Chapter 11
Soil Organic Carbon Stocks Under Different Agroforestry Systems of North-Eastern Regions of India

K. M. Manjaiah, S. Sandeep, T. Ramesh, and M. R. Mayadevi

Abstract Increasing concentrations of greenhouse gases, especially carbon dioxide, and exploring ways and means to mitigate them is a major challenge to the global community. Exploring terrestrial sinks of carbon is suggested as one of the options, and in this context agroforestry systems, with a mix of trees and crop plants, offer a good solution. India's North-Eastern Hill region has a rich tradition of agroforestry systems and is estimated to store between 85.34 and 121.87 Mg C ha^{-1}. However, stability of the stored soil carbon is a function of both quality of inputs and their interaction with soil components. Thus, agroforestry systems in the North-Eastern region spanning a wide range of climatic conditions ranging from alpine to tropical, rainfall pattern, vegetation, topography, land use, ethnicity, and cultural diversity vary in their carbon accumulation and sequestration potentials. Here, in this chapter we have attempted to review and synthesize the current knowledge on soil organic carbon sequestration status and processes in the agroforestry systems of North-Eastern Hill region.

Keywords Agroforestry · Carbon sequestration · North-Eastern region · Soil organic carbon

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1 Introduction

Sustaining and improving soil organic carbon (SOC) levels is essential for ensuring ecosystem health and productivity (Katyal et al. 2001). In addition to being a primary source of plant nutrients, SOC also stores a good amount of carbon and thereby helps in maintaining the overall environmental quality (Houghton 2007). Increase in greenhouse gas (GHG) concentration in atmosphere is considered as a major cause of global warming. The Intergovernmental Panel on Climate Change (IPCC 2007) estimates that the current GHG, especially CO_2, concentrations in the atmosphere have increased drastically and are about 30% more than the preindustrial levels. Global anthropogenic emissions of carbon dioxide to the atmosphere are mainly contributed by fossil fuel combustion and conversion of tropical forests to agricultural production lands (Lorenz and Lal 2015). Lal et al. (1998) reported that terrestrial carbon storage offers a good option to offset the annual atmospheric CO_2-C increments and suggest a 0.01% soil carbon content increase globally to achieve this goal.

Plant and soil carbon is estimated to represent nearly 25% of global carbon stocks (2000 ± 500 Pg). These carbon sink options can be significantly enhanced by judiciously managing or manipulating various biomes. In this connection, agroecosystems have the potential to remove and store about 42–90 Pg carbon from the atmosphere in a span of 50–100 years. Further, the dynamic relationship between plants and SOC depicts that changes in vegetative cover could have an influence on the global carbon budget by increasing or decreasing the terrestrial carbon storage.

Agroforestry is considered worldwide as a good option to address the problems arising from forest land conversions and subsequent positive carbon feedbacks to atmosphere. These systems strive to retain, introduce, or judiciously mix woody perennials or trees with crops, pastures, and livestock and derive ecological and economical benefits from their interactions (Nair 1993; Young 1997). Historically agroforestry systems have been practiced for sustainability and maintaining soil health. In recent times, it has been accepted as a sustainable alternative to single crop systems and shifting cultivation (Dixon 1995; Young 1997). Based on their end uses, tree components in the agroforestry systems provide for long-term carbon sinks. Sequestration of carbon in the agroforestry systems occurs in the aboveground and belowground biomass portions as well as soil. Their capacity to produce large volumes of biomass and extensive roots demands that this agroecosystem receives a wider attention in climate change mitigation strategies. Nair et al. (2010) estimated that the agroforestry systems have a capacity to store approximately 30–300 Mg C ha^{-1} in a 1 m soil depth.

Several agroforestry forms and methods are common throughout India. In North-Eastern region, this has evolved through generations and has seen a gradual cropping intensification. Shifting cultivation or *jhum* is the major agroforestry system practiced in the region wherein farmers maintain a high species diversity and the entire socioeconomic fabric depends upon this system. However, with shortening of rotation period, shifting cultivation has become ecologically less sound and resulted in land degradation. Other agroforestry systems practiced in the region are agri-silviculture, agri-horticulture, silvi-horticulture, pastoral silviculture, silvopastoral systems, and homegardens, each of which has immense potential to store carbon. North-Eastern region with its large diversity in climatic conditions and physiography supports these agroforestry systems in a wide range of soils and sequesters a high level of organic carbon in them compared to agricultural lands.

2 Major Agroforestry Systems in North-Eastern Hill Region

Agroforestry, defined as the practice of growing trees alongside farming, is a major practice in North-Eastern Hill (NEH) region and plays an important role in livelihood and land productivity enhancements. Such practices offer a multitude of functions ranging from soil and water conservation, soil fertility improvement, prevention of water logging, and eutrophication and biodiversity enhancement. Besides providing livestock fodder, they help reduce the pressure on natural forests for fuel and above all offer good carbon sequestration opportunities. They also enhance the system resilience to cope up with adverse climate change.

