Probir K. Ghosh · Sanat Kumar Mahanta
Debashis Mandal · Biswapati Mandal
Srinivasan Ramakrishnan *Editors*

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Agroforestry for Carbon Sequestration in Tropical India

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S. K. Dhyani, Asha Ram, Ram Newaj, A. K. Handa,
and Inder Dev

Abstract

Our atmosphere naturally contains CO_2, CH_4, N_2O, water vapor, and other gases creating a natural greenhouse effect. But increased concentrations of these gases in the atmosphere have created an imbalance and have enhanced the greenhouse effect causing warming of the globe. Global warming will adversely affect hundreds of millions of people and will pose serious threats to the global food system and to rural livelihoods. Global warming is mainly the result of rising CO_2 levels in the Earth's atmosphere. CO_2 concentration in the atmosphere is increasing at greater pace from decade to decade. To assure food security, adaptation, and mitigation to climate change is unavoidable. Many organizations worldwide are working for lowering CO_2 concentration through various strategies like reduction in energy use, developing low- or no-carbon fuel, and CO_2 sequestration by forestry/agroforestry and engineering techniques. Agroforestry has been recognized as a means to reduce CO_2 emissions and enhance carbon sinks. Agroforestry systems (AFS) offer important opportunities of creating synergies between both adaptation and mitigation actions. Recent studies under various AFS in diverse ecological conditions showed that these systems increase and conserve aboveground and soil carbon stocks and also have an important role in increasing livelihood security and reducing vulnerability to climate change. The potential of agroforestry systems to accumulate C is estimated to 0.29–15.21 Mg ha^{-1} $year^{-1}$. The carbon sequestration potential of AFS can be enhanced by stabilizing soil organic carbon through possible mechanisms including biochemical recalcitrance and physical protection and also reducing C losses. Furthermore, effectiveness of AFS to carbon sequestration depends on structure and functions of different component, environmental, and socio-economic factors. Carbon sequestration can be quanti-

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S. K. Dhyani
ICAR-Natural Resource Management Division, ICAR, New Delhi, India

A. Ram (✉) · R. Newaj · A. K. Handa · I. Dev
ICAR-Central Agroforestry Research Institute, Jhansi, India

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fied by destructive or nondestructive methods. Implementing agroforestry on farmers' fields for carbon sequestration will have major challenges which deserve to be addressed in an effective manner.

Keywords
Agroforestry · Carbon sequestration · Management practices · Tropical region

19.1 Introduction

Climate change is the single biggest environmental and humanitarian crisis of our time. The earth's atmosphere is overloaded with heat-trapping greenhouse gases (GHGs), namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which are threatening large-scale disruptions in climate with disastrous consequences. Change in climate is changing our economy, health, and communities in diverse ways. The global mean annual temperature at the end of the twentieth century, due to GHG accumulation in the atmosphere, has increased by 0.4–0.76 °C above that recorded at the end of the nineteenth century (IPCC 2007); however, presently it is increasing at the rate of 1.5 °C. Agriculture, change in land use, and forestry account for 25–30% of global anthropogenic GHG emissions to the atmosphere (IPCC 2007). The agricultural sector alone is responsible for about 10–12% of total non-CO_2 anthropogenic GHG emissions (FAOSTAT 2013). Global climate change and warming of the atmosphere may lead to greater variability in rainfall, rise in sea level, increased incidence of extreme weather events such as floods and droughts, heavy and intense storms, and decrease in crop yields in some of the tropical regions, threatening the livelihoods of communities living in the climatically vulnerable regions of the world. These changes are already being experienced by India and other parts of the world. The frequent droughts, flooding, and other weather vagaries in many parts of the country are affecting the livelihood of millions of people in general and small and marginal farmers in particular.

