## Chapter 7

# Carbon Sequestration in Agroforestry and Horticulture Based Farming Systems: Mitigating Climate Change and Advancing Food and Nutrition Security

**Abhishek Raj and Manoj Kumar Jhariya**

## 7.1 Introduction

Increasing burgeoning population necessitate the food requirement that leads to increasing pressure on natural resources *i.e.*, forests and soils resulted various anthropogenic activities such as deforestation and illicit felling of trees for agricultural land expansion, practices of intensive farming systems by higher synthetic inputs and in parallel promotion of several industrial developments have various deleterious released greenhouse gases (GHGs) into the atmosphere causing global warming and climate change (Meena et al. 2022; Yadav et al. 2022; Jhariya et al. 2022). On other side, the practices of intensive agriculture enhance the food products by intensifying soils through heavy synthetic inputs which satisfy the food requirement of burgeoning populations but nutrient availability in fruits and foods are low which affects the people's health and livelihoods (Banerjee et al. 2020). No doubt, food availability is more but irrespective of nutrient availability and quality under the practices of intensive agriculture system which is treated as unsustainable land use systems that affects both food and environmental security. In this context, both agroforestry systems (AFs) and horticulture-based farming systems (HBFs) are good strategies to improve peoples and environment health by providing quality and nutritive foods and absorption of atmospheric carbon (C) through C sequestration. Definitely, agroforestry will stand for climate change mitigation by sequestrating more to more C from the atmosphere through the process of C sequestration and maintain ecological stability (Nair et al. 2011; Raj et al. 2020a, b). The storage and

---

A. Raj
Pt. Deendayal Upadhyay College of Horticulture and Forestry, Dr. Rajendra Prasad Central Agriculture University, Pusa, Samastipur, Bihar, India

M. K. Jhariya (✉)
Department of Farm Forestry, Sant Gahira Guru Vishwavidyalaya, Sarguja, Ambikapur, Chhattisgarh, India

S. Ghosh et al. (eds.), *Emerging Solutions in Sustainable Food and Nutrition Security*, https://doi.org/10.1007/978-3-031-40908-0_7

sequestration potential are reported maximum in the region characterizing high rainfall of humid tropic and observed in between 0.3 and 15.2 Mg C/ha/year (Nair et al. 2011). Similarly, HBFs is not less and gain a wide recognition in term of climate change mitigation by high potential of C absorption and maintaining a greater stability of C balance in the environment along with sustainability in both agriculture and natural resources.

Agroforestry is well-known sustainable land use and location specific farming system and proven itself for diversified products, higher productivity from better interaction in tree-crop-soil combination, better soil health & quality, maintaining food and nutritional security (FNS), improving farmer's health and wealth through diversified products, and overall climate security through the better potential of C sequestration in the tropics (Jhariya et al. 2019a, b). A schematic model of agroforestry technology is depicted in Fig. 7.1.

Adoption of ecological and sustainable based intensification in AFs and HBFs can operationalized these farming practices in more efficient in term of intensifying ecosystem services by enhancing biodiversity with less synthetic inputs and less emission of GHGs into the atmosphere that helps in producing diversified multiple products with nutrient rich food and fruits which maintains people's health and environmental quality (Jhariya et al. 2015; Singh and Jhariya 2016; Roy et al. 2022). In this context, this chapter describes the scope, possibilities, adoptability and conceptual framework of different models in agroforestry and HBFs along with its C sequestration potential in the tropics of the world. Moreover, soil fertility, rhizosphere biology and nutrient sink capacity through the potential of C sequestration in

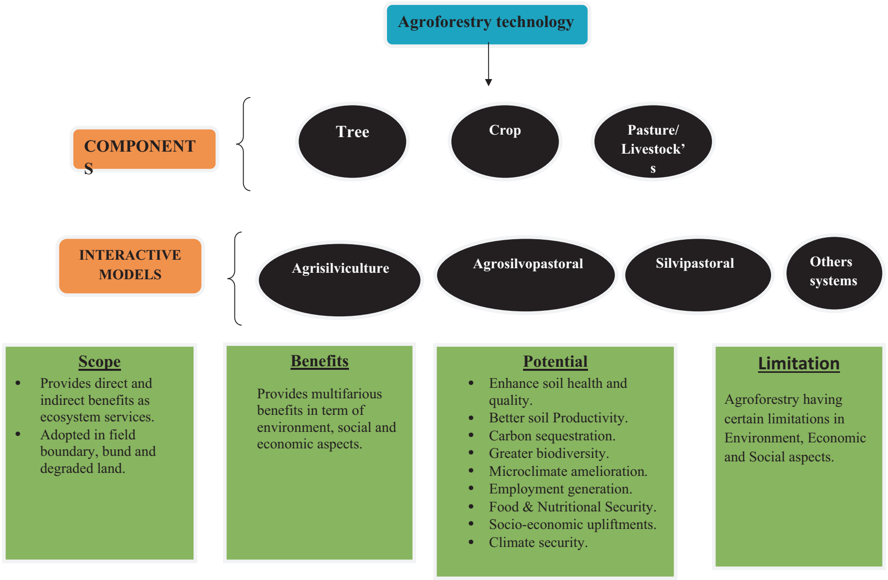

**Fig. 7.1** A schematic model of agroforestry. (Compiled from: Raj et al. 2020a, b; Banerjee et al. 2020; Jhariya et al. 2015, 2019a, b)

both AFs and HBFs are also discussed. In nutshell, this chapter is designed to gather a comprehensive detail regarding various models of agroforestry and HBFs, its C sequestration capacity, related improvement of soil health and quality and overall its role in maintaining food, nutrition, health and climate security as well as sustainability.

## 7.2 Carbon Sequestration: Global Overviews & Historical Development

Indeed, a question always triggered among the scientific community "*is C a friend or foe*?". However, various thoughts and wisdoms are arising on this topic but it is clear that C represent itself as an important constituent of the existing ecosystems that found in different forms especially carbon dioxide ($CO_2$) and directly or indirectly connected with delivery of important ecosystem services for wellbeing of humans and environment (Raj et al. 2019a, b). Movement of C (*i.e.* C cycling) along with other material and gaseous cycling (water, phosphorus, nitrogen and sulphur) intensify the ecosystem services through enhancement of biodiversity (both flora and fauna), biomass accumulation, improving net primary productivity, climate moderation, etc. But now, the day came and the efficiency of C cycling along with others are greatly affected due to several anthropogenic activities which directly or indirectly ruin our environment through depriving ecosystem services (Samal et al. 2022). Emissions of excessive C in the form of $CO_2$ into the atmosphere are a greater challenge of all developed and developing countries. However, we can say C is a *"friend"* for somewhat extent but its excessive form of emissions and unbalance proportions in the environment put to rethink over it and consider it as *"foe"*.

In the past especially before the pre-industrial era, the proportion and percentage of $CO_2$ was optimum and balanced among the varying components of environment but now it is rising and today, an unstoppable emission of C (in the form of $CO_2$) into the atmosphere is becoming global concern for all researchers, scientists, stakeholder, policy makers, etc. due to its characteristics of GHGs.

Emission of GHGs has become a hot topic for all researchers and policy makers at global level. Gases such $CO_2$, methane ($CH_4$), nitrous oxide ($N_2O$), ozone ($O_3$) and water vapor ($H_2O$) are considered as GHGs which is continuously emitted by several industrial developments, faulty land use practices, intensive farming systems in agriculture, heavy use of transportation systems, electricity consumptions and various commercial and residential activities that have deleterious impact on biodiversity which causes jeopardizing of our environment and ecosystems services. However, declining fruits quality due to lesser nutrients content, shortage of food-grain production, unexpected and untimely fruits and food production, insect pest emergence in agriculture, forestry and fruits orchards, depleting soil nutrients, less nutrient use efficiency, and overall morphological, physiological and anatomical disorders in plants are continuously observed due to emissions of various GHGs from different sectors which affects our dreams of FNS and climate security. In this context, storage and sequestration of C in environment and its components (lithosphere, hydrosphere and biosphere) are playing an important role in C balance and biomass productions (Awasthi et al. 2022; Manral et al. 2022; Thakrey et al. 2022). However, C sequestration in varying natural resources such as forest, agriculture, agroforestry, soils, etc. are a great topic to discuss which helps in better understanding and exploration of C sink capacity in the era of global warming and climate change (Prasad et al. 2021a, b; Meena et al. 2021).

Consequently, soil C sequestration gained an important attention by policymakers, national and international organization over the world. For example, “The year of soil” and “Decades of soil (year in between 2015 and 2024)” are important declaration of which the first was made by United Nations (UN) in the year 2015 and second was made by International Union of Soil Sciences (IUSS), respectively. However, the same IUSS has declared World Soil Day (WSD) with the simultaneous effort of Thai government on the occasion of World Congress of Soil Science in the year 2002. Moreover, the year 2015 was also remarkable for C sequestration due to approval of “4 per thousand” concept/resolution in the occasion of COP21 that was held in Paris. Although, the concept behind this resolution was sequestration of C in the soil ecosystem must be in depth of 40 cm with 0.4% rate in per year. That was something remarkable. However, maintaining global food and climate security along with promotion of sustainable development are defined objectives of C sequestration.

## 7.3 Agroforestry System and Horticulture Based Farming Systems (HFS): An Ecological Perspective

Of all-natural resources, agroforestry is more dynamic and diversified farming system which designed to make ecologically more stable and sustainable that comprises three elements (tree, crop and livestock’s) in complex manner, able to sustain and feeds by diversifying productions, intensify ecosystem services, maintaining soil, food, nutrition and climate security along with enhancing both socioeconomics and other environmental benefits (Leakey 1996). The practices of AFs are widely recognized by farming communities due to its numbers of positive signs such as a greater tree-crop-livestock’s interactions, sustainable land management practices, multifarious benefits, biodiversity management, varying ecosystem services, economically viable, socially acceptable, maintaining soil health and quality, enhancing flora and fauna populations, and improving food, nutritional and climate security that promotes ecological sustainability in the tropics (Cole 2010). AFs delivered various ecosystem services along with multiple products and tangible and intangible benefits such as timber, fuelwood, fodder for livestock’s and NTFPs (non-timber forest products) are considered as tangible (direct) benefits whereas biodiversity enhancement, soil fertility improvement, watershed management, FNS along with climate security are represented as intangible benefits (indirect benefits). However, due to scanty of quality and nutritive food and fruits HBFs is practiced by integrating various fruit tree species, vegetables, flowers and others. It does not only help in diversifying the nutritive and quality fruits but also maintain the health status of peoples and environment. Similarly, the horticultural land systems are developed by incorporating mixed horticultural vegetable, fruits, flowers and spices crops and these are categorized into fruits namely banana (*Musa paradisica*), pineapple (*Ananas comosus*), Mandarin orange (*Citrus reticulata*), passion fruit (*Passiflora edulis*), cashew nut (*Anacardium occidentale*), etc.; vegetable crops namely cowpea (*Vigna unguiculata*), cabbage (*Brassica oleracea*), French bean (*Phaseolus vulgaris*), radish (*Raphanu ssativus*), mustard (*Brassica nigra*), ash gourd (*Benincasa hispida*), cauliflower (*Brassica oleracea* var. botrytis), pumpkin (*Cucurbita pepo*), tomato (*Solanum lycopersicum*), chow-chow (*Sechium edule*), brinjal (*Solanum melongena*), okra (*Abelmoschus esculentus*), colocasia (*Colocasia esculenta*), etc.; different spices crops such as turmeric (*Curcuma longa*) and ginger (*Zingiber officinale*), etc.; and flowers namely orchids (family, Orchidaceae), rose (*Rosa chinensis*) and anthurium (*Anthurium andraeanum*), respectively. Further, various fruit trees that used in HBFs in different agro-climatic zones of India is depicted in Table 7.1 (Singh and Jhariya 2016).