North-Eastern region has a rich tradition of agroforestry practices. The agroforestry systems in this region include trees grown on agricultural lands, community forestry, and a variety of ethno-forestry practices. NEH region comprising of seven Indian states (Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura) spans an area of approximately 1,83,750 km^2 (Anonymous 2005). The region occupies a distinct position in the Indian subcontinent by way of its geographical position, altitudinal variations from 15 to 5000 m above mean sea level, typical physiography, precipitation, and alternating pressure cells in the Bay of Bengal and North-West India. The presence of tropical mountain air masses along with local winds develops a range of climate from tropical to alpine type and influences the regions' vegetation type (Barthakur 2004). This diverse yet unique climate has led to a rich biodiversity hotspot in this part of India with a varying forest type distribution from tropical moist evergreen to alpine forests. Rural population accounts for 80% of total population, and a clear majority derive their livelihood from agriculture and its allied sectors. Based on the climate, topography, soil, and type of dominant crop and livestock species, the North-Eastern region has been divided into six distinct agroclimatic zones as given in Fig. 11.1.

In the North-Eastern region, there exists a long tradition of deliberately planting trees alongside farm crops, and as such various agroforestry models exist that integrate crop husbandry, aquaculture, livestock, etc. to replace the *jhum* cultivation and complement soil productivity and promote sustainable production (Bhatt et al. 2006; Kirby and Potvin 2007; Nair et al. 2009a; Ramesh et al. 2013). Some of the major agroforestry systems in the region include homegardens, multistoreyed agroforestry systems, agri-horti-silviculture, horti-pastoral systems, agri-silviculture, and agri-horti-silvopastoral systems. Trees such as *Alnus nepalensis*, *Areca catechu*,

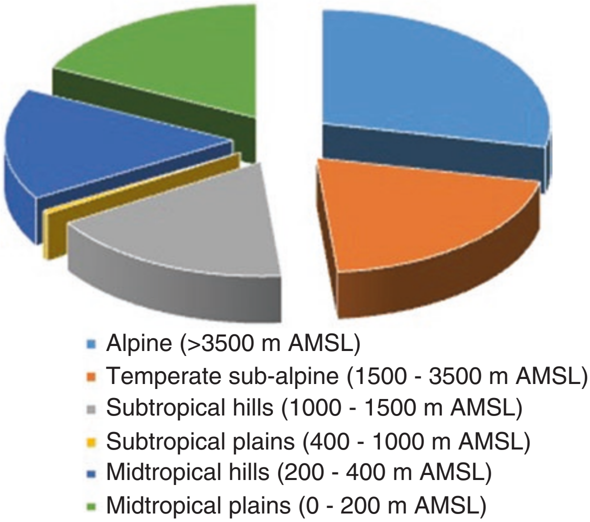

Fig. 11.1 Area distribution of different agroclimatic zones in North East India

Pinus kesiya, *Schima wallichii*, *Prunus domestica*, *Pyrus communis*, etc. are usually planted along with crops like coffee, ginger, maize, pineapple, and vegetables.

The climatic conditions and economic advantages are considered the major driving forces in selection of an intercrop and tree species in the region. Besides meeting the multifaceted farmer's needs such as economic produce, feed, timber, fuelwood, etc., agroforestry systems also provide several environmental benefits, viz., carbon storage in soil and tree biomass, thus reducing the positive feedbacks of carbon to atmosphere.

3 Carbon Stocks and Dynamics Under Different Agroforestry Systems

Carbon sequestration entails the transfer of carbon from atmosphere, especially CO_2-C and its safe storage in recalcitrant pools with long turnover times (UNFCCC 2007). The earth surface systems comprising of atmosphere, oceans, biosphere, and soil control the long-term biogeochemical cycling of global carbon over geological time scales of more than 100,000 years (Berner 2003). Ecosystem systems such as forest, agroforestry, and agricultural systems worldwide are considered potential sinks for atmospheric carbon. In this context, agroforestry systems will have a great impact on long-term carbon storage and fluxes in the terrestrial biosphere under the assumption that area under this system will substantially increase in the near future (Dixon 1995).