Carbon dioxide (CO_2) is the most important GHG. Although at the molecular scale carbon dioxide is not the strongest greenhouse gas, it is emitted in the greatest amounts from anthropogenic activities. Annual emissions of CO_2 have grown by about 80% between 1970 and 2004, from 21 to 38 Gt, and represented 77% of total anthropogenic GHG emissions. Since the industrial revolution, atmospheric CO_2 is increasing at greater pace from decade to decade. For the past 10 years, the average annual rate of increase is 2.07 ppm. This rate of increase is more than double the rate in 1960s (CO_2 now.org). The GHGs emissions should be reduced by 50–80% by 2050 to avoid the adverse consequences of global warming. There are three strategies of lowering CO_2 concentration from the atmosphere: (i) reducing the global energy use, (ii) developing low- or no-carbon fuel, and (iii) sequestering CO_2 from point sources or from the atmosphere through natural (vegetation/soils) and engineering techniques (Schrag 2007). There is a growing interest in the role of various types of land-use systems in stabilizing the atmospheric CO_2 concentration and reducing the CO_2 emissions or on increasing the carbon sink. India has made a number of efforts to address climate change. The government has launched the National Action Plan on Climate Change (NAPCC) in June 2008 to achieve its goals and deal with the issues related to climate change. In order to assess the impact of climate change/variability on agriculture, the Government of India through the Indian Council of Agricultural Research (ICAR) launched a flagship network project "National Initiative on Climate Resilient Agriculture" (NICRA), which is now referred as "National Innovations in Climate Resilient Agriculture" (NICRA). Many programmes and schemes have been initiated by the government and its scientific organizations to offset carbon emission. The Green India Mission is one of them with a target to achieve 33% tree cover of the total geographical area through agroforestry and social forestry as envisaged in National Forest Policy. The idea of reducing CO_2 from the atmosphere through forest conservation and management was discussed as early as in 1970s. But it was in 1990s that international action was initiated in this direction. In 1992, several countries agreed to the United Nations Framework Convention on Climate Change (UNFCCC), with the major objectives of developing national inventories of greenhouse gas emissions and sinks and reducing the emission of greenhouse gases (FAO 2001). Since the Clean Development Mechanism (CDM) under the Kyoto Protocol allows industrialized countries with a GHG reduction commitment to invest in mitigation projects in developing and least developed countries, there is an attractive opportunity for small and marginal farmers in these countries, who are the major practitioners of agroforestry, to benefit economically from their agroforestry practices (Nair et al. 2009); however, the mechanism is yet to be established for the economic benefits of farmers.

In the present-day context, agroforestry's contribution to climate change adaptation and mitigation through carbon sequestration is of relevance as countries develop mechanisms for Reducing Emissions from Deforestation and forest Degradation (REDD+). A large portion of country's population is still not secure for food, nutrition, fodder, and need of fuelwood, and agroforestry is well known to immensely contribute to address these challenges. In addition, agroforestry is a well-established remedy against extreme weather conditions resulting in failure of crops leading to a total loss of farmers' income. Being resistant to climate variations (drought, flood, heat and cold stress, etc.), trees ensure availability of nutritive food, fodder, and fuel when food crops are partially or fully destroyed. Climate change vulnerability map exhibits extreme to high vulnerability for the majority areas of South Asian countries. Agroforestry has an important role in reducing vulnerability, increasing resilience of farming systems, and buffering households against climate-related risks. Agroforestry is an integrated response to the threat of climate change as it supports both mitigation and adaptation ("mitigadaptation" – Van Noordwijk et al. 2011). Agroforestry generates adaptation benefits through its impact on reducing soil and water erosion, improving water management, and reducing crop output variability. Planting trees and shrubs also increases carbon sequestered both above and below the ground, thereby contributing to GHG mitigation (Verchot et al. 2007). As a mitigadaptation strategy, agroforestry offers additionally over the other options of mitigation, which comes from its conservation value and services to the environment

(Newaj and Dhyani 2008). Agroforestry systems (AFS) provide environmental services in addition to the economic gains and other contributions (Dhyani 2012). Globally, more than 70 countries have identified agroforestry as one of the important tools to adapt to or mitigate climate change (Richards et al. 2016). In India, evidence is now emerging that agroforestry systems are promising land-use system to increase and conserve aboveground and soil carbon stocks to mitigate climate change. There are ample evidences to show that the overall (biomass) productivity, soil fertility improvement, soil conservation, nutrient cycling, microclimate improvement, and carbon sequestration potential of an agroforestry system are generally greater than that of an annual system (Dhyani et al. 2009). Thus, the role of agroforestry as a carbon sequestration strategy has raised considerable expectations.

19.2 Agroforestry and Carbon Sequestration

The long-term C cycle that describes the biogeochemical cycling of C among surface systems consisting of oceans, the atmosphere, biosphere, and soil controls the atmospheric CO_2 concentration over geological timescales of more than 100,000 years (Berner 2003). The short-term C cycle over decades and centuries is of greater importance than the long-term cycle in forest, agroforestry systems (AFS), and agricultural ecosystems (Nair et al. 2010). The important processes of this cycle are the fixation of atmospheric CO_2 in plants through photosynthesis and return of part of that C to the atmosphere through plant, animal, and microbial respiration as CO_2 under aerobic and CH_4 under anaerobic conditions (Fig. 19.1). The other responsible factors for CO_2 emission are vegetation fire, burning of fossils and fuels, burning and land cleaning for cultivation, etc., but much of this emitted carbon is recaptured in subsequent regrowth of the vegetation (Lorenz and Lal 2010; Nair et al. 2010).