**Table 7.1** Fruit tree used in horticulture-based farming systems (HBFs) in India

| Agro-climatic zones | Fruit trees used in HBFs | Regions |
|---|---|---|
| Western Himalayan region (Reported as largest region of Indian Himalaya) | *Prunus dulcis* (Almond)<br>*Prunus armeniaca* (Apple apricot)<br>*Prunus avium* (cherry)<br>*Prunus persica* (peach)<br>*Prunus domestica* (plum)<br>*Fragaria ananassa* (strawberry)<br>*Juglans regia* (walnut) | Distributed in the regions of Himachal Pradesh (H.P.), J&K and Uttarakhand |
| Eastern Himalayan region | *Citrus sinensis* (Orange)<br>*Musa paradisiaca* (Banana)<br>*Prunus avium* (cherry)<br>*Citrus limon* (Lemon)<br>*Carica papaya* (Papaya) | Distributed throughout the North Eastern regions of India and some part of West Bengal (W.B.) |
| Lower Gangetic plain region | *Mangifera indica* (Mango)<br>*Psidium guajava* (Guava)<br>*Litchi chinensis* (Litchi) | Some part of West Bengal (W.B.) |
| Middle Gangetic plain region | *Mangifera indica* (Mango)<br>*Carica papaya* (Papaya)<br>*Psidium guajava* (Guava)<br>*Syzygium cumini* (Jamun)<br>*Litchi chinensis* (Litchi) | Northern region of Uttar Pradesh (U.P.) and Bihar |
| Upper Gangetic plain region | *Mangifera indica* (Mango)<br>*Psidium guajava* (Guava)<br>*Syzygium cumini* (Jamun)<br>*Carica papaya* (Papaya)<br>*Prunus persica* (Peach) | Throughout the Uttar Pradesh (U.P.) |

(continued)

**Table 7.1** (continued)

| Agro-climatic zones | Fruit trees used in HBFs | Regions |
|---|---|---|
| Trans Gangetic plain region | *Mangifera indica* (Mango)<br>*Phyllanthus emblica* (Aonla)<br>*Psidium guajava* (Guava)<br>*Citrus reticulata Blanco* (Kinnow) | Regions of Delhi, Punjab, Haryana, Rajasthan and Chandigarh |
| Eastern plateau and hills region | *Mangifera indica* (Mango)<br>*Psidium guajava* (Guava)<br>*Malus domestica* (Apple)<br>*Phyllanthus emblica* (Aonla)<br>*Citrus limon* (Lemon)<br>*Punica granatum* (Pomegranate)<br>*Carica papaya* (Papaya) | Regions of West Bengal (W.B.), Jharkhand, Chandigarh, Madhya Pradesh (M.P.), and in some parts of Odisha and Maharashtra. |
| Central plateau and hills region | *Mangifera indica* (Mango)<br>*Phyllanthus emblica* (Aonla)<br>*Ziziphus mauritiana* (Ber)<br>*Citrus reticulate* (Mandarin orange) | Covering three states viz., Madhya Pradesh (M.P.), Rajasthan and some parts of Uttar Pradesh (U.P.). |
| Western plateau and hills region | *Mangifera indica* (Mango)<br>*Carica papaya* (Papaya)<br>*Musa paradisiaca* (Banana)<br>*Vitis vinifera* (Grapes)<br>*Citrus limon* (Lemon)<br>*Citrus reticulate* (Mandarin orange)<br>*Punica granatum* (Pomegranate) | Distributed in the regions of Madhya Pradesh (M.P.) and Maharashtra. |
| Southern plateau and hills region | *Mangifera indica* (Mango)<br>*Psidium guajava* (Guava)<br>*Musa paradisiaca* (Banana)<br>*Citrus limon* (Citrus)<br>*Vitis vinifera* (Grapes)<br>*Manilkara zapota* (Sapota) | Mostly covered the southern region of Tamil Nadu and Andhra Pradesh (A.P.) |
| East coast plains and hills region | *Mangifera indica* (Mango)<br>*Malus domestica* (Apple)<br>*Musa paradisiaca* (Banana)<br>*Annona reticulate* (Custard apple)<br>*Manilkara zapota* (Sapota) | Covered the regions of Tamil Nadu and Andhra Pradesh (A.P.) and in some parts of Odisha and Pondicherry. |
| West coast plains and ghat region | *Mangifera indica* (Mango)<br>*Citrus limon* (Citrus) | Distributed throughout the southern regions of Tamil Nadu, Karnataka and Kerala, whereas in some parts of Maharashtra, and Goa. |
| Gujarat plains and hills region | *Mangifera indica* (Mango)<br>*Musa paradisiaca* (Banana)<br>*Phoenix dactylifera* (Dates)<br>*Vitis vinifera* (Grapes)<br>*Psidium guajava* (Guava)<br>*Manilkara zapota* (Sapota) | Mostly covered the western parts of Gujarat, Dadra and Nagar Haveli and two union territory regions of Daman and Diu. |

(continued)

**Table 7.1** (continued)

| Agro-climatic zones | Fruit trees used in HBFs | Regions |
|---|---|---|
| Western dry region | *Ziziphus mauritiana* (Ber)<br>*Citrus limetta* (Mosambi)<br>*Punica granatum* (Pomegranate)<br>*Citrus reticulata Blanco* (Kinnow) | Mostly covered the region of Rajasthan |
| Island region | *Mangifera indica* (Mango)<br>*Carica papaya* (Papaya)<br>*Manilkara zapota* (Sapota) | Distributed throughout the regions of Lakshadweep (union territory) and Andaman and Nicobar Islands (A&N) |

Compiled from: Singh and Jhariya (2016)

## 7.4 Agroforestry Systems in the Tropics of Developed and Developing Countries

The area of AFs is not confined and limited but it spreads up to 1023 m ha globally (Nair et al. 2009a, b) of which India covered 25.32 m ha (Dhyani et al. 2013) whereas 8.0 million ha area was covered by homestead garden in Southeastern Asia (Kumar 2006) and in the U.S.A. around 235.2 million ha area was covered by silvopastoral system, hedgerow cropping, windbreaks and other riparian buffers (Nair and Nair 2003). Similarly, as per CAFRI (Janshi) and Bhuvan LISS III, around 13.75 million ha area covered under AFs in India (Rizvi et al. 2014).

Agroforestry is practicing in the tropic from a time immemorial and committed for multifarious benefits through delivering a better ecosystem services which is possible by adoption of wide array of scientific practices and management to understand better tree-crop-animal's interactions along with promising soil and climate security. In turn an improved soil quality and better environment can enhance the agroforestry performance in the tropics. In this context, a model is developed for understanding the synergy exists between environment and soil for agroforestry performance in the tropics which is depicted in Fig. 7.2 (Sun et al. 2017). It is quite interesting to know that, AFs is very flexible, location specific and can adopt easily in the varying regions of the tropics (tropical, temperate and humid regions); although it can be modifies by varying biophysical, topography, socioeconomics and climatic situations but wherever adopted it work more efficiently. Of the tropics, tropical region comparatively more promising in term of suitability, adoptability and diversity of agroforestry models than humid and temperate regions. However, many models have been developed and distributed constantly in both developing (Asian and African continent) and developed countries (European continent) of the world due to its decade of development (King 1987). Similarly, feasibility and interactions among tree-crop-animals, natural resource availability, land features, soil (edaphic) characteristics and climatic situations decide the type of agroforestry models *viz.*, agrisilvicultural, silvipasture and agrisilvopastoral, etc. varied from arid to humid tropics which is depicted in Table 7.2.

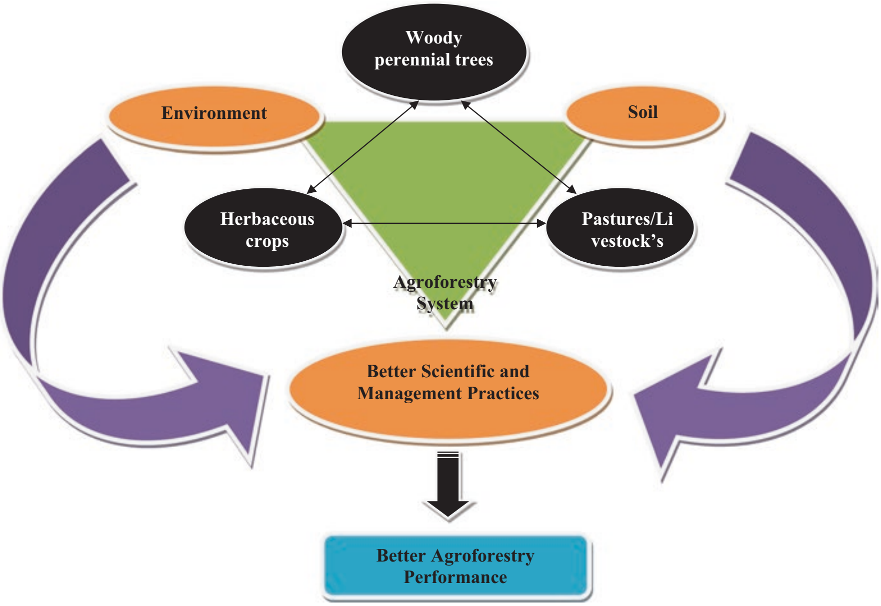

**Fig. 7.2** Synergy between environment and soil for agroforestry performance in the tropics. (Compiled from: Sun et al. 2017)

**Table 7.2** Agroforestry models in different tropics of the world

| | Humid tropic | Arid tropic | Highland tropic |
|---|---|---|---|
| Areas | It is distributed in the regions of South-east Asia, African continent and Central America. | Mostly covered the area of Indian subcontinent, some parts of savanna and Sahara region of Africa and S. America. | Mostly covered Indian Himalayan region, South-eastern Asia, and some parts of Central Africa. |
| Climatic situations | Climate is typically humid with less hot condition and higher rainfall (>1000 mm). Soil order is generally Oxisols and Ultisols types. | Climate is typically hot arid with less rainfall (<1000 mm) and Soil order is generally Entisols, Vertisols and Alfisols. | This region is characterized by humid and cold climate and Soil order is generally Andosols, Oxisols, and Ultisols types. |
| Prefer models | This tropic having variety of models such as homestead gardens, alley cropping systems, plantation crop-based combinations and multitier tree gardens systems. | This tropic having variety of models such as silvopastoral based AFs, wind-break system, shelterbelts and model comprising various MPTs on agricultural farms. | This tropic highly recommended for silvopastoral based AFs, plantation crop-based combinations and model practices for soil-water management and conservations etc. |

## 7.5 Carbon Sequestration Potential in Different Agroforestry Models

Sequestering atmospheric C and its fixation into both vegetation and soil helps in mitigating the global issue of climate change besides adding biomass into the woody vegetation. However, C sinks potential of AFs depend on nature and types of woody perennial tree species and associated herbaceous crops that represents tree-crop interactions and their management practices. Likewise, C allocation pattern in different components of tree species are also varies for example, the value of C content in tree branches was similar to stem but higher than root part which is followed by foliage and stem bark whereas the same C value was similar in *Acacia nilotica*, *Eucalyptus tereticornis*, *Butea monosperma* and *Azadirachta indica* followed by *Dalbergia sissoo* = *Albizia procera*, and *Anogeissus pendula* = *Emblica officinalis* respectively (Prasad et al. 2010). Similarly, Murthy et al. (2013) have estimated around 12–228 and 68–81 Mg C/ha of agrisilvicultural system practicing in humid tropical lands and dry lowlands of S-E Asia. Also, C sinks capacity of AFs in different world are depicted in Table 7.3. In general, agroforestry potentially sequesters more C and gain higher biomass as compared to other sole based cropping (monocropping) and tree plantation systems. Moreover, C sequestration potential in tropical agroforestry systems (TAS) are varies from 12 to 228 Mg/ha and as per this estimates the projected C sequestration value is 1.1–2.2 Pg in terrestrial ecosystems by next coming 50 years through the practices of AFs in the coverage area of 585–1215 × $10^6$ ha of the total earth surface (Albrecht and Kandji 2003). Similarly, integration of some nitrogen (N) fixing leguminous trees-crops-grass are also a better option for C storage and sequestration along with enhancing the N availability, fertility, and health status of both vegetation and soils in the legume-based AFs (Verchot et al. 2011; Montagnini and Nair 2012). Legume based agroforestry models helps in minimizing $N_2O$ and $CO_2$ emissions into the atmosphere and makes them balance in environment for better ecosystem and ecological sustainability. This will help in mitigating climate change issues and maintains the health of overall agroecosystems (Jhariya et al. 2018). Similarly, the silvopastoral system has potential to enhance greater biomass rather than sole based system. For example, the value of overall biomass was higher by 35.0% in silvopastoral system (*Azadirachta indica* + *Cenchrus ciliaris*) rather than neem sole based system. This would help in better understanding of silvopastoral potential role in biomass enhancement along with several other ecosystem services for better ecosystem (Mangalassery et al. 2014).