The agroforestry systems' potential for long-term carbon storage depends on the biological CO_2 uptake and its subsequent conversion to long-lived, inert materials, i.e., bio-sequestration (U.S. DOE 2008). Bio-sequestration can temporarily immobilize carbon from active cycling and, in particular, convert CO_2 from one reservoir into another with longer turnover times (IPCC 2007). Carbon movement from the atmospheric reservoir to biotic or terrestrial pools could be considered accumulation as this process genuinely contributes to the climate change mitigation (Powlson et al. 2011). It should also be noted that increasing carbon stocks in agroforestry systems within a given period of time is a single step, whereas the sequestration potential of the system also depends on the fate of those stored carbon. Carbon sequestration occurs in soils of agroforestry systems both directly and indirectly. Direct sequestration occurs by conversion of CO_2 to inorganic compounds (e.g., calcium and magnesium carbonates), whereas indirectly it occurs by plant CO_2 fixation into biomass which gets subsequently added as SOC during decomposition processes. Soil carbon sequestration concepts and mechanisms, though similar across these systems, manifest differently depending on their specific characteristics. The magnitude of variation (increase/decrease) in soil organic stocks depends on the type and degree of land use, its changes, and land management.

NEH region with a high variability in climatic conditions ranging from alpine to tropical, rainfall pattern, vegetation, topography, land use, ethnicity, and cultural diversity is also found to be highly variable in the organic carbon contents of soil. In general, soils of this region are low in nutrient reserves, exchangeable bases, and organic matter content and mild to strongly acidic with high aluminum toxicity. As such, the agroforestry systems' potential to increase carbon stocks on the infertile acid soils of NEH region appears to be variable. The SOC stocks of the major land uses (excluding the area under settlements, water bodies, and snow-covered areas of Sikkim) are given in Fig. 11.2.

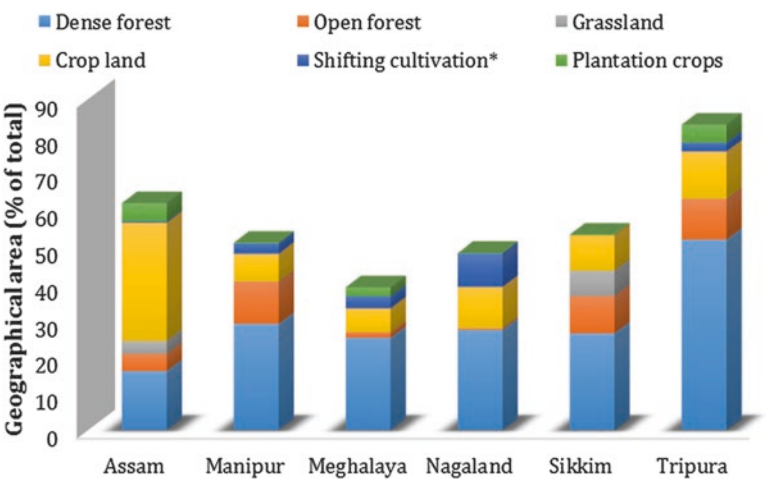

Fig. 11.2 Land use – land cover distribution of North-Eastern region (2004–2005) (*Current + abandoned: Source NRSA 2011)

Carbon storage in an agroforestry system should be considered a dynamic process that can be split into different phases. These systems during their establishment phases are most likely to be carbon sources due to rapid carbon and nitrogen losses from soil as well as vegetation. This will be followed by a phase of quick accumulation, and during maturation of the tree species, large quantities of carbon will be accumulated in the tree parts and soil. A good amount of carbon is returned to the atmosphere when the trees are felled and new cropping is taken up on the land (Dixon 1995). Hence agroforestry systems that produce a positive net accumulation from the initial carbon stock position after a few rotations alone can be considered to sequester carbon in the long run.

Conversion of natural forests to croplands or even agroforestry systems reduces its carbon stocks. SOC contents in the surface layers of managed plantation and *jhum* fallows were observed to be less than natural forest to the tune of 51.68% and 48.55% in Tripura. Studies have also shown that in all land uses of the region, SOC stock decreases toward the lower layers. In general, from 0–10 to 10–30 cm soil depth, there is a reduction in 8.4–43.3% organic carbon content among natural forest, managed plantations, and *jhum* fallows. Reduction in soil fertility and crop productivity, residue removal, burning, soil erosion, bare fallowing, and intensive tillage are attributed as some of the causes for large losses of SOC on cultivation of virgin soil (Lal and Kimble 2000; Paustian et al. 2000). The total organic carbon stock (up to 1 m depth) of these systems was found to vary from 85.34 to 121.87 Mg C ha^{-1}. Modifying silvicultural systems is suggested to rapidly maximize carbon accumulation in these systems. Total soil organic stocks under major land use systems of NEH region are shown in Fig. 11.3.