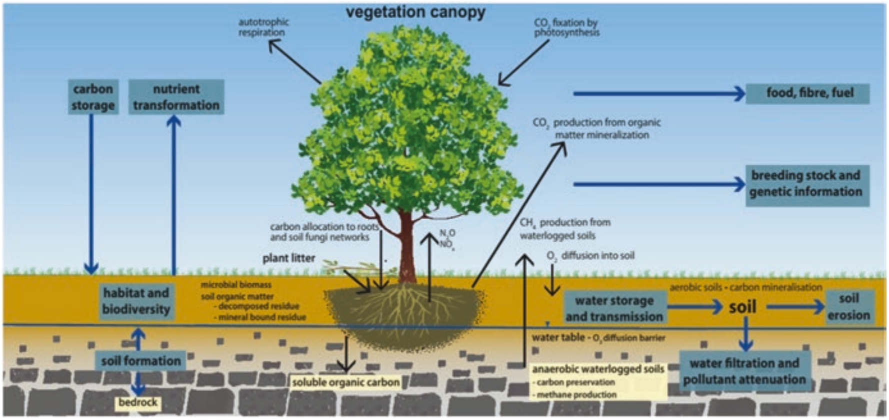

Fig. 19.1 Soil–plant–carbon interrelationships and associated ecosystem services (Victoria et al. 2012)

19.3 Carbon Sequestration Potential of Agroforestry Systems

Today, AFS has become a well-established approach to integrated land management, not only for renewable resource production but also for ecological and environmental considerations. It provides a win–win opportunity to combine the twin objectives of climate change adaptation and mitigation. Although AFS is not primarily designed for carbon sequestration, there are many recent studies that substantiate the evidence that agroforestry systems can play a major role in storing carbon in aboveground biomass (Murthy et al. 2013) and in soil and in belowground biomass (Nair et al. 2009). Agroforestry represents the combination of crops with trees which play an important role in C sequestration (Takimoto et al. 2009); with an increase in the number of trees (high tree density) in a system, the overall biomass production per unit area of land will be higher, which in turn may promote more C storage in aboveground and belowground biomass.

A significant fraction of the atmospheric C could be captured and stored in plant biomass and in soils with adoption of agroforestry systems. However, increasing C stocks in a given period of time is just one step; the fate of those stocks is what ultimately determines sequestration. In AFS, C sequestration is a dynamic process and can be divided into phases for the sake of understanding. At establishment, many systems are likely to be sources of GHGs (loss of C and N from vegetation and soil). Then follow a quick accumulation phase and a maturation period when tons of C are stored in the boles, stems, roots of trees, and in the soil (Saha and Jha 2012). At the end of the rotation period, when the trees are harvested and the land returned to cropping (sequential systems), part of the C gets released back to the atmosphere (Dixon 1995). Therefore, effective sequestration can only be considered if there is a positive net C balance from an initial stock after a few decades. In fact, many recent research findings reported that sequestration of atmospheric carbon was higher by agroforestry systems than treeless agriculture or pasture land-use systems under similar ecological conditions (Haile et al. 2008; Nair et al. 2009; Ajit et al. 2013).

The carbon sequestration potential of agroforestry systems has been successfully established theoretically; however field measurements to validate these concepts are limited. The inherent variability in the estimates of potential carbon storage in agroforestry systems and the lack of uniform methodologies has made comparisons difficult (Jose 2009). The fact that agroforestry systems can function as both source and sink of carbon has been presented in many literatures (Dixon 1995; Montagnini and Nair 2004). There is also clear evidence to suggest that the type of agroforestry system influences greatly the source or sink role of trees. According to the IPCC (2007), agroforestry systems offer important opportunities of creating synergies between both adaptation and mitigation actions with a technical mitigation potential of 1.1–2.2 Pg C in terrestrial ecosystems over the next 50 years. According to Murthy et al. (2013), the potential of AFS to accumulate C is estimated to be 12–228 Mg ha^{-1}, with an average of 95 Mg ha^{-1} (Table 19.1). However, the amount of C in any AFS depends on the structure and function of the different component

Table 19.1 Carbon storage potential[a] of agroforestry systems in different ecoregions of the world (Murthy et al. 2013)

Continent	Ecoregion	System	Carbon storage potential (Mg C ha^{-1})
Africa	Humid tropical high	Agrosilvicultural	29–53
South America	Humid tropical low dry lowlands	Agrosilvicultural	39–102, 39–195
Southeast Asia	Humid tropical dry lowlands	Agrosilvicultural	12–228, 68–81
Australia	Humid tropical low	Silvipastoral	28–51
North America	Humid tropical high humid tropical low dry lowlands	Silvipastoral	133–154
			104–198
			90–175
Northern Asia	Humid tropical low	Silvipastoral	15–18

[a] Carbon storage values were standardized to a 50-year rotation

within the systems and across species and geography (Albrecht and Kandji 2003; Newaj and Dhyani 2008). Besides the potential of AFS to accumulate and sequester carbon, these systems could evolve into a technological alternative for reducing deforestation rates in tropical and subtropical zones while also offering a wide variety of products and services to rural communities (de Jong et al. 1995). Furthermore, the effectiveness of agroforestry systems in sequestering carbon depends on both environmental and socio-economic factors of a particular area (Mutuo et al. 2005).

