gC = 1 gigatons C = 1 Gt C = 1 billion metric tons of C) could be stored below- and above-ground over 50 years in AFS (Lorenz and Lal 2014). The SOC sequestration in AFS is uncertain and may reach up to 300 Mg C ha^{-1} to 100 cm depth. Nair et al. (2009) estimated the C sequestration range of 5–10 kg C ha^{-1} in 25 years in AFS of arid and semi-arid ecosystem and 100–250 kg C ha^{-1} in humid environment in 10 years. According to a report of IPCC (2007), agroforestry has the potential of 1.1–2.2 Pg C sequestrations in terrestrial ecosystem in the next 50 years (Jose 2009). According to Oelbermann et al. (2004), the C storage capacity in above-ground plant parts in AFS to be estimated is 1.9×10^9 and 2.1×10^9 Mg C $year^{-1}$ in temperate and tropical ecosystem. The C storage capacity of agri-silviculture system varies 68–81 and 12–228 Mg C ha^{-1} in dry lowland and humid tropical lands of Southern Asia. The potential of silvipastoral systems in North America is highest with a storage value of 90–198 Mg C ha^{-1} (Murthy et al. 2013). In accordance with Richards and Stokes (2004), the forest lands can sequester up to 250 million metric tons of C $year^{-1}$ which shares about 12% of the CO_2 emissions in the United States. The advanced plantation of *Cassia siamea* increases the SOC concentration at the rate of 50 kg $ha^{-1}year^{-1}$in upper 10 cm soil profile due to its capacity of higher litter-fall (5–7 Mg ha^{-1} $year^{-1}$) that helps to sustain the higher SOC content (Lal et al. 1998). The mean C sequestration rate of different agroforestry measures in different ecological conditions is presented in Table 1.8.

Table 1.8 Agroforestry measures and mean soil carbon sequestration rate (kg C ha^{-1} $year^{-1}$) (Udawatta and Jose 2011; World Bank 2012)

Practice	Africa	Asia	Latin America	North America
Include tress in field	1204	562	1065	–
Intercropping	629	803	1089	–
Ally farming	1458	–	–	3400
Tree crop farming	1359	–	–	–
Improved fellow	2413	–	–	–
Diversify trees	–	–	1365	–
Silvipastoral	–	–	–	6100
Riparian buffers	–	–	–	2600

1.8.8 Grassland/Pasture Management

Globally, the grasslands/grazing lands occupy 3460 Mha which cover about 31% of the Earth's land surface (Lal 2004a, b, c). They are grouped into three categories based on their relative soil C sequestration potential. First are the are *natural grasslands*, which are not protected and are not under livestock, agriculture, and other usages and, therefore, remain undisturbed in natural state. Second are the *degraded grasslands* are poorly managed where no improvement can be expected in short term. Third are the grasslands which are prone to management improvements. There is a wide scope to enhance the SOC and SIC storage of degraded grasslands through restoration and implementation of sustainable soil conservation approaches. Moreover, transforming marginal croplands to more ruminative pastures also confiscate C.

Globally, grassland ecosystem shares more than 10% of the cumulative C storage among all the vegetation (Nosberger et al. 2000). In grassland ecosystem, up to 98% of the total C can be found sequestered below-ground, that is why the soil is the largest C storing body of the terrestrial C pool (Jones and Donnelly 2004). Grassland management mainly affects the soil C sequestration by altering C inputs in soil via root turnover and exudation, root and shoot biomass, and NPP (Schuman et al. 2002). Beside the root biomass and their decomposition, root exudation, rhizodeposition, mucilage production, and sloughing from living roots also contribute to soil C. In most of the grassland ecosystem, about 75–80% of the cumulative root biomass remains in top 30 cm soil profile, but accurate determination of C transfer from different sources is difficult because the root growth, death, and subsequent decomposition occur concurrently and at varied rates as per the species and climatic conditions. In temperate grasslands, an extensive stock of accumulated C is situated in soil profile in roots and soil. The measured and modelled rate of C sequestration ranges from 0 to >8 Mg C ha^{-1} $year^{-1}$ (Jones and Donnelly 2004).