The most dominant and traditional cultivation practice in NEH region is shifting cultivation (*jhum* cultivation) where approximately 3869 km^2 area is brought under this system every year and has been reported to have the lowest carbon stocks among the different land uses. Shifting cultivation in the region involves clearing

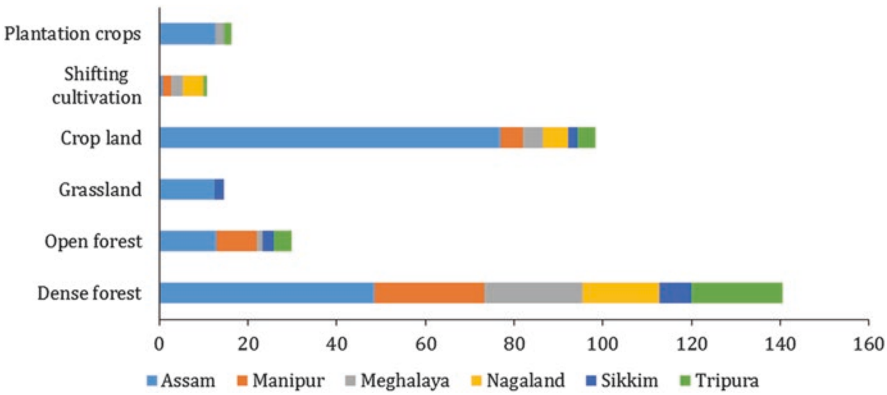

Fig. 11.3 SOC stock (Tg) under major land use systems of North-Eastern region (Source: Choudhury et al. 2011)

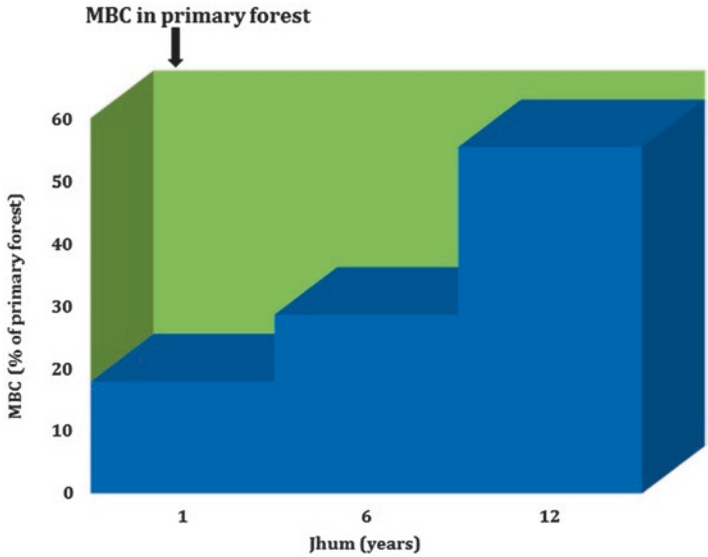

Fig. 11.4 Variations in microbial biomass carbon (MBC) content with jhumming age in North East India (Source: Ralte et al. 2005)

forest lands in steep slopes and burning followed by seed sowing with onset of rains. The continuum of processes physically exposes the soil for planting, eliminates vegetation cover, and usually has a short rotation period of 2–3 years. This leads to rapid soil degradation and hence carbon storage. For example, microbial biomass carbon (MBC), a major soil carbon pool and an indicator of soil health, was observed to decline rapidly by clearing and burning of forests for shifting cultivation in the region (Fig. 11.4). However, with passage of time, this carbon fraction was found to recuperate by way of steady buildup of organic matter and nutrients with successional stage of the ecosystem. The detritus and nutrients provided by these ecosystems act as the basic source for MBC buildup in *jhum* areas with age.

Agroforestry plays a decisive role in microclimate of soil, availability of substrates and carbon allocation patterns in plant, and thereby the CO_2 efflux from soil to atmosphere. These systems continuously return large amounts of organic material from the standing biomass and help build stable carbon pools in soil. The quantity of carbon and nutrient inputs to the soil in agroforestry systems is directly dependent on tree and crop composition productivity, management system, and site-specific edaphic and climatic factors (Nair 1993). The quality of the added organic inputs is yet another key factor controlling the decomposition rate and nutrient release (Kwabiah et al. 1999, 2001). Multipurpose tree species used in agroforestry systems of the NEH region were found to improve both the quantity and quality of SOC as a function of soil type and climate in the region (Parton et al. 1987; Saha et al. 2007). Several studies (Saha and Jha 2012; Ramesh et al. 2013) in the NEH region have reported an improvement of approximately 20–32% carbon when mul-