Carbon sequestration (CS) in terrestrial pools includes the aboveground plant biomass, such as timber and fuelwood, and belowground biomass, such as roots, soil microorganisms, and the relatively stable forms of organic and inorganic C in soils and deeper subsurface environments. The Soil Science Society of America (SSSA) recognizes that C is sequestered in two ways in soils: direct and indirect (SSSA 2001). Direct soil CS occurs by inorganic chemical reactions that convert CO_2 into soil inorganic C compounds such as calcium and magnesium carbonates. Indirect CS occurs by the process of photosynthesis which captures CO_2 from the atmosphere and stores as plant biomass. Some of this plant biomass is then deposited as soil organic carbon (SOC) during decomposition processes. The amount of soil C sequestered at a site reflects the long-term balance between C uptake and release mechanisms (Nair et al. 2010). It is clear from the above that carbon sequestration occurs in two major segments of the agroforestry system: aboveground and belowground. Each can be partitioned into various subsegments: the former into specific plant parts (stem, leaves, etc., of trees and crop components) and the later into living biomass such as roots and other belowground plant parts, soil organisms, and C stored in various soil horizons. The total amount sequestered in each part differs greatly depending on a number of factors, including the region, the type of system (and the nature of components and age of perennials such as trees), site quality, and previous land use. On average, the soil and aboveground parts are estimated to hold major portions, roughly 60% and 30%, respectively, of the total C stored in tree-based land-use systems (Lal 2005, 2008).

19.3.1 Aboveground Carbon Sequestration

According to Nair et al. (2010), aboveground C storage is the incorporation of C into plant parts either in the harvested product or in the in situ remaining living parts. The aboveground biomass (AGB) that is not removed from the site is eventually reincorporated into the soil as plant residues and organic matter. A summary of mean vegetation (above- and belowground) CS rates in some major AFSs around the world (Table 19.2) presented by Nair et al. (2009) shows that the estimates of

Table 19.2 Mean vegetation (above- and belowground) carbon sequestration potential[a] of prominent agroforestry systems[d]

Agroforestry/land-use system[b]	Age[c] (year)	Mean vegetation C (Mg ha^{-1} year^{-1})	Source
Fodder bank, Ségou, Mali, W African Sahel	7.5	0.29	Takimoto et al. (2008b)
Live fence, Ségou, Mali, W African Sahel	8	0.59	Takimoto et al. (2008b)
Tree-based intercropping, Canada	13	0.83	Peichl et al. (2006)
Parklands, Ségou, Mali, W African Sahel	35	1.09	Takimoto et al. (2008b)
Agrisilviculture, Chhattisgarh, India	5	3.23	Swamy and Puri (2005)
Silvopasture, W Oregon, USA	11	1.11	Sharrow and Ismail (2004)
Silvopastoralism, Kurukshetra, India	6	1.37	Kaur et al. (2002)
Silvopastoralism, Kerala, India	5	6.55	Kumar et al. (1998)
Cacao agroforests, Mekoe, Cameroon	26	5.85	Duguma et al. (2001)
Cacao agroforests, Turrialba, Costa Rica	10	11.08	Beer et al. (1990)
Shaded coffee, SW Togo	13	6.31	Dossa et al. (2008)
Agroforestry woodlots, Puerto Rico	4	12.04	Parrotta (1999)
Agroforestry woodlots, Kerala, India	8.8	6.53	Kumar et al. (1998)
Home and outfield gardens	23.2	4.29	Kirby and Potvin (2007)
Indonesian home gardens, Sumatra	13.4	8.00	Roshetko et al. (2002)
Mixed species stands, Puerto Rico	41	5.21	Parrotta (1999)
Block plantation, Karnataka, India	7–10	3.71	Ajit et al. (2014)

[a] Though reported as carbon sequestration potential, the values are based on C-stock estimates

[b] Values for similar systems (in terms of location and age) were pooled wherever possible regardless of species

[c] "Age" of the system, though not clearly defined, is assumed to be the number of years since the establishment of the tree component in the system

[d] These systems were selected from many reports of this nature to provide a broad spectrum of agroforestry systems (live fences to multistrata systems) in different geographical regions

Modified Nair et al. (2009)

CSP in AFSs are highly variable, ranging from 0.29 to 15.21 Mg C ha^{-1} $year^{-1}$. The range of CS shows direct manifestation of the ecological production potential of the system, depending on a number of factors, including site characteristics, land-use types, species involved, stand age, and management practices. Agroforestry systems on humid and tropical sites have higher potential to carbon sequestration than the arid, semiarid, and temperate sites. Considering that aboveground CS estimates are direct expressions of AGB production, the basic mechanism of the two functions (CS and AGB production) is the same: uptake of atmospheric CO_2 during photosynthesis and transfer of fixed C into vegetation (sequestration involves the additional step of "secure storage" of such fixed C).