In nutshell, AFs represents itself as a C farming system due to its huge potential in capture and storage of C in both vegetation (tree-crop) and soils which requires a good management practices to improve C sink capacity that helps in producing higher biomass and maintain C balance in ecosystem for better environment and ecological sustainability (Jhariya et al. 2019a).

**Table 7.3** Carbon sinks capacity of agroforestry systems in different world

| Different AFs in the tropics | Soil carbon sink capacity | References |
|---|---|---|
| Agri-silviculture based agroforestry model comprising *Gmelina* tree in Chhattisgarh state of India | 30.20 US ton ha$^{-1}$ | Swamy and Puri (2005) |
| Homestead/Kitchen garden system in Panama City of central and South America | 49.6–2.5 US ton ha$^{-1}$ | Kirby and Potvin (2007) |
| Homestead/Kitchen garden system in African continent | 220.5 US ton ha$^{-1}$ | Nair (2012) |
| Silvopastoral based AFs in African continent | 1.65–3.85 US ton ha$^{-1}$ | |
| Alley-cropping system comprising tree as *Populus deltoides* and crops as soybean, wheat and maize in Canada | 1.38 US ton ha$^{-1}$ | Oelbermann et al. (2006) |
| Silvopastoral based AFs comprising tree as *Pinus elliottii* and grass (*Paspalum notatum*) in USA | 7.60–26.7 US ton ha$^{-1}$ | Haile et al. (2008) |
| Mixed tree stands system in Puerto Rico | | |
| *Casuarina* and *Eucalyptus* based mixed tree stands in Puerto Rico, U.S.A. | 68.23 US ton ha$^{-1}$ | Parrotta (1999) |
| *Casuarina* and *Leucaena* based mixed tree stand in Puerto Rico, U.S.A. | 62.39 US ton ha$^{-1}$ | |
| *Leucaena* and *Eucalyptus* based mixed tree stands in Puerto Rico, U.S.A. | 68.01 US ton ha$^{-1}$ | |
| Silvopastoral based AFs comprising tree *Quercus suber* (commonly known as cork oak) in Spain | 29.21–55.3 US ton ha$^{-1}$ | Howlett (2009) |
| Silvopastoral based AFs comprising tree *Betula pendula* in Spain | 146.6–165.3 US ton ha$^{-1}$ | Howlett et al. (2011a, b) |
| Silvopastoral based AFs comprising tree species like *Eucalyptus* along with a grass *Brachiaria* species in the region of Brazil | 389.1 US ton ha$^{-1}$ | Tonucci et al. (2011) |
| Silvopastoral based AFs in USA | 564.4 US ton ha$^{-1}$ | Haile et al. (2010) |
| Alley-cropping system comprising tree species as *Populus deltoids* commonly known as poplar in Canada | 62.83 US ton ha$^{-1}$ | Bambrick et al. (2010) |
| Agri-silviculture based model comprising *Poplar* in Punjab, India | 10.4 US ton ha$^{-1}$ yr$^{-1}$ | Chauhan et al. (2010) |
| Agri-silviculture based model comprising *Subabul* in Andhra Pradesh, India | 3.05 US ton ha$^{-1}$ yr$^{-1}$ | Rao et al. (1991) |
| Silvopastoral based AFs comprising tree species *Acacia nilotica* (babul) in Haryana region of India. | 3.09 US ton ha$^{-1}$ yr$^{-1}$ | Kaur et al. (2002) |
| Kerala based homestead garden in India | 1.76 US ton ha$^{-1}$ yr$^{-1}$ | Saha et al. (2009) |
| Agri-silviculture based model comprising tree species *Casuarina equisetifolia* in the region of Tamil Nadu, India | 1.73 US ton ha$^{-1}$ yr$^{-1}$ | Viswanath et al. (2004) |

(continued)

**Table 7.3** (continued)

| Different AFs in the tropics | Soil carbon sink capacity | References |
|---|---|---|
| Silvopastoral based AFs comprised *Brachiaria brizantha* (commonly known as bread grass) as fodder species intercropped with species such as *Guazuma ulmifolia* (bay cedar) and *Cordia alliodora* (salmwood) in the region of Costa Rica | 145.5 US ton $ha^{-1}$ | Amezquita et al. (2005) |
| Silvopastoral based AFs comprised tree species *Acacia mangium* (commonly known as black wattle) intercropped with fodder species of *Arachis pintoi* in the region of Costa Rica | 190.7 US ton $ha^{-1}$ | |
| Agri-silviculture based model comprised poplar tree and *Hordeum vulgare* (barley)as agriculture crop in Canada | 86.5 US ton $ha^{-1}$ | Peichl et al. (2006) |
| Agri-silviculture based model comprised *Pseudotsuga menziesii* (commonly known as Douglas fir) tree species intercropped with *Trifolium subterraneum* (native to Northwestern Europe) in the region of USA | 105.8 US ton $ha^{-1}$ | Sharrow and Ismail (2004) |
| Alley-cropping system comprising tree as Subabul (*Leucaena leucocephala*) in western region of Nigeria in the African continent | 14.9 US ton $ha^{-1}$ | Lal (2005) |
| *Pterocarpus* and *Gliricidia* based protein bank/ fodder bank system in the region Mali | 36.81 US ton $ha^{-1}$ | Takimoto et al. (2008) |
| Agri-silviculture based model comprised N fixing *Gliricidia* trees intercropped with *Zea mays* (maize crop) in the region of Malawi | 135.6 US ton $ha^{-1}$ | Makumba et al. (2007) |

## 7.6 Soil Carbon Sequestration in Agroforestry Systems: A Global Scenario

Soil, as we call "*soul of infinite life*". Yes, it is true and can't be denied due to sustaining whole life by supporting biodiversity (tree, crop, animals and other natural resources), anchoring tree roots, harboring various soil inhabiting flora and fauna including beneficial micro-organisms, stores essential nutrients, maintain rhizosphere populations, and deliver multifarious ecosystem services to maintain ecosystem structure. However, better management practices in AFs and soils could be helpful in enhancing C value through effective sequestration process (Raj et al. 2020a, b). Addition and decomposition of litter fall, twigs, barks and other tree's fallen residues/materials can enhance the C content value that directly and indirectly increase the population of earthworm and soil inhabiting beneficial microorganisms and their interactions will improve the fertility and health status of soils (Bertin et al. 2003). Moreover, tree species, their types, nature, tree-crop interactions, shedding leaf litters, its texture and decaying rate along with agents that involve in decompositions will surely affects the extent of C accumulation, sink capacity and C release into the soils. Similarly, management practices in AFs also add some inputs in C addition which reflects health status of soils (Jhariya et al. 2019b). However, tropical soils contributed higher biomass, more C contents and diverse form of microorganism as compared to temperate soils. Thus, soil C-sequestration value in different AFs in the world is depicted in Table 7.4.

Moreover, integrating tree with some pasture/grass species (known as silvopastoral system) are gaining wide recognition for reclamations of degraded land and having great potential of C sink either into vegetation and soils that help in biomass increment and improvement of soil fertility. Silvopastoral system can store more organic C into the soils through greater potential of C sequestration. In addition, integrating leguminous N fixing multipurpose tree (MPTs) with some valuable pastures could be a great option to minimize GHGs emission and climate change mitigation along with diversifying products (as timber, fuelwood, fodder for livestock's, etc.), intensifying ecosystem services and maintain N and C status into the soils for better ecosystem. Therefore, this system can be going in the direction of improving higher biomass, soil organic C and N availability. Legume trees such as Acacia species and subabul (*Leucaena leucocephala*) have great capacity to capture and fix C into soils that can be stored in the form of soil organic carbon (SOC) as a pool which

**Table 7.4** Soil carbon-sequestration value in different agroforestry systems in the world

| Agroforestry practices including species | Areas | Depth of soil (cm) | Soil carbon value (Mg/hectare) | Author |
|---|---|---|---|---|
| Different forms of mixed stands system comprising *Casuarina* and *Eucalyptus* species, *Leucaena* and *Casuarina* species, and *Leucaena* and *Eucalyptus* tree species of 4 years aged | Distributed in Puerto Rico | 0–40 | Soil C value of these three combinations were 62, 57, and 62 respectively. | Parrotta (1999) |
| AFs comprised agrisilviculture model having tree (*Gmelina arborea*) and different eight agricultural crops of total 5 years aged | Covered most part of Chhattisgarh state in Central India | 0–60 | Soil C value was 27.4 | Swamy and Puri (2005) |
| Homestead gardens | Practiced in the region of Ipet_-Embera, Panama | 0–40 | Soil C value varied in between 2.3 and 45 | Kirby and Potvin (2007) |
| Silvipasture models having *Pinus elliottii* (slash pine) and *Paspalum notatum* (bahia grass) of total 8–40 years old aged | Practiced in the region of Florida (USA) | 0–125 | Soil C value varied in between 7 and 24.2 | Haile et al. (2008) |
| Hedgerow intercropping system having varying combination of hybrid poplar (*Populus deltoids*) + wheat crop, soybeans (*Glycine max.*) and maize (*Zea mays*) of total 13 years old | Practiced in the most part of South Canada | 0–40 | Soil C value was 1.25 | Oelbermann et al. (2006) |

improve the fertility and health status of tropical soil (Cadisch et al. 1998). Moreover, combination of *Leucaena leucocephala* and *Dalbergia sissoo* could potentially sequester more C as compared to sole based plantation system that can help in combating global warming and climate change issues (Sheikh et al. 2015). Similarly, integrating legume trees with eucalyptus tree-based plantation were worked more effectively in term of storage and sequester of C into the soils (Kaye et al. 2000). However, many studies were conducted for better understanding of the potential role of silvopastoral system (rather than monocropping/sole based cropping system) in SOC enhancement through better C sequestration as compared and its role in climate change mitigation. For example, the value of SOC was increased from 36.30% to 60% in silvopastoral system (*Azadirachta indica* + *Cenchrus ciliaris*) rather than sole cropping system (Mangalassery et al. 2014). Moreover, C sinks value in soil of different silvopastoral systems are depicted in Table 7.5. As per one estimate, well managed silvopastoral model has potential to sequester approximate 0.012 TgC/ha and predicted value is 0.6 TgC/ha up to the year 2040 by converting 630 m ha degraded croplands/grassland system into AFs (Kirby and Potvin 2007; Ghosh and Mahanta 2014).