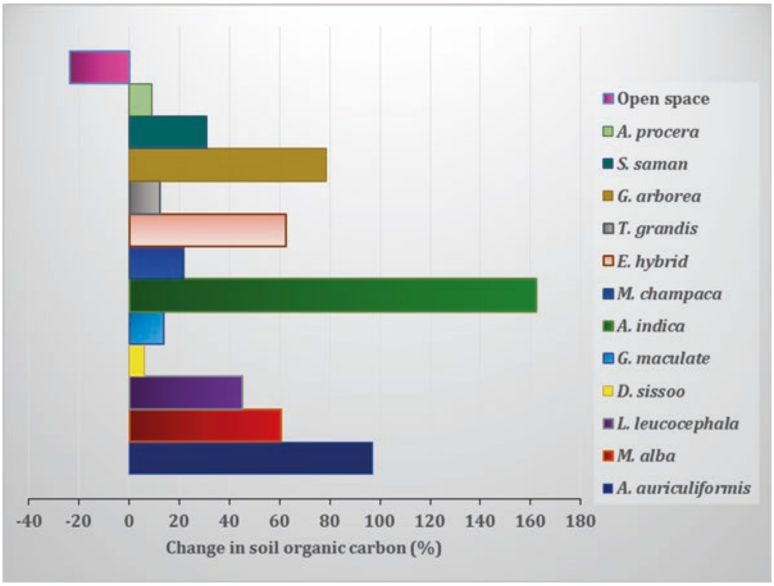

Fig. 11.5 Changes in SOC (%) over the years (between 4th and 16th year) under various multipurpose trees in North East India (Source: Datta and Singh 2007)

tipurpose tree species were grown alongside crops. The quality of the stored carbon was also found enhanced with respect to cellulose, hemicellulose, carbon/nitrogen and lignin/nitrogen ratios.

Roots contribute approximately 20–25% of the total tree biomass, and the constant addition to soil organic matter pool through leaf and root decay furthers the carbon status improvements in the agroforestry systems (Balkrishnan and Toky 1993). The enhanced soil carbon accumulation can also be attributed to the better soil aggregation and higher vegetative cover throughout the year in these systems. Several other studies (Saha et al. 2007, 2010) have also reported an enhancement of SOC up to 160% under various multipurpose tree species used in the agroforestry systems of the region. The carbon enrichment under agroforestry system occurs with greater vegetative cover, enhanced litter, and extensive root distributions (Figs. 11.5 and 11.6). Similarly, tree species such as *Pinus kesiya* when used in agroforestry systems lead to carbon accumulation by way of generating acidic pine needles that lower soil pH, thereby reducing the rate of SOC decomposition. In general, multipurpose tree species used in the region in agroforestry systems improves the SOC content of soil though to varying degree depending upon the type of system, their structure and function, nature and composition of trees and crops, and management options.

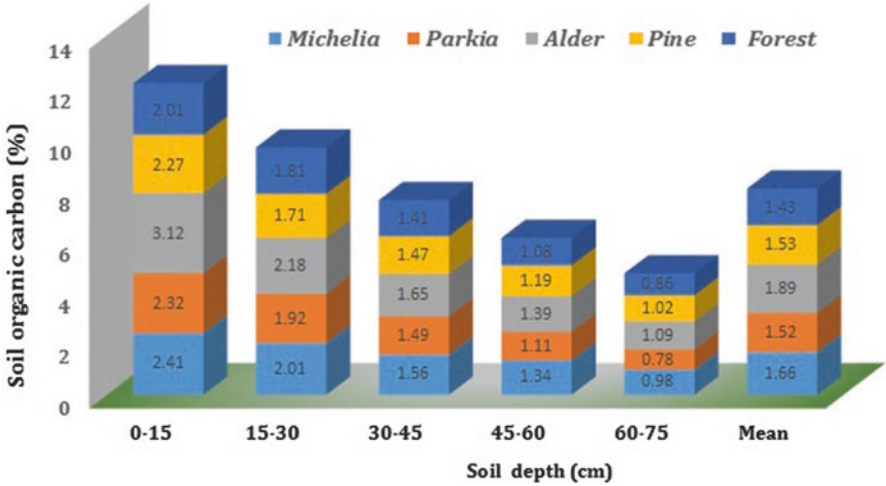

Fig. 11.6 Soil organic carbon (%) under different multipurpose tree species in the NEH (Source: Ramesh et al. 2013)

4 Influence of Soil Parameters on Carbon Stocks

Soil physicochemical properties play a major role in the soil carbon sequestration of agroforestry systems. These factors alter plant productivity and root growth and influence both the quantity and quality of litter and in turn affect the carbon dynamics in these systems (Ojima et al. 1991; Nair et al. 2010; Laganière et al. 2010; Cusack et al. 2009). Several studies (Kizito et al. 2006; Liste and White 2008) have shown that the hydraulic uplift of water by roots of a single tree will lead to an enhanced water uptake by neighboring plants as well in the agroforestry system which will in turn positively affect carbon sequestration by way of increased productivity and enhanced decomposition of carbon. Surface horizons of intensively managed agricultural landscapes are highly prone to erosion which will be reduced drastically by incorporating trees in the system (Lal 2005).