Many studies are available in published literature on carbon sequestration potential of various trees species in AFS (Newaj et al. 2014; Table 19.3) in India. In such studies most common tree density was in the range of 312 to 800 trees per hectare (usually preferred by the farmers in planted AFS), and the reported CSP varied from

Table 19.3 Carbon sequestration potential (CSP) of trees in India (Newaj et al. 2014)

Location	Agroforestry system	Tree species	No. of tree per hectare	Age (year)	CSP (Mg C ha^{-1} $year^{-1}$)	References
Himachal Pradesh	Agrihorticulture	Fruit trees	69	–	12.15	Goswami et al. (2013)
Khammam, Andhra Pradesh	Agrisilviculture	*L. leucocephala*	4444	4	14.42	Prasad et al. (2012)
			10,000	4	15.51	
SBS Nagar, Punjab	Agrisilviculture	*P. deltoids*	740	7	9.40	Chauhan et al. (2010)
Dehradun, Uttarakhand	Silviculture	*E. tereticornis*	2500	3.5	4.40	Dhyani et al. (1996)
			2777*	2.5	5.90	
Kurukshetra, Haryana	Silvipasture	*A. nilotica*	1250	7	2.81	Kaur et al. (2002)
		D. sissoo	1250	7	5.37	
		P. juliflora	1250	7	6.50	
Chandigarh	Agrisilviculture	*L. leucocephala*	10,666	6	10.48	Mittal and Singh (1989)
Tripura	Silviculture	*T. grandis*	444	20	3.32	Negi et al. (1990)
		G. arborea	452	20	3.95	
Tarai region Uttarakhand	Silviculture	*T. grandis*	570	10	3.74	Negi et al. (1995)
			500	20	2.25	
			494	30	2.87	
Jhansi, Uttar Pradesh	Agrisilviculture	*A. procera*	312	7	3.70	Newaj and Dhyani (2008)

(continued)

Table 19.3 (continued)

Location	Agroforestry system	Tree species	No. of tree per hectare	Age (year)	CSP (Mg C ha^{-1} year^{-1})	References
Jhansi, Uttar Pradesh	Agrisilviculture	*A. pendula*	1666	5.3	0.43	Rai et al. (2002)
Jhansi, Uttar Pradesh	Silviculture	*A. procera*	312	10	1.79	Rai et al. (2000)
		A. amara	312	10	1.00	
		A. pendula	312	10	0.95	
		D. sissoo	312	10	2.55	
		D. cinerea	312	10	1.05	
		E. officinalis	312	10	1.55	
		H. binata	312	10	0.58	
		M. azaderach	312	10	0.49	
Hyderabad, Andhra Pradesh	Silviculture	*L. leucocephala*	2500	9	10.32	Rao et al. (2000)
		E. camaldulensis	2500	9	8.01	
		D. sissoo	2500	9	11.47	
		A. lebbeck	625	9	0.62	
		A. albida	1111	9	0.82	
		A. tortilis	1111	9	0.39	
		A. auriculiformis	2500	9	8.64	
Hyderabad, Andhra Pradesh	Agrisilviculture	*L. leucocephala*	11,111	4	2.77	Rao et al. (1991)
			6666	4	1.90	
Raipur Chhattisgarh	Agrisilviculture	*G. arborea*	592	5	3.23	Swamy and Puri (2005)
Coimbatore Tamil Nadu	Agrisilviculture	*C. equisetifolia*	833	4	1.57	Viswanath et al. (2004)
Kerala	Home garden	Mixed tree spp.	667	71	1.60	Saha et al. (2009)

*Average of the 1111 and 4444 trees/ha

0.49 to 9.4 Mg C ha^{-1} year^{-1}, although for the complete picture of all the studied systems considered together (irrespective of tree densities), the CSP varied from 0.39 to 11.47 Mg C ha^{-1} year^{-1} (age varied from 2.5 to 30 years). Studies conducted in different parts of the world reported carbon sequestration potential of different AFS in the range of 0.29 to 15.21 Mg C ha^{-1} year^{-1} in above ground and 30 to 300 Mg C ha^{-1} up to 1 m of soil depth (Nair et al. 2010). Thus the existing trees on farmers' fields not only add some income to small and marginal farmers but also help in mitigating global warming by enhancing carbon sequestration potential of Indian agriculture (Ajit et al. 2013; Dhyani et al. 2016).