**Table 7.5** Silvopastoral systems and its carbon sink value in different parts of the world

| Silvopastoral models in the regions | Carbon sink value | References |
|---|---|---|
| This model comprises jaragua grass (*Hyparrhenia rufa*) as a grass species prevalent in the region of Nicaragua, Central America | C sink value was 150 Mg C/ha in the soil at 0.6 m depth. | Ruiz et al. (2004) |
| Practiced in the same region of Nicaragua, Central America where three grass species such as Guinea grass (*Panicum maximum*), palisade grass (*Brachiaria brizantha*) and dhoob grass (*Cynodondactylon*) were used. | C sink capacity was 158 Mg C/ha in the soil ecosystem at certain depth. | |
| Woody perennial trees were integrated with jaragua grass and palisade grass in the region of Costa Rica | C sink value was varied from 3.5 in sole *Hyparrhenia rufa* grass species to 12.5 Mg C/ha in palisade grass + *Diphysarobinioides* tree species. | Andrade et al. (2008) |
| Incorporation of valuable fodder grass with eucalyptus tree species and other sole based eucalyptus plantation in the region of Brazilian Cerrado | C sink value in soil varied from 461 Mg/ha in pasture to 393 Mg/ha in the sole based eucalyptus plantation. | Tonucci et al. (2011) |
| *Quercus suber* (Dehesa cork oak tree) based silvopastoral system practiced in the region of Spain | It was observed C value was increased by 50.2, 37.0 and 26.5 Mg/ha as per increasing the distances of 2.0, 5.0 and 15.0 m from the tree *Quercus suber* at the depth of 1 m. | Howlett et al. (2011a, b) |
| Integration of N fixing *Inga feuilleei* (Inga tree species) with *Setaria sphacelata* (pasture grass) based silvopastoral system practiced in the region of Ecuadorean Andes | C sink value was increased by 8.0% and 11.4% under the *Setaria sphacelate* and *Inga feuilleei*, whereas 20 Mg C/ha was reported under Inga tree species. | Rhoades et al. (1998) |

(continued)

**Table 7.5** (continued)

| Silvopastoral models in the regions | Carbon sink value | References |
|---|---|---|
| This system consisted both natural grassland and other silvopastoral models having leguminous N fixing trees such as subabul (*Leucaena leucocephala*), *Albizia* species (*Albizia amara*) and sickle bush (*Dichrostachys cinerea*) along with grasses such as *Stylosanthes hamata* (Caribbean stylo), *Chrysopogan fulvus* (Beardgrass) and *Salvia scabra* (coast blue sage), etc. | The C sink value was 6.72 ton C/ha/yr in silvopastoral which is two times more than 3.14 ton C/ha/yr in natural grassland system. This data represents that silvopastoral system has higher potential of C sequestration rather than other sole and natural grassland system. | NRCAF (2007) |
| Amla (*Emblica officinalis*), Eucalyptus species, *Albizia* species and Sissoo (*Dalbergia sissoo*) based silvopastoral systems practiced in natural grassland semi-arid regions of Uttar Pradesh, India. | The C storage value was 1.9–3.4 ton C/ha in silvopastoral system as compared to 3.9 ton C/ha in sole pasture/grasses system. | Rai et al. (2009) |
| Silvopastoral systems comprised $N_2$ fixing leguminous tree such as subabul (*Leucaenea leucocephala*) with buffel grass (*Cenchrus ciliaris*) and Caribbean stylo (*Stylosanthes hamata*). | The value of OC content was increased by 1.70–2.30 times in the soil. | |
| Practiced silvopastoral systems in wasteland/degraded areas | The value of soil C was observed in between 24.3 and 35.0 Pg (pictogram) | Narain (2008) |
| The system comprised both tree species (*Acacatortilis*) *and grass* (*Cenchrus setegerus*) *in the Regional Research Station (RRS) of* Kukma (Gujarat), India. | The C sink value in underground was 23.4% (1.6 ton/ha) of total pool value of C stock of the systems. | Kumar (2010) |

## 7.7 Horticulture Based Farming Systems (HFS) in the Tropics

If we look on the statistical figure on horticultural productions and land use systems then we see around 300 m MT of productions was reported through horticulture which is quite higher than 275 m MT of agricultural grains productions. This higher production promotes per capita consumption of variety of vegetables and fruits over the period. Of this figures, perennial horticultural crops produced around 214 MT/yr from 12.1 Mha areas of which fruits, plantation crops, spices and nuts contributed 6.1, 3.2, 2.6 and 0.14 Mha areas, respectively. These figures pull the attentions of growers towards perennial horticultural crops and related land use systems due to higher production systems, maximum area coverage, low inputs of energy and water than other annual field crops in agriculture and AFs (Ganeshamurthy et al. 2020). Although, HBFs/fruit based AFs comprises various models such as agri-horticulture system (agricultural crops and fruit trees/vegetables/spices/flower crops), horti-pastoral system (Integration of different fruit trees/vegetables/spices/flower crops with livestock's/pasture), agri-horti-silviculture system (integrating three components of agricultural crops, different fruit trees and trees other than fruits), multitier horticulture system, different horticultural land use systems and homestead gardening practices that are mostly widespread in humid, arid and semiarid tropics of the world.

HBFs are playing an important role in providing various nutritious and quality fruits and vegetables and having potential to cover minimum dietary needs of both vegetables and fruits /day/capita which is 220 and 85 gram per head per day rather than available 80 and 60 gram, respectively (Roy 2011). Some fruit trees like guava (*Psidium guajava*), Indian gooseberry or amla (*Emblica officinalis*), plum (*Prunus domestica*), mango (*Mangifera indica*), apple (*Malus domestica*), papaya (*Carica papaya*) and *Citrus species*, etc. are very commonly used in different agroclimatic zones of India. As per Singh and Malhotra (2011), in rainfed regions horticulture crops add additional income along with maintaining food, nutrition and climate security.

### *7.7.1 Agrihorticulture (Crops + Fruit Trees)*

This system comprised a simultaneous integration of agricultural crops (both annual and perennials characteristics) and fruit trees/vegetables/flower/spices, etc. in unit land and widespread in the marginal and dry areas of different agroclimatic zones mostly dominant in India, Sri Lanka, Nepal and Bangladesh (Pant et al. 2014). In this context, the recommended combination of agriculture crops with horticulture trees under agri-horticulture model in HBFs prevailed in dry region of Rajasthan is depicted in Fig. 7.3 (Bhandari et al. 2014). Also, Table 7.6 showing varying

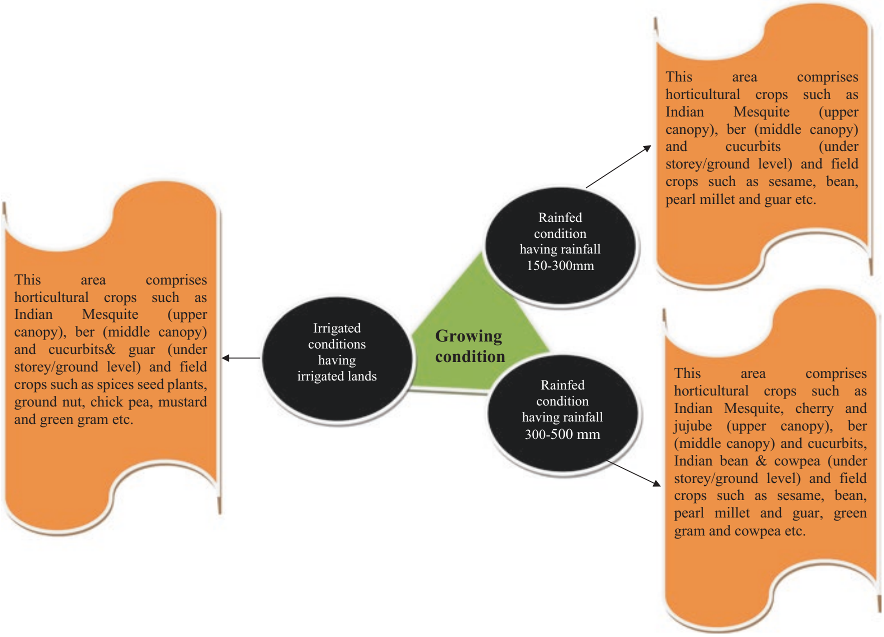

**Fig. 7.3** Agri-horticulture model in Horticulture based farming system in dry region of India (Bhandari et al. 2014)

**Table 7.6** Varying tree-crop combinations of agri-horticulture system practiced in agro-climatic zones of India (NRCAF 2007)

| Agro-climatic zone | Tree-crop-grass component |
|---|---|
| 1.Western Himalayan region | Integration of apple tree (*Malus pumila*) with the field crops such as millets and wheat |
| | Integration of peach tree (*Prunus persica*) with the field crops such as millets and soybean; soybean, millets |
| Eastern Himalayan region | Integration of alder tree (*Alnus nepalensis*) with the field crops such as coffee and cardamom. |
| Lower Gangetic plains | Mostly irrigated type of agrihorticulture system. Integration of mango (*Mangifera indica*), banana (*Musa paradisica*) and litchi (*Litchi chinensis*) with the agricultural crops such as maize, paddy and wheat. |
| Middle Gangetic plains | Mostly irrigated type of agrihorticulture system. Combination of mango and *Citrus spp.* with the agricultural crops such as wheat and rice. |
| Trans Gangetic plains | Mostly irrigated type of agrihorticulture system. Ecologically & economically sound combination in which Aonla (*Emblica officinalis*) is combined with green & black gram. |
| Central-plateau and hills | Mostly irrigated type of agrihorticulture system. This zone comprised a good combination of fruit tree *Psidium guajava* + field crops such as ground nut and Bengal gram. |
| | Rainfed Agrihorticulture system is practiced in this zone. Ecologically& economically sound combination in which Aonla is combined with green & black gram. |
| Western plateau and hills | Mostly irrigated type of Agrihorticulture system. Ecologically sound practices comprised tree components such as Teak (*Tectona grandis*) and Sapota (*Achrus sapota*) + crops such as maize and paddy. |
| | Combination of Indian nut palm (*Areca catechu*) + *cardamom* (*Elettaria cardamomum*) and black pepper (*Piper nigrum*) are prevalent in this agroclimatic zones. |
| Southern plateau and hills | A good fruit tree and crop combination comprised both Imli (*Tamarindus indica*) and chilli (*Capsicum annuum*) |
| West coast plains and hills | Rainfed Agrihorticulture system is practiced in this zone. This zone comprised fruit tree such as Jack fruits (*Artocarpus heterophyllus*) and black pepper (*Piper nigrum*). |
| | Coconut (*Cocus nucifera*) and *paddy* combination are prevalent and suited in this region as per climatic condition. |
| Island region | Coconut and *paddy* are also reported in this agroclimatic zone. |

tree-crop combinations of agri-horticulture system is practiced in different agro-climatic zones of India (NRCAF 2007). However, this system consists short duration of juvenile fruit and vegetable plants which is sometimes combined with other MPTs, therefore it produces other products like good quality timber, fodder, fuelwood, NTFPs in addition to food grains and horticultural produce. That's why, farmers mostly prefer agri-horticultural system rather than agri-silvicultural system due to less juvenile phase, high nutritive and quality fruits, vegetables and spices, and having good economic returns in short durations in agri-horticultural system (Kareemulla et al. 2002).

### 7.7.2 Hortipastoral (Fruit Trees + Pasture/Animals)

This system is highly recommended on degraded and wasteland areas due to its great reclaiming potential along with supplying nutritive and quality fruits, vegetables, highly palatable leguminous fodder/pastures (to livestock's) that maintains health status of farmers and animals (Kumar et al. 2011). However, various form of horti-pastoral models are existing namely Aonla (*Emblica officinalis*) based horti-pastoral system for conservation purpose of soil and water, Bael (*Aegla marmelos*) based hortipastoral system, Tamarind (*Tamarindus indica*) based hortipastoral system, etc. spreads in the rainfed regions, custard apple (*Annona sp.*) based hortipastoral system, Kinnow (*Citrus nobilis* × *C. deliciosa*) based hortipastoral system distributed in the partial irrigation system, etc. that enhance the biodiversity, improve ecosystem services and maintains income and health status of poor farmers and local communities in the tropics (Kumar et al. 2009).

### 7.7.3 Agrihortisilviculture (Crops + Fruit Trees + Tree Other Than Fruits)

The model itself represents an integration of three components such as agricultural crops, different fruit trees/vegetable crops and trees other than fruits respectively. This system nurtures all the biodiversity and maintains health, wealth, and food and climate security in every aspect. "*Is this system being more diversifies, secure and sustainable than others in HBFs*?" The answer is "yes" because having more components represents more diversity which intensified ecosystem services along with other multifarious tangible (timber, fuelwood, fodder, NTFPs, etc.) and intangible benefits in term of money, health, microclimate amelioration, soil health and quality through fertility improvement and climate change mitigation through C sequestration, etc. The peculiar significance of this system having higher possibility of income generation through mature fruit trees rather than monsoon dependable agricultural crops.