The agronomic management approaches strongly influence the C sequestration rates and the future C stocks in grasslands. Grasslands have potential for building the C stock in the soil strata which can be substantially enhanced by change in management environments. According to an estimation of NRSC, on adopting the C-rich conservation agricultural practices on grasslands (grazing and pasture lands),

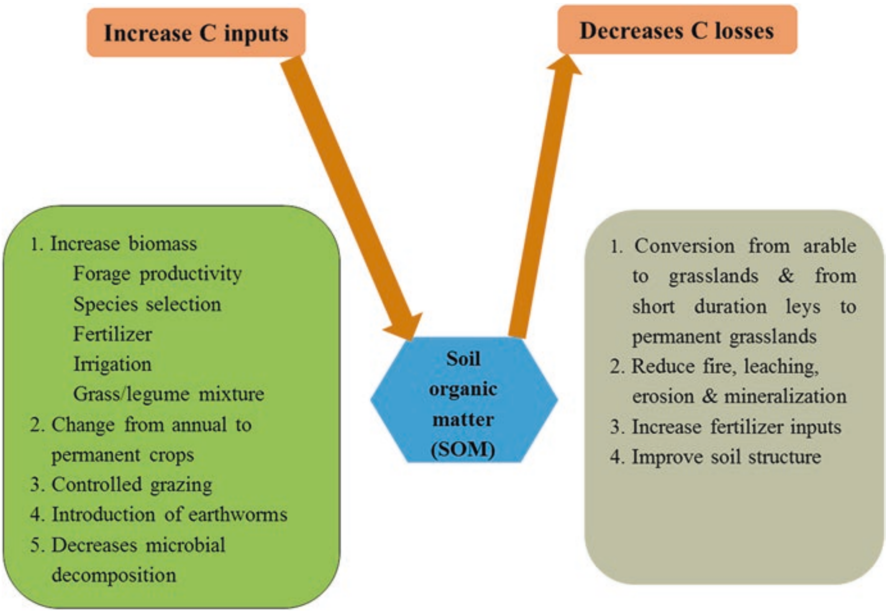

Fig. 1.10 Schematic illustration of management options to increase SOM in grassland ecosystems

0.020.44 Mg C ha^{-1} $year^{-1}$ can be accumulated in soil in the coming decades (Chambers et al. 2016). The implementation of sustainable agronomic practices in 40.5 Mha grasslands over the next decades could result in sequestration of 18 Tg C $year^{-1}$. These management options include judicious use of organic and inorganic sources of nutrition, controlled grazing, appropriate mixture of grasses and legumes as per the climatic conditions, expansion of soil microbial diversity, and irrigation (Lal 2004a, b, c). The improved pasture management results in SOC sequestration of 0.11–3.04 Mg C ha^{-1} $year^{-1}$ at the annual building rate of 0.54 Mg C ha^{-1} (Conant et al. 2001). In the United Kingdom, SOC content increased at the annual rate of 0.02% for 12 years by adapting grass leys. However, the amount of SOC retained or sequestered by soil depends on the input-output balance of C by different strategies under grassland ecosystem (Fig. 1.10).

1.9 Conclusion and Future Outlook

The amount of C that a soil can sequester rely on the vegetation it supports, soil depth, its drainage capacity, mineral composition, soil temperature, and the relative proportion of soil water and air. The C sequestration potential of a soil depends on its capacity to maintain the stock of resistant plant materials to biological decomposition, chemical makeup of SOM, and accumulate the humic fractions more. The improved land-use change regulates the budget and transfers of C in terrestrial ecosystem. Therefore, promoting the cultivation of crops sustainably offers multiple advantages, e.g. augmenting crop and soil productivity, adapting climate change resilience, and high turnover of above- and below-ground biomass into the soil system, thus sequestering atmospheric C and dropping concentration of GHGs from atmosphere. The continuous vegetation on soil surface ensures the good soil health and soil C concentration at variable soil depth as per the specific crop; increases soil sustainability by mixed cropping, intercropping, crop rotation, cover cropping, multiple cropping, and relay cropping; and generates and adds greater amount of qualitative plant biomass into the soil. To manage the future problems in agriculture C sequestration is an option. Therefore, approaching integrated nutrient management (INM) encompassing manures and other C-rich resources sustains soil health and increases N availability and SOC sequestration. Moreover, location-specific scientific research is needed to point out the best management practices that enhance NUE, maintain/improve soil health, boost crop production and SOC sequestration, and minimize greenhouse gas (GHG) release in the biosphere. In fact, more research to quantify the C sequestration potential with higher degree of confidence is required under different soil management situations.

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