19.3.2 Belowground (Soils) Carbon Sequestration

It is a well-established fact that soils play a vital role in the global C cycle. The soil C pool comprises soil organic C (SOC) estimated at 1550 Pg and soil inorganic C approximately 750 Pg both to 1 m depth (Batjes 1996). This total 2300 Pg soil C pool is three times the atmospheric pool (770 Pg) and 3.8 times the vegetation pool (610 Pg); a reduction in soil C pool by 1 Pg is equivalent to an atmospheric enrichment of CO_2 by 0.47 ppmv (Lal 2001). Thus, every change in soil C pool would have a significant effect on the global C budget. The historical amount of CO_2–C emitted into the atmosphere from the terrestrial ecosystems is estimated to be approx. 136–55 Pg, of which soils account for approx. 78–12 Pg (Lal 2007). The literature on soil carbon sequestration (SCS) potential of AFS is scanty, although rather plentiful reports are available on the potential role of agricultural soils to sequester C. Review the available information on SCS in AFS worldwide, summarized by Nair et al. (2009) in Table 19.4.

Studies on carbon sequestration in soil revealed a general trend of increasing SCS in agroforestry compared to other land-use practices (with the exception of forests). Furthermore, it is noted that the estimated values of SCS in AFS varied greatly and were a reflection of several factors including biophysical and socioeconomic characteristics of the system and sampling methods/procedures (Nair et al. 2010).

Belowground biomass of trees in the form of roots comprises about one-fifth to one-fourth of the total living biomass, and there is a constant addition of organic matter to the soil through decaying dead roots (Dhyani and Tripathi 2000), which leads to increases in the C status of the soil. Accumulation of 2.91% organic C was observed under areca nut + jackfruit + black pepper + cinnamon (tejpatra) followed by 1.85% under areca nut + betelvine + miscellaneous trees as against 0.78% only in a degraded land in the same period. MPTS like *Alnus nepalensis*, *Parkia roxburghii*, *Michelia oblonga*, *Pinus kesiya*, and *Gmelina arborea* with greater surface cover, constant leaf litter fall, and extensive root systems increased soil organic carbon by 96.2%, enhanced aggregate stability by 24.0%, improved available soil moisture by 33.2%, and in turn reduced soil erosion by 39.5%. Soils under *Acacia auriculiformis*, *Leucaena leucocephala*, and *Gmelina arborea* always have high humification rate, while soils under the canopy of *Acacia auriculiformis*, *Michelia champaca*, *Tectona grandis*, and *Dalbergia sissoo* show low humification of the organic matter. Such improvements in soil quality under tree-based AFS have a direct bearing on long-term sustainability and productivity of soil (Subba Rao and Saha 2014).

19.3.3 Agroforestry: Role in CO_2 Sequestration – Some Research Initiatives

The Central Agroforestry Research Institute (CAFRI), Jhansi, has been working on CS potential of various agroforestry systems since 2000 through in-house and

Table 19.4 Soil organic carbon (SOC) stock reported in various agroforestry systems[a] (Nair et al. 2010)

Agroforestry system/species	Location	Age (year)	Soil depth (cm)	Soil C (Mg ha^{-1})	References
Mixed stands, *Eucalyptus* + *Casuarina* (C), C + *Leucaena* (L), *Eucalyptus* + L	Puerto Rico	4	0–40	61.9, 56.6, and 61.7	Parrotta (1999)
Agroforest (*Pseudotsuga menziesii* + *Trifolium subterraneum* L.	Western Oregon, USA	11	0–45	95.89	Sharrow and Ismail (2004)
Agrisilviculture (*Gmelina arborea* Roxb. + eight field crops)	Chhattisgarh, Central India	5	0–60	27.4	Swamy and Puri (2005)
Tree-based intercropping: hybrid poplar + barley	Ontario, Canada	13	0–20	78.5	Peichl et al. (2006)
Silvopastoral system: *Acacia mangium* Willd. + *Arachis pintoi* Krapov. & W. C. Gregg	Pocora, Atlantic coast, Costa Rica	10–16	0–100	173	Amezquita et al. (2005)
Alley cropping *Leucaena* – 4-m wide rows	Western Nigeria	5	0–10	13.6	Lal (2005)
Alley cropping: hybrid poplar + wheat, soybeans, and maize rotation	Southern Canada	13	0–40	125	Oelbermann et al. (2004)
Alley cropping system: *Erythrina poeppigiana* (Walp.) O. F. Cook + maize and bean (*Phaseolus vulgaris* L.)	Costa Rica	19	0–40	162	Oelbermann et al. (2004)
Gliricidia sepium + maize	Zomba, Malawi	10	0–200	123	Makumba et al. (2007)
Agroforest (home and outfield gardens)	Ipetı´-Embera, Panama		0–40	45.0	Kirby and Potvin (2007)
Shaded coffee, *Coffea robusta L. Linden* + *Albizia* spp.	South western Togo	13	0–40	97.27	Dossa et al. (2008)
Silvopasture: slash pine (*Pinus elliottii* Engelm.) + bahiagrass (*Paspalum notatum* Flügge)	Florida, USA	8–40	0–125	6.9–24.2	Haile et al. (2008)
Faidherbia albida (Delile) A. Chev. parkland	Ségou, Mali	35	0–100	33.3	Takimoto et al. (2008a)
Live fence (*Acacia nilotica* (L.)	Ségou, Mali	8	0–100	24	Takimoto et al. (2008a)
Willd., *Acacia senegal* (L.)					
Willd., *Bauhinia rufescens* L., *Lawsonia inermis* L., and *Ziziphus mauritiana* Lam.)					