## 7.8 Carbon Footprint of Agriculture Versus Fruits and Vegetables Crops

The horticultural land use systems comprise various fruits and vegetable crops are having less contribution in GHGs emissions; for example, low GHGs emissions were observed in potato and other root vegetable crops due to high productivity potentials. However, Joshi et al. (2009) have predicted the annual demands for different vegetables and its contribution in global warming potential (GWP) are 127.01 Mt and 21.7 Mt $CO_2$ eq. whereas fruit crop like apple (*Malus domestica*) has 86.0

Mt of annual demands and 30.7 Mt $CO_2$ eq. of global warming potential (GWP) by the year 2020–2021. The estimated figure indicates an apple has less demands but higher contribution in GWP as compared to vegetable crops. However, agricultural food crops have more in demands and GWP value as compared to fruits and vegetables. For example, the demands (Mt) and GWP (Mt $CO_2$ eq.) values of wheat, rice and pulses are 83.0 and 29.1, 173.0 and 246.3, 16.0 and 15.5, respectively by the year 2020–2021. These figures are enough to say about comparative studies on demand and GWP of horticulture (fruits and vegetables) versus agricultural food crops.

Similarly, many authors have quantified GHGs emissions and related GWP (global warming potential) contribution by various agricultural and horticultural crop production through a series of field experiments at IARI, New Delhi and according to them, the vegetables crops such as potato, cauliflower and brinjal contributed in $CO_2$ emissions (g/kg) are in the order of cauliflower (13.3) > brinjal (12.5) > potato (10.0) whereas overall maximum potential in global warming ($CO_2$ eq.) are observed in brinjal (31.1) followed by cauliflower (28.2) and least value in potato (24.9), respectively. Similarly, the value of $N_2O$ was similar as 0.1 g/kg whereas $CH_4$ was zero among these horticultural crops. The horticultural fruit crops such as banana, apple and other spices contributed in $CO_2$ emissions (g/kg) are in the order of spices (100) > apple (41.7) > banana (10.0) whereas overall maximum potential in global warming ($CO_2$ eq.) are observed in similar fashion i.e. spices (845.0) > apple (331.4) > banana (71.6) respectively. Similarly, the value of $N_2O$ was highest in spices (2.5) followed by apple (1.0) and least value (0.2) observed in banana whereas $CH_4$ was zero among these horticultural crops (Majumdar et al. 2002; Bhatia et al. 2004; Chhabra et al. 2009; Pathak et al. 2009).

## 7.9 Carbon Sequestration Potential in Horticulture Based Farming Systems/Fruit Based Agroforestry Systems

It is well known fact about the potential of horticultural based land use systems in C sequestration than the other farming technology i.e. agriculture and AFs in the tropics. However, perennial crops contributed major role in $CO_2$ sequestration than annual crops. In this context, a study has been conducted on varying horticulture-based farming systems and it was observed that C sequestration potential was maximum in mango-based land used systems followed by cashew (*Anacardium occidentale*), rose (*Rosa chinensis*), vegetables and medicinal and aromatic plants-based land used systems. In addition, higher inputs of plant residues into the soil of perennial systems resulted into less $CO_2$ emission than other annual crops in agriculture systems. Somehow, perennial horticultural based farming systems helps in gaining economic benefits through C credits. Therefore, applying an effective strategy of better C management and soil health improvement would be helpful in enhancing C sequestration technology in both perennial based horticulture systems and AFs (Ganeshamurthy et al. 2020). Similarly, many studies have been conducted on different horticulture-based models for C storage and sequestration. C sequestration capacity varies as per varying horticulture land use systems. For example, agri-horticulture model has been proven a better farming practice for mitigation of $CO_2$ and having higher economic gain with C credits as compared to other practices like agriculture, silvopastoral and varying land use practices of forest ecosystem in the Himalaya regions (Rajput et al. 2017). Horticultural orchards having greater capacity to enhance C storage value in subsoil region than other AFs due to deep rooting characteristics in perennial orchard system. An attempt has been made to justify the question "*Is species associations affect the C sequestration potential?*" Indeed, the potential of C storage and sequestration will vary as per varying combinations of plants, its types, nature and including management practices in climatic situations. In this context, the highest C sink value (140.1 t $ha^{-1}$) was observed in the combination of *Cocos nucifera* (coconut tree) and *Syzygium cumini* (Jamun) which is followed by139.0 C t $ha^{-1}$ in *Cocos nucifera* + *Mangifera indica* and least value has been observed in *Cocos nucifera* + *Garcinia indica* (Garcinia) as 132.2 C t $ha^{-1}$ whereas coconut sole plantation reported only 98.2 C t $ha^{-1}$, respectively (Bhavya et al. 2017).

As we know, horti-silviculture systems are ecologically sound and diversified horticulture-based farming systems which can withstand in less moisture condition in dry region of the tropics. C sink capacity and sequestration of horticulture-based farming systems in this region will helps in enhancing C stocks in both vegetations and soils in various farming models. However, C sink capacity in any systems depends on nature and type of plant species and its sink potential in any farming systems. Various studies have been conducted on this topic; for example, Singh and Singh (2015) reported C sink values in the form of biomass C, soil C which was compared with total C values in the various tree combinations of horti-silviculture systems vs. sole tree systems in the dry region of Rajasthan. According to the study (Singh and Singh 2015) the C sink value in soil ecosystem was higher as compared to biomass C. Also, C value was observed higher value in tree combinations in horti-silviculture systems than sole tree systems due to greater diversity and sink potential of horti-silviculture rather than single cropping systems. Nutrient losses through leaching would be less in tree combinations in horti-silviculture systems due to closed type of nutrient cycling. Therefore, different trees combinations including fruit trees in horti-silviculture systems are used for a comparative study on C sink potentials in both soils and vegetation as biomass C. In this context, comparative studies of soil C and total C sink in horti-silviculture vs. sole tree systems in dry regions of Rajasthan (India) are depicted in the Fig. 7.4.

From the Fig. 7.4, it clearly demonstrates that maximum total C value (soil + biomass) was 5.07 Mg/ha reported in the combination of *Cordia myxa* + *P. cineraria* based AFs due to greater potential of C sequestration. Therefore, the capturing and storing of atmospheric C depends on tree-crop combination, its type of interaction, nature of species, feasibility of combinations and related management practices that affect the potential of C sequester into both vegetation and soil components in horticulture-based farming systems. This can be justified by Yadav et al. (2015) which demonstrated that the combination of pear (*Pyrus communis*) and wheat

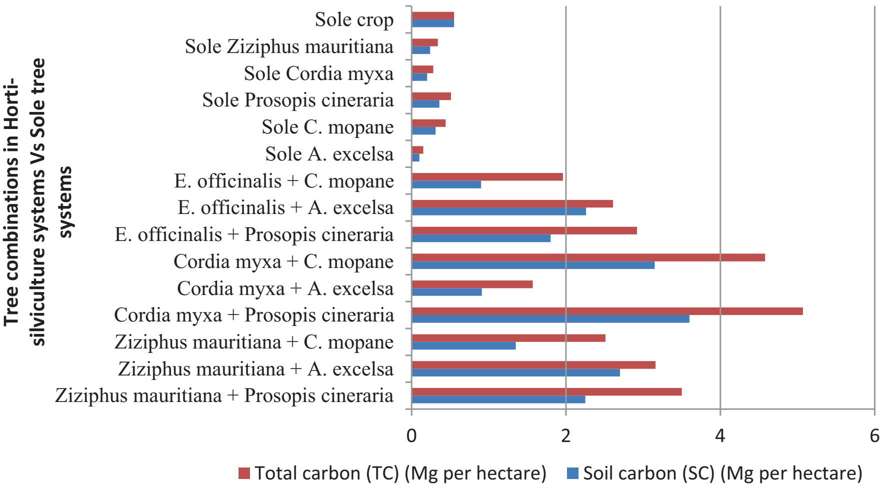

**Fig. 7.4** Comparative studies of soil carbon and total carbon sink in horti-silviculture vs. sole tree systems in dry regions of Rajasthan (India) (Singh and Singh 2015)

(*Triticum aestivum*) had maximum value of biomass (38.0 Mg/ha), C storage (17.0 Mg/ha) and C stock equivalent $CO_2$ (62.3 Mg/ha) respectively rather than sole wheat cropping system. This result represented that combination of fruit trees with the crops having more value of biomass and C than sole based cropping system. Secondly, type and nature of horticulture tree and crop combinations and their interactions deliver the potential of biomass and C sequestration. In the same study, it found that the combination of pear and wheat has maximum rate of biomass (12.0 Mg/ha/yr), C storage (5.3 Mg/ha/yr) and C stock equivalent $CO_2$ (19.6 Mg/ha/yr) which is followed by other less valuable interactive combinations of apricot (*Prunus armeniaca*) + wheat having 11.5, 5.2 and 19.0 Mg/ha/yr, respectively. Thus, fruit trees under HBFs showed a significant improvement in enhancing total biomass and C sink value which needed more study for better understanding the interactions and its positive impacts on our environment.

## 7.10 Soil Carbon Sequestration in Horticulture Based Farming Systems (HBFs)

Horticulture based land use systems has proven itself a good C farming system due to greater potential of tapping, sequestration and storing of atmospheric C into soil that helps in reclamation of degraded lands by improving productivity along with diversity enhancement which maintains ecological sustainability (Wang et al. 2010). Especially, perennial horticultural crops having higher potential in C sequestration than agriculture and AFs (majorly annual crops) in the tropics (Shrestha and Malla 2016; Janiola and Marin 2016; Chandran et al. 2016; Bhavya et al. 2017).

**Table 7.7** Soil carbon storage and carbon dioxide sequestration value (Mg/ha) under different horticulture land-use systems

| Soil depth (cm) | Carbon storage & carbon dioxide sequestration value in Mg/ha | Horticulture based different land-use system of 4 years aged | | | | |
|---|---|---|---|---|---|---|
| | | Mango based orchard | Cashew based orchard | Rose block plantation | Vegetable based block plantation | Medicinal and aromatic based block plantation |
| 0–15 | C storage | 1375.0 | 1244.1 | 1006.0 | 990.0 | 974.0 |
| | $CO_2$ sequestration | 5045.3 | 4566.0 | 3691.1 | 3633.3 | 3574.4 |
| 15–30 | C storage | 1361.2 | 1245.0 | 1004.0 | 973.3 | 954.2 |
| | $CO_2$ sequestration | 4996.0 | 4569.2 | 3683.3 | 3572.2 | 3502.0 |
| 30–50 | C storage | 1811.2 | 1679.5 | 1306.0 | 1308.4 | 1265.0 |
| | $CO_2$ sequestration | 6647.2 | 6164.0 | 4793.0 | 4802.0 | 4642.5 |
| 50–100 | C storage | 4478.2 | 4075.5 | 3215.2 | 3110.1 | 3082.3 |
| | $CO_2$ sequestration | 16435.0 | 14957.1 | 11801.0 | 11414.0 | 11312.0 |
| 1 m | $CO_2$ value | 9025.4 | 8244.1 | 6530.5 | 6382.0 | 6275.5 |

Compiled: Bhavya et al. (2017)

However, Bhavya et al. (2017) has emphasized the importance of perennial crops in horticulture land use systems and according to the study; emission of $CO_2$ was less due to higher input of residues into the soil in perennial systems rather than other annual crops. Also, the C sequestration potential of different horticulture land use systems (4 years old) were reported and found in the ranked of mango-based orchard > cashew-based orchard > rose (*Rosa chinensis*) block plantation > vegetable-based block plantation > medicinal and aromatic based block plantation, respectively. Therefore, both soil C stock and $CO_2$ sequestration value (Mg/ha) were calculated at different depths in varying cropping systems of horticulture land use practices which is depicted in Table 7.7. Thus, perennial horticulture-based farming systems showed greater potential in C sequestration and higher soil C stocks which would be helpful in enhancing soil fertility and health (Chandran et al. 2016).