Trees will have a higher soil carbon sequestration potential than crop or pasture plant species as they help store more carbon in the relatively stable micro-sized (<53 μ) and macro-sized aggregates (53–250 μ) in agroforestry systems (Jobbágy and Jackson 2000; Nair et al. 2009b). Such organo-mineral complexes in these systems provide physical protection and biochemical recalcitrance to soil carbon and help to create a stable pool in these ecosystems. Studies by Mikutta et al. (2006) showed that most of recalcitrant carbon is bound in organo-mineral complexes in tree-based land uses; however, the formation of such complexes takes longer time to materialize (Six et al. 2000). Such aggregates protect SOC by (i) forming a physical barrier between carbon substrates and degradative forces in soil, (ii) controlling food web interactions, and (iii) influencing microbial turnovers (Fig. 11.7).

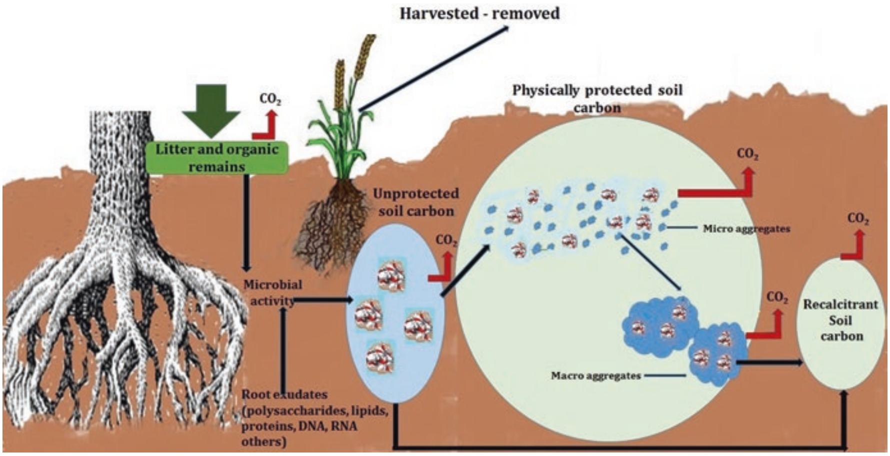

Fig. 11.7 Model of soil organic dynamics and stabilization under agroforestry systems

Agroforestry systems with long rotation periods generate a continuous flow of litter, and many of the compounds in fresh soil organic matter are protected by organo-mineral complexes or physically within the macroaggregate, but readily decompose when exposed. Thus, the process of carbon sequestration in these systems hinges to a large extent on the formation and stability of macroaggregates and availability of fresh soil organic matter.

The enhancement of microbial communities, their activities, and overall biodiversity under the tree species may also provide a favorable environment for greater SOC sequestration (Mitchell et al. 2010). However, field-based studies of such soil carbon processes and mechanisms in tree-based ecosystems such as agroforestry systems of NEH regions are scanty. Ecosystems such as agroforestry systems with high input of good-quality organic residues tend to have a high amount of soil microbial biomass and activities as these organic substrates provide microorganisms a ready source of energy (Hassink 1994). This in turn enhances the MBC and microbial biomass nitrogen (MBN) pools in these soils. A study by Ralte et al. (2005) shows that in North-East India, the presence of tree species (primary forests) enhances MBC pools when compared to *jhum* fallows, tea garden, and orange orchards. Hence, agroforestry systems which integrate trees along with crops can be expected to have a better soil carbon pool status than its agricultural crop alone counterparts.

Apart from the positive effects obtained by integrating trees into agricultural systems (Nair et al. 2010), there can also be several possible adverse interactions (e.g., pests, drought, fires, plant competition, etc.) which may lead to reduced tree performance and carbon sequestration in agroforestry systems (Burgess et al. 2004; Sileshi et al. 2007; Mosquera-Losada et al. 2010; Rigueiro-Rodríguez et al. 2009). SOC stocks represent a dynamic balance between organic material input and their decomposition losses and as such exist in a variety of carbon pools with a wide