(continued)

Table 19.4 (continued)

Agroforestry system/species	Location	Age (year)	Soil depth (cm)	Soil C (Mg ha^{-1})	References
Fodder bank Sahel (*Gliricidia sepium* (Jacq.) Kunth ex Walp., *Pterocarpus lucens* Willd. and *P. erinaceus* Poir.)	Ségou, Mali	6–9	0–100	33.4	Takimoto et al. (2008a)
Home gardens	Kerala, India	35	0–100	101–126	Saha et al. (2009)
Dehesa system	Central Spain	30	0–100	27–50	Howlett (2009)
Shaded cacao systems	Bahia, Brazil	30	0–100	302	Gama-Rodrigues et al. (2010)

Values for similar systems (in terms of location and age) were pooled wherever possible regardless of species

externally aided projects. The research conducted under the projects estimated carbon sequestered and CO_2 equivalent carbon sequestered in *Albizia procera*, *Dalbergia sissoo*, *Hardwickia binata*, and *Emblica officinalis*–based agroforestry systems for their rotation period (30, 50, 45, and 25 years, respectively) using CO_2FIX model. In northwestern India using GIS and RS, the spectral signatures for poplar and *Eucalyptus* were generated and the area under these two agroforestry systems was estimated. The work on mitigating potential of agroforestry system on climate change was carried out to estimate the carbon sequestration potential of agroforestry practices in Bundelkhand region. Under NICRA project, carbon sequestration potential of existing agroforestry systems in farmer's field has been estimated so far for 51 districts in 16 states (Uttar Pradesh, Gujarat, Bihar, West Bengal, Rajasthan, Punjab, Haryana, Himachal Pradesh, Maharashtra, Tamil Nadu, Andhra Pradesh, Karnataka, Madhya Pradesh, Chhattisgarh, Orissa, and Telangana). The achievement made so far indicated the number of trees on farmer's field is 18.42 trees per hectare in these states. The net carbon sequestered in agroforestry system existing on farmer's field under different states is 11.35 Mg C ha^{-1} from baseline over a simulated period of 30 years. The carbon sequestration potential (CSP) of agroforestry system is 0.35 Mg C ha^{-1} $year^{-1}$and the total CSP is 7.230 million tons of C in these states (Newaj et al. 2017). Thus, the existing agroforestry systems on farmers' fields are estimated to mitigate more than 33% of the total GHG emissions from agriculture sector annually at the country level (Ajit et al. 2016). On the basis of research conducted so far, agroforestry practices applicable to different suitable sites for sequestering atmospheric carbon in wood biomass as well as soils can be selected as stated below.

19.4 Enhancing Carbon Sequestration Through Agroforestry

19.4.1 Stabilization of Carbon in Soil

Stabilization of carbon is as much essential as fixing it. Developing strategies to sequester organic carbon (C) in soils depend on understanding the key factors that affect soil organic carbon (SOC) stabilization and the capacity of individual soils to stabilize additional SOC. The sequestration of stable SOC has been attributed to several possible mechanisms including biochemical recalcitrance, physical protection or inaccessibility, and the formation of organo-mineral complexes involving fine (clay–silt) soil particles (Baldock and Skjemstad 2000; von Lutzow et al. 2006; Dungait et al. 2012; Beare et al. 2014). The SOC associated with fine soil particles is generally regarded has highly stable, with a relatively long turnover time and slow response to changes in management (Beare et al. 2014). It also represents a large proportion of the total SOC in most soils and therefore serves as a useful measure of the stable organic C. A number of studies have shown that total SOC content is strongly and positively correlated with the amount of fine mineral particles in soils. This relationship is generally attributed to the role that the fine fraction plays in providing mineral surface for the formation of organo-mineral complexes. Besides fine fractions, many land-use practices such as no till, manure and compost additions, and enhanced residue return are used to increase soil organic carbon (SOC) content (Feng et al. 2013). Major sources of SOC are C inputs from plant roots (e.g. lignin, suberin, and rhizodeposition), mycorrhizal fungi, and illuviation through bioturbation and leaching (Nguyen 2003; Wallander et al. 2004; Rasse et al. 2005).