## 7.11 Soil Organic Carbon (SOC) & Soil Fertility in Horticulture and Other Farming System

Indeed, a great synergy exists between SOC and fertility status of soils. SOC plays an important role in global C cycle, promotes efficient nutrient cycling and maintaining soil fertility along with ecological sustainability (Lenka et al. 2017). If we compared perennial horticultural system with other annual farming system then it is clearly demonstrated that perennial systems are more efficient in C sequestration and maximum SOC than other annual cropping system that helps in enhancing soil fertility, health and mitigate our changing climate. Similarly, the value of total soil organic carbon (TSOC) was highest (29.0 Mg C/ha) in *Psidium guajava* followed by *Syzygium cumini* (27.3 Mg C/ha), *Litchi chinensis* (26.0 Mg C/ha), and least value (19.2 Mg C/ha) in *Mangifera indica* whereas the value of OOC (oxidizable organic C) was recorded maximum (26.0 Mg C/ha) in *Psidium guajava* followed by both *Syzygium cumini* and *Litchi chinensis* having same value (25.1 Mg C/ha)and least (16.5 Mg C/ha)was observed in *Mangifera indica*, respectively on reclaimed sodic soils of perennial horticultural land use systems in the tropics (Datta et al. 2015).

The rate and dynamics of C sequestration and pool stocks varies as per varying land use practices such as AFs, HBFs, horti-silvi-pastoral system, forestry and another mangrove ecosystem. As per Das and Itnal (1994) the value of SOC increased from 4.2 g/kg to 7.1 and 7.3 g/kg while converting sole cropping to agroforestry and agri-horticulture land use systems of 6 years old. The maximum value of SOC was observed under forest land which was followed by other land use systems in the rank of natural grasslands > varying fruits orchards > Eucalyptus plantation respectively in 30 cm depth of soil ecosystem. Of all these practices, fruit orchards played remarkable role in SOC pools and observed in the rank of apple > mango > litchi > citrus species > guava with respective value of SOC was 105.2, 53.2, 45.5, 43.1, 39.0 ton/ha. Thus, apple orchard has greatest potential of climate change mitigation through highest contribution in SOC pool as compared to other perennial fruit orchards (Gupta and Sharma 2011). However, different horticultural land used systems such as orchards of jamun (*Syzygium cumini*), *Psidium guajava* (guava), *Litchi chinensis* (litchi) and mango (*Mangifera indica*) have different value of SOC and highest value (133 Mg C/ha) was observed in guava orchard along with maximum (76 Mg C/ha) C content in passive pool which increased with depth in all other land used systems (Datta et al. 2015). Similarly, SOC content was highest (9.5 g/kg) in *Vicia faba* cover crop management system as compared to 8.7 g/kg in conventional tillage practices under 5 years of Mediterranean vineyards of Sicily at Italy (Novara et al. 2019). Moreover, a dense forest ecosystem has more diverse species which intended to higher sequestration of C than other land use system having sole plantation system. That's why the value of SOC at 1 m soil depth was maximum (1.29%) in dense mixed forest followed by 1.22% in horticultural plantation system and least value in agricultural system (Koppad and Tikhile 2014).

## 7.12 Carbon Sequestration and Nutrient Sink/Input in AFs and HBFs

One question always strikes i.e. "*Why horticulture land use systems are preferable for more C sequestration than other farming systems such as agriculture and agroforestry?*" However, there is a various vast array of hypothesis behind it but it is clear that perennial horticulture system having more potential of C sequestration that enhance nutrient sink capacity rather than other farming practices. Although, perennial fruits systems contain high biomass C which is 25–100 times higher than agricultural land use system. Hence, perennial horticultural systems are preferable and adopted to degraded and some others vacant land than agricultural crops and AFs. Undoubtedly agroforestry and horticultural systems reduced GHGs emission into the atmosphere and mitigate climate change issue by sequestrating more atmospheric C. But horticulture-based plantation system has proven more C sequestration potential than agroforestry and other farming practices. In this context, many authors have worked out and justify this hypothesis by some practical and research works. For example, a comparative study was conducted on C sink potential in between agroforestry land use system and horticultural land system for offsetting GHGs emissions (Bloomfield and Pearson 2000). By 2050, the potential of C sequestration will be more (16.4 GtC) as compared to 6.3 GtC through AFs in the tropics (Brown et al. 1996) whereas these sequestration value will be 3.5 GtC in horticulture systems as compared to 1.15 GtC in AFs by upcoming 2050 (Trexler and Haugen 1994).

Absorption and fixation of atmospheric C by woody perennials trees and fruits plants in agroforestry and HBFs are proven a better solution for mitigation climate change by reducing the level of GHGs in the atmosphere. However, sequestration of C in soils & vegetation plays an important role in maintaining soil health & quality in AFs & HBFs. Improvement of soil physico-chemical properties is a good indicator for soil health in AFs and HBFs which is itself a complex type of farming systems in which nutrient leaching is less as compared to sole based cropping system due to closed type of nutrient cycling and nutrient pumping is possible through deep rooting system of trees & fruit crops that adds more availability of essential nutrient to plants. Apart from the soil improvement, these systems add more biomass and C input, increase nutrient input, add more organic matter into the soil, efficient nutrient cycling, improve the rhizosphere zone, increase microbial population, minimize soil & water erosion, evaporation and nutrient leaching losses gets checked and overall improvement of micro-climate is observed. In this context, a model (Fig. 7.5) is developed which represents C sequestration and soil health in AFS and HBFS (Sarvade et al. 2019; Shi et al. 2018; de Stefano and Jacobson 2018).

Thus, AFs and HBFs have proven itself as a good strategy for soil, environment and food security. Woody perennial trees in both AFs and HBFs make availability of leaves, twigs and other residues and its decomposition add organic matter into the soils that improve productivity, fertility and nutrients uptake capacity of soils which in turn enhance the C sequestration potential of the systems that improve overall soil ecosystems. In turn, healthy soils having optimum nutrients and water availability and provide anchorage to various models of AFs and HBFs in the tropics that produce healthy, nutritious and good quality food, fruits and maintain FNS in the era of hunger and malnutrition problems. In this context, a model (Fig. 7.6) is developed on soil for sustainability of AFs and HBFs in the tropics (Dollinger and Jose 2018; Colmenares et al. 2020). However, farmers get motivated, take a lesson and adopted the better scientific oriented farming systems which help in building their health, income & livelihoods (Dollinger and Jose 2018; Colmenares et al. 2020).

Das et al. (2020) has reported the maximum value (1.63%) of SOM in livestock's and horticultural based farming systems as compared to 1.6% in AFs. This is due to

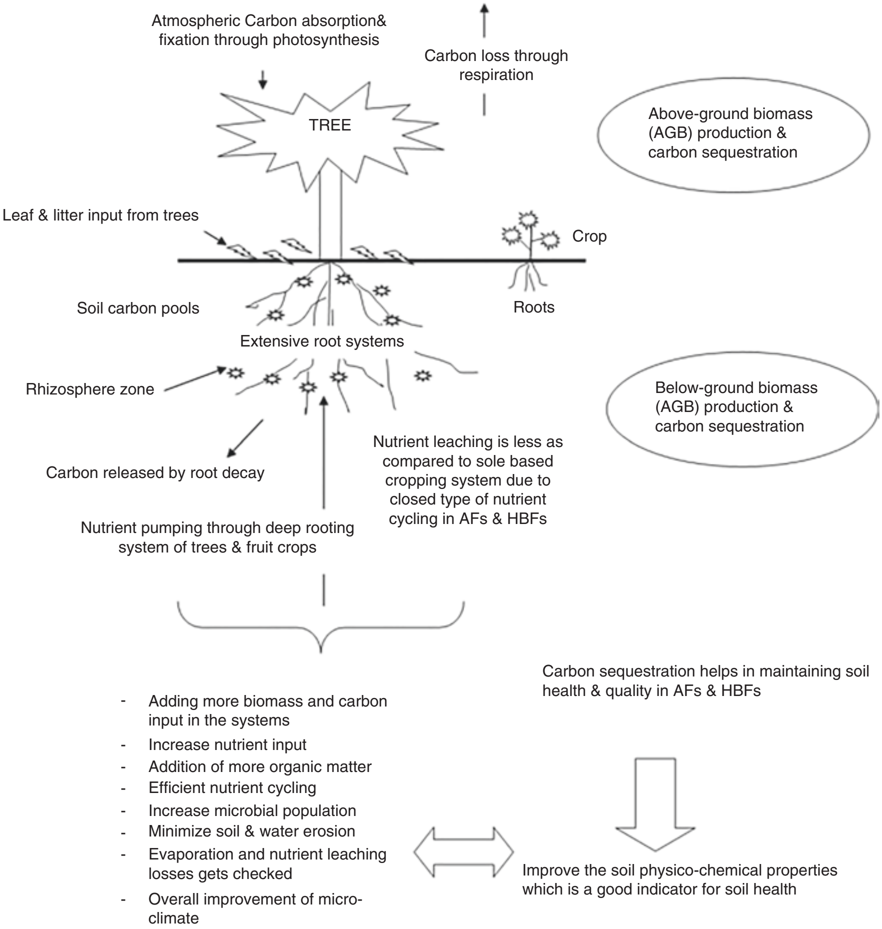

**Fig. 7.5** Carbon sequestration and soil health in AFS & HBFS (Sarvade et al. 2019; Shi et al. 2018; de Stefano and Jacobson 2018)

ameliorating potential of acidic soils by minimizing Al-toxicity was more in livestock's and HBFs as compared to AFs. Das et al. (2020) also investigated on nutrient input and according to the study agri-hort-silvi-pastoral systems contributed highest input of exchangeable potassium (K) whereas maximum value of phosphorus (P) was observed in both agriculture and livestock's-based farming systems due to availability of cow dung and its continuous dressing over time. Therefore, agriculture system contributed more in total fertility build-up followed by agri-horti-silvi-pastoral and livestock's-based farming systems.

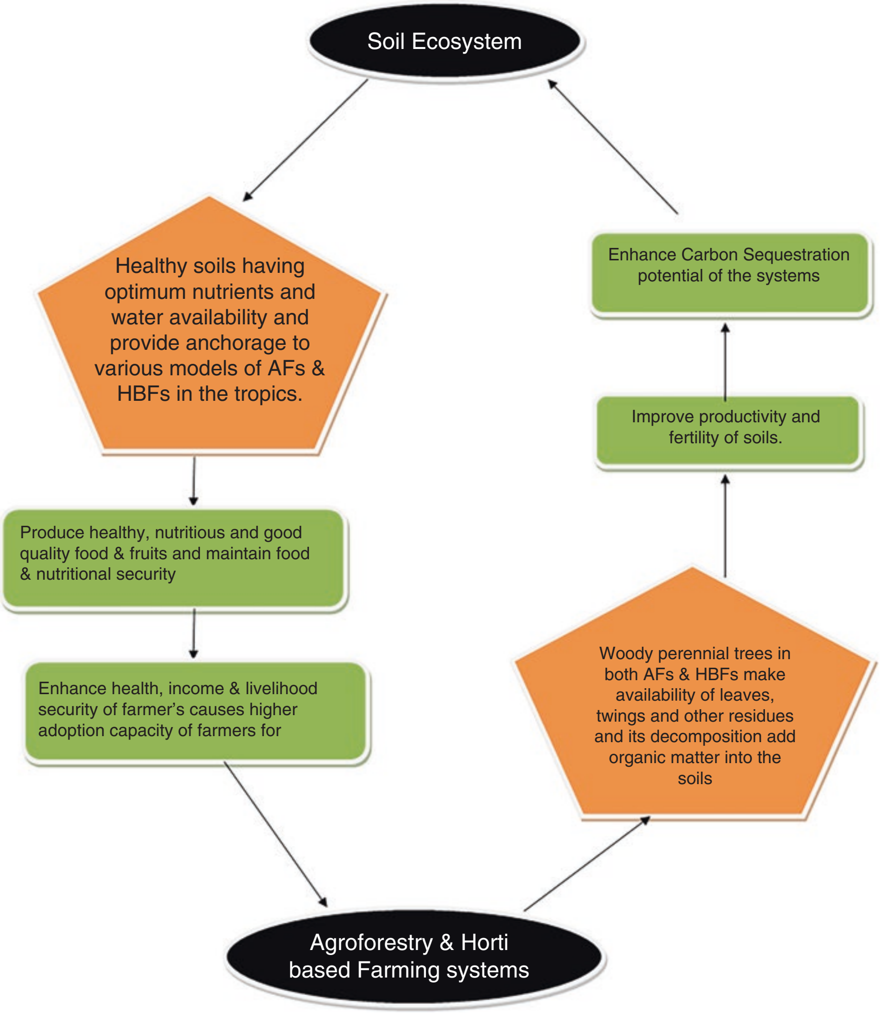

**Fig. 7.6** Soil for sustainability of agroforestry and horticulture-based farming systems in the tropics (Dollinger and Jose 2018; Colmenares et al. 2020)