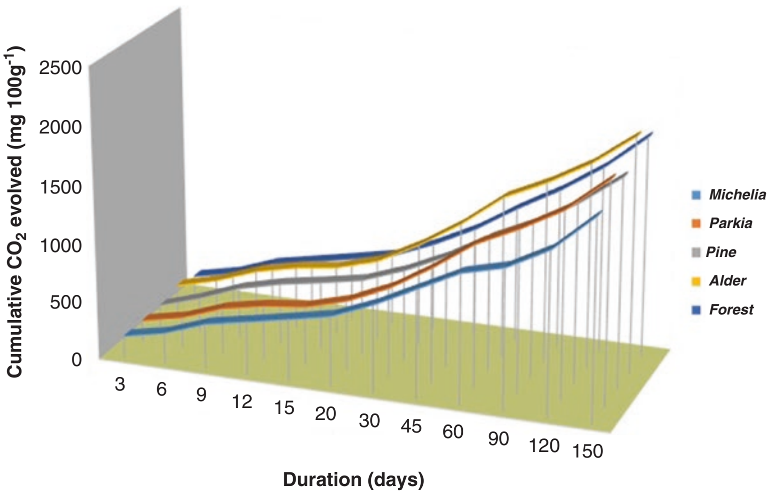

Fig. 11.8 Cumulative CO_2 efflux from soils of various multipurpose tree species at 35 °C in NEH region of India (Source: Ramesh et al. 2013)

range of mean residence times (Jenkinson and Rayner 1977; Saggar et al. 1994; Torn et al. 1997; Oelbermann et al. 2006). For example, non-woody plant materials and fresh litter are quickly decomposed and usually have a mean residence time of approximately 3–4 years. On the other hand, woody materials form a part of the passive SOC pool and persist for longer periods of 1000 years or more by way of their chemical inertness or physical protection rendered by soil (Parton et al. 1987).

Multipurpose tree species used in agroforestry systems of the NEH region were found to promote high CO_2 production with declining soil pH, wherein they promote H^+ release for cation uptake by plant, enhance litter accumulation, release organic acids from decaying organic matter, and increase root respiration (Tripathi et al. 2009; Yao et al. 2010; Ramesh et al. 2013). High biomass productivity and larger belowground carbon allocation by tree species lead to enhanced carbon source availability for biochemical decomposition and CO_2 releases from these systems (Fig. 11.8).

As such, there can be significant changes in this CO_2 efflux between tree species depending upon the soil parameters, litter fall rate, contribution from root biomass, chemical complexities of the added biomass, decomposition rate, and microbial community acclimatization to the prevailing environments (Chaudhary et al. 2009). Nevertheless, soil aggregation and ensuing physical and chemical protective mechanisms under such systems reduce the quantity of CO_2 released when compared to non-agroforestry practices. However, some authors argue that soil aggregation should be considered as a transitional soil property and would exert carbon protection only to a limited extend as the aggregates destroy and reform themselves constantly (Six et al. 2004; Kong et al. 2005; Sandeep and Manjaiah 2014). Hence under high temperature, there is a high chance that the physically protected SOC is exposed to degradation forces either by carbon desorption from adsorption sites (Hulscher and Cornelissen 1996) or by enhanced efficacy of enzymes (Reichstein et al. 2005).

Integration of crop production systems with trees and their management strategies will alter the rate and quantity of sequestered carbon (Nair et al. 2010). Soil management practices in agroforestry systems affect quality and amount of carbon inputs especially the belowground components (Nair et al. 2009b). In general, SOC accumulation in any agroforestry system is usually a complex mix of partially decomposed components, fire residues, and microbial end products rather than humic materials alone. Environmental factors help in physical disconnection, e.g., from organo-mineral associations, enzymatic decomposition, electron acceptors, and freezing/thawing that govern the SOC cycling (Schmidt et al. 2011). Carbon residues added to the surface get incorporated with the mineral matrix either by solubilization or by physical mixing or by transport and subsequent adsorption (Lorenz and Lal 2005). As plant roots act as the primary vector for most of the carbon (litter and rhizodeposition) entering the SOC pool within and outside the soil aggregates, the depth distribution of the tree species may be considered an important factor for carbon distribution and its long-term carbon storage in the soil profiles of the agroforestry systems (Rasse et al. 2005). However, there exists limited knowledge of carbon rhizodeposition by mixed plant communities such as agroforestry which hampers the rigorous quantification of carbon sequestration potential of these systems (Jones et al. 2009).

Dissolved organic carbon (DOC), though forms only a small portion of SOC, is a direct belowground carbon input (Bolan et al. 2011). The major sources of DOC in agroforestry systems include stemflow, through fall, humus, freshly deposited leaf litter, and crop residues as well as applied organic amendments. The subsoils of NEH being developed under a humid tropical climate are rich in amorphous iron and aluminum oxides and hydroxides and play a significant role in DOC retention. Thus, agroforestry systems with high contribution of DOC can contribute to their effective translocation and formation of mineral-bound SOC, a process that ensures carbon accumulation in the region (Bolan et al. 2011; Schrumpf et al. 2013).