19.4.2 Increasing Carbon and Reducing Its Losses from Soil

There are wide management options and farming practices available that can increase SOC levels by either increasing inputs or decreasing losses, for example, stubble retention (Table 19.5). Inputs can also be increased by direct additions of organic materials, namely, composts, manures, and other recycled organic materials.

Table 19.5 Management practices that increase soil organic carbon (Chan 2008)

Management category	Management practices to increase soil carbon
Crop management	Soil fertility enhancement, better rotation, erosion control, irrigation
Conservation tillage	Stubble retention, reduced tillage, no tillage
Pasture management	Fertilizer management, grazing management, earthworm introduction, irrigation, improved grass species, introduction of legumes, sown pasture, introduction of perennial pastures
Organic amendments	Animal manure, green manure, recycled organics, vermicompost

Theoretically, any management practice that can increase production from an area of land should lead to increase in SOC storage because of the increase in carbon inputs. Farmers are familiar with practices such as fertilizer application, improved rotations, improved cultivars, and irrigation which can lead to large yield increases. Productivity increases can also be achieved by crop intensification practices such as double cropping, opportunity cropping, and multiple cropping. However, it should be noted that some of these yield-increasing practices involve the use of fertilizers and irrigation water which require large energy consumption and therefore increase carbon dioxide emission (Chan 2008).

Conservation farming is gaining worldwide acceptance rapidly as a farming practice to improve soil and water conservation. In cropping, cultivation is either reduced (reduced tillage) or completely eliminated (no tillage), and stubble (crop residue) is retained in the field. Reduced tillage reduces carbon losses (from both reduced cultivation and reduced fossil fuel usage) and stubble retention increases carbon inputs to the soil; both of these lead to SOC increases.

19.5 Limitations for Carbon Sequestration

It has been long believed that when trees or shrubs replace pastures or grasslands, there is an automatic increase of C stocks. Today, it is becoming increasingly clear that this does not happen all the time. For example, in a study conducted by Jackson et al. (2002) in the United States, it was shown that the invasion of grasslands by shrubs increased C in vegetation although to a much lower extent than expected. On the other hand, soil C had increased only on the drier sites and actually decreased in the wetter sites. As a result, the net C balance was marginally positive for the dry sites but negative for the wetter sites. Such findings suggest that the current land-based methods of C assessment may have led to an overestimation of C sinks in many areas of the globe (Jackson et al. 2002; Goodale and Davidson 2002). These inaccuracies will be compounded further if we consider that changes in C fluxes are likely to occur in the next 50 years as a result of shift in global climate, land use, and land cover. The magnitude and direction these changes will take remain largely unknown (Wang and Hsieh 2002). Similarly, degraded soils and wastelands occupy a large proportion of the earth's area, and there is a general belief that converting them into agroforestry would be a major global opportunity to absorb a significant portion of the atmospheric CO_2 (Dixon 1995). However, cultivating trees or crops in substandard soils still remains a challenge to growers and agriculturists. On problematic soils (saline, alkali, and acid soils) or in arid and semiarid areas, trees usually perform poorly, making such environments less suitable for agroforestry. Consequently, if biomass production is not adequate, significant positive changes in soil carbon are unlikely to occur in agroforestry systems. There have been many reports indicating unchanged, or even declining, SOM levels after high intensification (HI) on substandard soils and in dry environments (Akyeampong 1999). Moreover, in dry environments, the tree-crop competition for water usually results in low crop yields, which makes HI unattractive for dry land farmers. As shown in this review and many other studies, improved fallow is a promising technology for increasing C stocks in degraded soils. But a major problem with implementing sequential agroforestry systems in general is that farmers have to forego growing crops during the fallow phase, which can stretch on one or more cropping seasons. Pests and diseases are other key issues that deserve to be addressed more adequately if farmers want high biomass production in tropics.

19.6 Conclusion

Rising level of greenhouse gases particularly CO_2 in the atmosphere is a matter of great concern among the environmentalists and policymakers throughout the world. Among the various available options for mitigadaptation of global warming, agroforestry has emerged as a good option and is getting attraction for its high carbon sequestration potential (above- and belowground) along with ease of adaptability, profitability, and sustainability for its practitioners. The target of carbon sequestration through agroforestry can only be achieved through selection, identification, and promotion of suitable agroforestry systems, developing tree species through breeding/biotechnological tools for high carbon sequestration potential, ease of rules and laws through agroforestry policy, and by providing incentives, credit facility, and insurance cover for the agroforestry practitioners.

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