## 7.13 Carbon Sequestration and Rhizosphere Biology in AFS and HBFS

Today, the soil ecosystem is gaining high attention and is characterized by vast scientific frontiers in the rhizosphere make a remarkable position and active portion due to stabilizing a link between plant root and soil interface that involves effective biogeochemical processes and maintains ecosystem stability (Hiltner 1904; Hartmann et al. 2008). The major questions are "*How the rhizosphere system involve* *in feeding the world and maintains environmental/ecological sustainability*?" and "*How plant root system involves in C transfer from atmosphere to rhizosphere*?" As we know, rhizosphere exists in between plant root and soil interface that harbor all living microorganisms which makes nutrient availability and transfer. However, plant types, age and varying biotic and abiotic stresses affects rate of loss of C i.e. C transfer which is 40% of total photosynthate is lost through extensive root systems into rhizosphere system that promotes the bacterial multiplication for better growth and development inside this zone. In turn, a healthy microorganism promotes healthier plants through better uptake, storage, nutrient cycling, pathogen suppression and better soil structure. Therefore, rhizosphere promotes microbial productions which intends for healthier and diversified farming systems by healthier soil that leads to high biomass production, quality food and fruit productions along with better C sequestration potentials of systems. That's why we call "*better rhizosphere biology involves in food and environmental security through better C sequestration*". Thus, there is a great synergy between rhizosphere biology and soil-food-climate security.

## 7.14 Carbon Sequestration in Relation to Climate Change and Food Security

Carbon storage and sequestration play key role in biomass production (Raj and Jhariya 2021a, b) in term of timber, fiber, NTFPs including nutritive fruits which ensure food and nutrition security under changing climate. Agroforestry system performs unique functions in climate change adaptation and mitigation through C sequestration potential. Food productions in agroforestry system are linked with C storage in term of vegetation and soil biomass (Nair et al. 2009a, b; Niles et al. 2002). However, a climate resilient agroforestry and horticulture-based farming system enhance grains and fruits biomass which ensure food security and its sustainable utilizations among peoples. As per Lal and Bruce (1999), approx. 0.75–1.0 Pg yr$^{-1}$ of C sequestration has been reported under global croplands ecosystem. Storing C in soil under agroforestry and horticulture-based system play key role in belowground biomass production which also maintain SOC pools. "Soils for food security and climate" are key initiatives of "4 per 1000" which was successfully launched in the year 2015. This initiative under The Paris Agreement has stressed on limiting global warming below 2 °C. This is targeted to enhance SOC sequestration with three objectives including climate change mitigation, adaptation and food security improvement for long term (Demenois et al. 2020). Similarly, integrating perennials crops (cacao and coffee) in agroforestry systems enhance C sinks than sole cropping system. Increasing perennial trees in farms under semi-arid regions promotes agroforestry systems and its C sequestration potential under changing climate (Brandt et al. 2018). Horticulture based mixed farming systems integrated various crops, fisheries and livestock enhance plant productivity along with climate change mitigation and adaptation (Newaj et al. 2016). This system also provides many nutritive food and fruits that ensure food security for healthy ecosystem. Similarly, this system is more diversified which buffer excessive temperature and enhance C sink and biomass production for healthy diets under changing climate (Bailey 2016; Waldron et al. 2017).

## 7.15 Agroforestry and Horticulture Role in Food and Nutritional Security Under Changing Climate

As per FAOSTAT (2018), 821, 151 and 613 million of people, including children, and women are undernourished, stunted and suffered from iron deficiency respectively. Whereas 2 billion people including adults are under obese and overweight. These are due to unhealthy, untimely and less nutritive food consumption. At the same time the current food production systems, especially intensive agriculture, contribute significantly to the environmental degradations. Beside the producing nutrient rich crops, the environmental footprint can be minimized by adopting agroforestry and horticulture-based farming system which ensures environmental health as well as global hunger problem under changing climate. In Kenya, women play important role in climate change mitigation by some innovative techniques of rainwater harvesting systems under varying agroforestry system which ensure food and water security by their collective efforts (Gabrielsson and Ramasar 2013). Thus, different agroforestry models and its adoptions provide various ecosystem services including food production and nutritional security through climate change mitigation (Sanz et al. 2017). Moreover, agroforestry systems improve biodiversity, food productivity, and ecosystem restoration under varying climatic situations (Paudela et al. 2017; Newaj et al. 2016). World Bank (2012) reported a global food production must be increased by 70% for upcoming 35 years due to higher demands of food production by 9 billion populations. However, it is still unclear to examine how climate change affects overall plant productivity and food security in agroforestry system. Global climate change decline agroforestry productivity and various ecosystem services particularly in developing countries. However, many developing countries are still facing food insecurity. In this context, adopting sustainable farming system including climate resilient agroforestry technologies and horticulture-based farming system would be helpful in soil-food-climate security for long term (Ospina 2016). However, forest-based farming system including afforestation activities also improves soil, food and environmental security along with other natural resource conservation (Raj et al. 2020a, b, 2022). Climate resilient agroforestry system ensures greater food diversification which provides healthier diet to people. Horticulture based farming system comprises different perennial fruits plants which is highly nutritive and regulate people health and economy. These integrated farming systems maintain soil-food and climate security along with ecosystem health and environmental sustainability.

## 7.16 Management Aspects for Improving Carbon Sequestration

As we know, unscientific and faulty land use practices disturb the global C cycle due to imbalance of emissions and sinks of C that affects the status of SOM and related ecosystem services (Jaiarree et al. 2014). A proper land use system always enhances the performance of varying farming systems in storage and sequestration of C along with multiple benefits through ecosystem services. Intensification in agriculture, perennial horticulture and AFs resulted higher synthetic inputs that leads to land degradation and minimizing C stocks in both vegetations and soils. In this context, applying ecological and sustainable intensification in these varying farming practices can intensify ecosystem services through enhancing biodiversity with higher production of food and fruits along with food-soil-climate security through better C sequestration potential (Jhariya et al. 2021a, b).

In nutshell, a better management practices in farming systems are needed for better rhizosphere biology, healthier microbial populations, better nutrient inputs and uptake by plants, soil health fertility improves that results greater potential of C sequestrations, maximize the availability of SOC which helps in maintaining healthier ecosystem performance (Fig. 7.7) (White III et al. 2017; Ahkami et al. 2017). Similarly, tree-crop interaction play major role in establishment and performance of multistoried perennial's horticulture based farming system and AFs in which management practices must be apply for better understanding of ecological and economic interactions between woody (timber and fruit trees) and non-woody components (annual crops, grasses and pastures, etc.). Therefore, varying components and their interactions provide a scope for number of scientific studies which explores the underlying ecological principles of these farming systems at temporal and spatial scale over the time. Soil management is an important aspect which regulates proper growth and productivity of agroforestry and horticulture systems comprising both annual and perennial crops. Whereas, C sink is possible through healthy soils and healthy soil is possible through better soil management practices. Thus, management must be focused in taking account of soil management which directly correlates with C sequestration that helps in healthy and quality productions in both AFs and HBFs. Conservation tillage, proper mulching, applying cover crops, maintaining soil fertility, nutrient availability, enhancing nutrient use efficiency, water management through better irrigation system, technology for controlling soil and water erosion, etc. are many options that must be follow for better soil C sequestration.

## 7.17 Critical Research Needs for Enhancing Carbon Sequestration in AFS & HBFS

An ample of research has already been conducted that explore the complex nature of horticulture-based farming and AFs having multiple array of significance in term of varying ecosystem services but some parts of research remain unaddressed. For

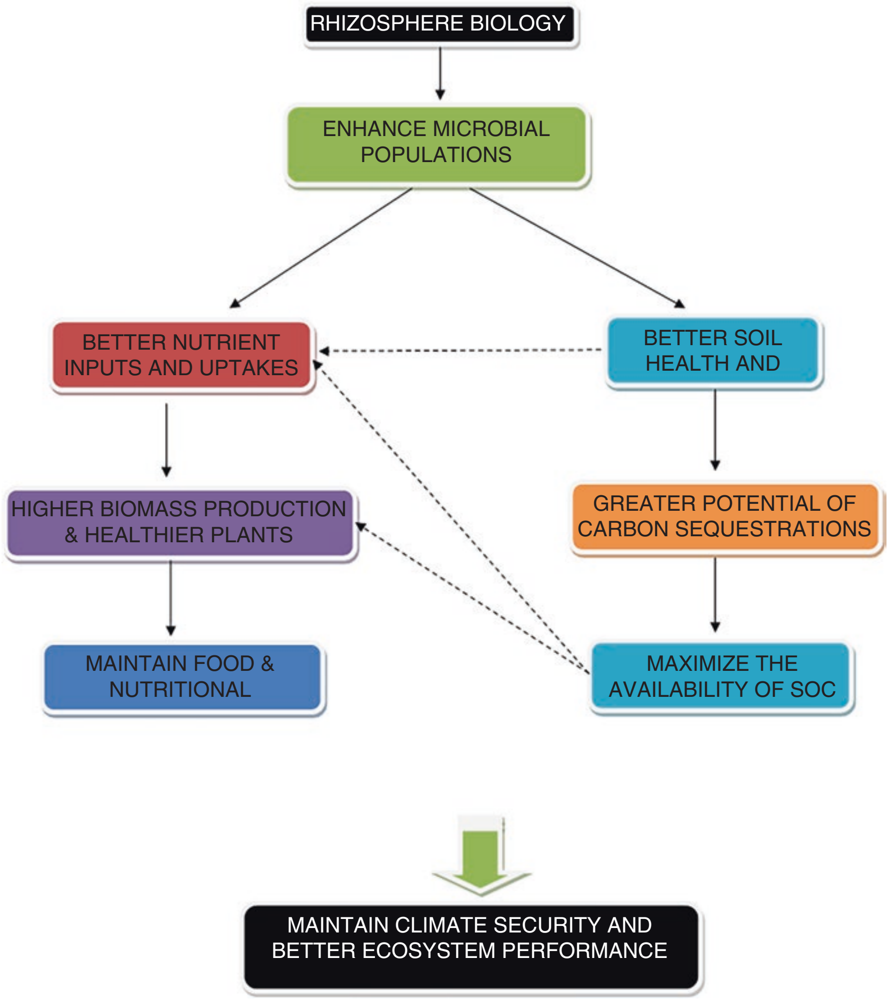

**Fig. 7.7** Rhizosphere biology for better ecosystem performance (White III et al. 2017; Ahkami et al. 2017)

example, research is needed to understand the underlying truth of tree-crop-animals-soil interactions and related productivity, profitability and in accordance of political and social milieu in agroclimatic zones. Similarly, research should be undertaken for development of degraded, waste and salt affected areas through AFs and perennial HBFs in agroclimatic zones of India. Further, a detailed study on C sequestration potential of different woody perennial trees comprising timber and fruit tree are needed. However, many authors have reported the potential C sink value of different trees used in urban forestry, agroforestry, HBFs and other land used practices in the tropics which are depicted in Table 7.8. As per Forrester et al. (2006) some indigenous tree species like neem (*Azadirachta indica*), Mahua (*Madhuca latifolia*),