Biotic and abiotic factors play a major role in carbon stabilization in an ecosystem. Though microbial-derived organic materials play a crucial role in carbon stability, the molecular complexities of the plant inputs as such have only a secondary role. Within a given soil environment, carbon stabilization can be perceived as a function of resource availability and microbial ecology. In general, processes which retard or physically exclude accessibility of carbon to decomposing forces and organo-mineral/organometal interactions can ensure long-term carbon stabilization in soils. Kögel-Knabner et al. (2008) noted that physical protection of organic carbon is essential for short-term carbon stabilization from decades to centuries, whereas organo-mineral complexes or organometal complexes are required for their long-term storage spanning centuries to millennia. Chemical composition-induced recalcitrance as well as physical protection will allow carbon fractions to sustain in soil sufficiently long enough to form stable organo-mineral complexes (Six et al. 2000). Agroforestry systems should focus on using suitable tree and crop combinations so that these sequences of processes are not disrupted and organic carbon exposed to decomposition (Ewing et al. 2006). In short, the sequestration of SOC in agroforestry systems can be summarized as a complex interaction of carbon with its environment vis-à-vis chemistry of the organic compound, soil minerals, climate, soil reaction and its redox state, water availability, and the microbial ecology in the soil microenvironment (Schmidt et al. 2011).

5 Management Strategies for Enhancing Carbon Storage in Agroforestry Systems

Soil carbon content in agroforestry systems can be enhanced by increased biomass additions along with reduction in their decomposition rates. The decomposition rates of SOC in these systems can be decreased by adopting measures that reduce water and nutrient losses and soil management strategies that enable physical, chemical, and biological mechanisms of carbon stabilization (Lal and Follett 2009). Like agricultural systems, reduction in cultivation intensity along with soil supplementation with mineral fertilizers, irrigation, and residue incorporation will lead to enhanced carbon sequestration in agroforestry systems (Nair et al. 2010).

Soil management strategies such as manure additions will influence the formation and stability of soil micro- and macro-sized aggregates in agroforestry systems, hence carbon stabilization and sequestration. However, the effects of fertilizers and herbicide applications have showed mixed effects on soil aggregation and carbon storage in these systems of the NEH region. The anthropogenic impacts on soil carbon sequestration through management practices can be achieved only to a certain extent. There is a limit for the carbon entering and stabilizing in a soil, and it has been noted that beyond a certain limit, carbon additions may not necessarily get incorporated into microaggregates, rather get added to the more labile macroaggregates that will be easily decomposed (Gulde et al. 2008). Hence the effects of improved management strategies on SOC contents in the agroforestry systems of the region can be considered highly site-specific.

Agroforestry systems with multiple species are reported to have greater potential than the best-performing monocultures in productivity and carbon sequestration due to increased belowground interactions (Ong et al. 2004). Agroforestry management for carbon sequestration should include aspects such as the selection of tree species, stand density, rotation length, and silvicultural management (Nair et al. 2009a). Studies by Saha et al. (2009) showed that the soil carbon stock (1 m depth) was directly related to plant diversity wherein smaller-sized homegardens had higher tree densities and could store up to 119.3 Mg ha^{-1} than larger-sized agroforestry systems (108.2 Mg ha^{-1}).

Tree species with extensive and deep root systems will have a higher carbon sequestration potential in the agroforestry system due to a high potential for carbon input into the system (Kell 2012; Lorenz and Lal 2010). For example, broadleaf trees have an extensive deeply anchored root system than coniferous trees and therefore generate higher carbon inputs from roots in the soil profile. However scanty reports exist on the ability of different agroforestry species and mixed plantations to store carbon in deeper mineral soils of NEH region (Jandl et al. 2007). In conclusion, comprehensive studies are required to assess whether these agroforestry systems can be manipulated specifically to maximize the soil carbon sequestration by exploring the sequestration potential of the entire soil profile in the presence of different tree species and their associated root-derived carbon inputs.

6 Conclusions

The traditional practice of agroforestry for achieving maximum resource use efficiency has recently received much interest and attention due to its potential for carbon sequestration and thereby climate change mitigation. Including woody perennials or trees specifically enhances climate benefits among other ecological benefits. Agroforestry systems in the NEH region promote soil carbon sequestration both by increased carbon inputs and enabling physical and chemical protection of added residues. Stability of the stored carbon can be summarized as function of its interaction with the environment that includes chemistry of the organic compound, soil minerals, climate, soil pH and its redox state, water availability, and microbial ecology. As existing reports on carbon storage potential and its decomposition losses from soils are highly variable, site-specific agroforestry management can be recommended only after gaining a comprehensive knowledge of the sequestration processes in soil profiles of the NEH region.

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