**Table 7.8** Carbon sink value in different tree species

| Different tree species | Carbon sink value reported by authors | Reference |
|---|---|---|
| Australian wattle (*Acacia auriculiformis*) | 7.7 Mt C/year | Raizada et al. (2003) |
| North Indian rosewood (*Dalbergia sissoo*) | 3.6 Mt C/year | |
| Coast she oak (*Casuarina equisetifolia*) | 1.9 Mt C/year | |
| Gamhar (*Gmelina arborea*) | 1.4 Mt C/year | |
| California redwood (*Sequoia sempervirens*) | 5000 t C/ha | Runyon et al. (1994) |
| Douglas-fir (*Pseudotsuga menziesii*) | 1000 t C/ha | |
| Deodar (*Cedrus deodara*) | 469.1 t C/ha | Sharma et al. (2011) |
| Bahera (*Terminalia bellirica*) | 327.78 t C/ha | Hangarge (2012) |
| Eucalyptus spp. | 320.67 t C/ha | Chavan and Rasal (2011) |
| Black wattle (*Acacia mangium* Willd.) | 292.02 t C/ha | Ilyas (2013) |
| Tropical clumping bamboo (*Bambusa balcooa*) | 234.17 t C/ha | Borah and Chandra (2010) |
| Indian Bat tree (*Ficus amplissima*) | 221 t C/ha | Hangarge (2012) |
| Teak (*Tectona grandis*) | 181 t C/ha | Sreejesh et al. (2013) |
| Rubber tree (*Hevea brasiliensis*) | 136 t C/ha | Dey (2005) |
| Poplar (*Populus deltoids*) | 115 t C/ha | Gera et al. (2006) |
| Mango (*Mangifera indica*) | 104.41 t C/ha | Chavan and Rasal (2012) |
| Ban oak (*Quercus leucotrichophora*) | 77.3 t C/ha | Sharma et al. (2011) |
| Siris tree (*Albizia lebbeck*) | 11.97 t C/ha | Jana et al. (2009) |
| Sal (*Shorea robusta*) | 8.97 t C/ha | |
| Ten years orchard of Mango (*Mangifera indica*) | 58.1 kg tree$^{-1}$ by | Shinde et al. (2015) |
| Fifteen years orchard of Mango (*Mangifera indica*) | 115.4 kg tree$^{-1}$ | |
| Ten years orchard of Coconut (*Cocos nucifera*) | 56.6 kg tree$^{-1}$ | |
| Fifteen years orchard of Coconut (*Cocos nucifera*) | 126.3 kg tree$^{-1}$ | |
| Ten years orchard of Jamun (*Syzygium cumini*) | 38.7 kg tree$^{-1}$ | |
| Fifteen years orchard of Jamun (*Syzygium cumini*) | 78.8 kg tree$^{-1}$ | |
| Ten years orchard of Guava (*Psidium guajava*) | 32.9 kg tree$^{-1}$ | |
| Fifteen years orchard of Guava (*Psidium guajava*) | 54.3 kg tree$^{-1}$ | |
| Mango tree orchards of Indian subcontinent | 285.0 MT C | Ganeshamurthy et al. (2019) |

peepal (*Ficus religiosa*) and tamarind (*Tamarindus indica*), etc. have high potential to sequester more C and fix into them as biomass which also helps in minimizing the pollution in urban and rural areas. Moreover, a critical research is needed to understand the soil genesis and its pedology for better soil health management which is directly link with rhizosphere biology, microbial population, C sequestration potential, extent of SOC, nutrient use efficiency, quality food and nutritious fruits productions and other varying ecosystem services for better environment and ecological stability.

Thus, research should be undertaken in accordance of maximizing potential of C sequestration in both vegetation and soils in agroforestry and horticulture land use systems which can be possible through understanding the interaction magnitude among tillage practices, varying climatic situations and soil types on C sequestration. Also, topics such as (a) exploration the C sequestration potential of various agroforestry and perennial horticulture system in agroclimatic zones, (b) evaluation the synergy between C and soil-crops health & productivity, (c) evaluating the practices of C sequestration for GHGs emissions, (d) horticultural waste based biochar production and its role in C balance and SOC in soils, (e) quantifying the impact of tree pruning for better light penetrations and photosynthesis in varying fruits orchard along with its significant role in retaining soil C through conversion of tree pruned biomass into biochar and its application into the soil and (f) evaluating the significance of conservation practices in both AFs and HBFs beyond the C sequestrations etc. should be addressed.

## 7.18 Policy and Legal Framework

As we know, C sequestration is win-a-win strategy to combat global warming and other negative consequences of climate change which already popularized by various government, NGO, national and international organizations and policy maker in the world. Policy must be in frame of conducting more research on C sequestration potential of varying land use farming systems in priority basis. Governance and policy should develop a legal framework on exploration and understanding of C sequestration and SOC pools through better soil management practices in horticulture and AFs in varying agroclimatic zones. Policy should be aimed towards regulating C balance and enhancing C sink into both vegetation and soils to offset GHGs emissions by every practical aspect which would be helpful in maintaining tree-crop-soil health, productivity and climate security for ecological sustainability in long term basis.

## 7.19 Conclusion

Today, emissions of GHGs are major challenges and it can be minimized by practices of better horticulture and AFs that not only mitigate the issue of climate change but also helps in maintaining C balance in environment, enhance SOC and nutrients input into the systems, promotes microbial population through better rhizosphere technology, intensify the ecosystem services through enhancing biodiversity, resource use-efficiency, maximize productivity i.e., quality food and fruits that helps in maintaining food-nutrition-climate security. It is now crystal-clear hypothesis and assumption regarding better performance of perennial horticultural systems in C sequestration than other farming practices like agroforestry and annual cropping systems. Also, perennial horticultural land use systems deliver better economic return through C credits. Soil stores much C pools for long time by better soil management practices, healthy rhizosphere biology, less synthetic inputs under eco-intensification practices that all intensify the ecosystem services and whole ecosystem sustainability. Thus, better management of soil and whole farming systems are important for better consequences of C sequestration in term of biomass productions and others uncountable tangible and intangible benefits through ecosystem services which maintains ecological sustainability.

## 7.20 Future Thrust

The C dynamic, its source and sink are the key criteria for planning C reduction, emission, financing and trading. The AFs, HBFs and other agroecosystems related land-use are the key concern in terms of food security, climate change and C emission-reduction processes. In this connection proper monitoring, modelling and assessment are needed time to time with upgradation of technology in different land-use to strengthening the knowledge regarding the trends of C emission-reduction. Similarly, the limited studies are available on C sequestration potential of diverse fruit and vegetable-based horticulture land use systems in different agro-climatic zones in India. Surely, it will give a new dimension to study and emphasis should be given on to identify a suitable species and develop a suitable propagation protocols along with better management practices which would help in enhancing C sequestration and productivity of varying perennial fruits and vegetables. Thus, more studies are needed to quantify C sequestration potential and various types of footprints in different land system. Further, various models were properly tested in different agro-climate zone along with varying site conditions for incorporation and promotion of C enrich technology in different plantation activities and government schemes. The potential of C sequestration by various indigenous species and the species having wider ecological amplitude were screened out for achieving the higher C sink and to move forwards with sustainable approach.

## References

Ahkami AH, White RA, Handakumbura PP, Jansson C (2017) Rhizosphere engineering: enhancing sustainable plant ecosystem productivity. Rhizosphere 3:233–243. https://doi.org/10.1016/j.rhisph.2017.04.012

Albrecht A, Kandji ST (2003) Carbon sequestration in tropical agroforestry systems. Agric Ecosyst Environ 99:15–27

Amezquita MC, Ibrahim M, Llanderal T, Buurman P, Amezquita E (2005) Carbon sequestration in pastures, silvopastoral systems and forests in four regions of the Latin American tropics. J Sustain For 21:31–49

Andrade HJ, Brook R, Ibrahim M (2008) Growth, production and carbon sequestration of silvopastoral systems with native timber species in the dry lowlands of Costa Rica. Plant Soil 308(1–2):11–22

Awasthi P, Bargali K, Bargali SS, Jhariya MK (2022) Structure and functioning of *Coriaria nepalensis* wall dominated Shrublands in degraded hills of Kumaun Himalaya. I. Dry matter dynamics. Land Degrad Dev 33(9):1474–1494. https://doi.org/10.1002/ldr.4235

Bailey A (2016) Mainstreaming agrobiodiversity in sustainable food systems. Scientific foundations for an agrobiodiversity index-summary. Bioversity International, Rome, p 30

Bambrick AD, Whalen JK, Bradley RL, Cogliastro A, Gordon AM, Olivier A, Thevathasan NV (2010) Spatial heterogeneity of soil organic carbon in tree-based intercropping systems in Quebec and Ontario, Canada. Agrofor Syst 79:343–353

Banerjee A, Jhariya MK, Yadav DK, Raj A (2020) Environmental and sustainable development through forestry and other resources. Apple Academic Press Inc., CRC Press, Tayler and Francis Group, Palm Bay, FL/Oakville, ON, p 400. https://doi.org/10.1201/9780429276026. ISBN:9781771888110

Bertin C, Yang X, Weston LA (2003) The role of root exudates and allelochemicals in the rhizosphere. Plant Soil 256(1):67–83

Bhandari DC, Meghwal PR, Lodha S (2014) Horticulture based production systems in Indian arid regions. In: Nandwani D (ed) Sustainable horticultural systems, sustainable development and biodiversity, vol 2. Springer International Publishing, Cham, pp 19–49. https://doi.org/10.1007/978-3-319-06904-3_2. isbn:978-3-319-06903-6

Bhatia A, Pathak H, Aggarwal PK (2004) Inventory of methane and nitrous oxide emissions from agricultural soils of India and their global warming potential. Curr Sci 87:317–324

Bhavya VP, Kumar A, Kumar S (2017) Land use systems to improve carbon sequestration in soils for mitigation of climate change. Int J Chem Stud 5(4):2019–2021

Bloomfield J, Pearson HL (2000) Land use, land-use change, forestry, and agricultural activities in the clean development mechanism: estimates of greenhouse gas offset potential. Mitig Adapt Strateg Glob Chang 5:9–24

Borah RP, Chandra A (2010) Carbon sequestration potential of selected bamboo species of Northeast India. Ann For 18(2):171–180

Brandt M, Rasmussen K, Hiernaux P, Herrmann S, Tucker CJ, Tong X, Tian F, Mertz O, Kergoat L, Mbow C, David J, Melocik K, Dendoncker M, Vincke C, Fensholt R (2018) Reduction of tree cover in West African woodlands and promotion in semi-arid farmlands. Nat Geosci 11(5):328–333. https://doi.org/10.1038/s41561-018-0092-x

Brown S, Sathaye J, Cannell M, Kauppi P (1996) Management of forests for mitigation of greenhouse gas emissions. In: Watson RT, Zinyowera MC, Moss RH (eds) Climate change 1995: impacts, adaptations and mitigation of climate change: scientific-technical analyses. Cambridge University Press, New York

Cadisch G, Oliveira OC, de Cantarutti R, Carvalho E, Urquiaga S (1998) The role of legume quality in soil carbon dynamics in savannah ecosystems. In: Bergstrom I, Kirchmann H (eds) Carbon and nutrient dynamics in natural and agricultural tropical ecosystems. CAB International, Wallingford

Chandran P, Ray SK, Durge SL (2016) Scope of horticultural land-use system in enhancing carbon sequestration in ferruginous soils of semi-arid tropics. Curr Sci 97(7):1039–1046

Chauhan SK, Sharma SC, Chauhan R, Gupta N, Srivastava R (2010) Accounting poplar and wheat productivity for carbon sequestration in agrisilviculture system. Indian Forester 136(9):1174–1182

Chavan BL, Rasal GB (2011) Sequestered carbon potential and status of Eucalyptus tree. Int J Appl Eng Technol 1(1):41–47

Chavan BL, Rasal G (2012) Total sequestered carbon stock of *Mangifera indica*. J Environ Earth Sci 2:37–48

Chhabra A, Manjunath KR, Panigrahy S, Parihar JS (2009) Spatial pattern of methane emissions from Indian livestock. Curr Sci 96:683–689

Cole RJ (2010) Social and environmental impacts of payments for environmental services for agroforestry on small-scale farms in southern Costa Rica. Int J Sustain Dev World Ecol 17:208–216

Colmenares OM, Brindis RC, Verduzco CV, Grajales MP, Gómez MU (2020) Horticultural agroforestry systems recommended for climate change adaptation: a review. Agric Rev 41:14–24

Das SK, Itnal CJ (1994) Capability based land use system: role in diversifying dryland agriculture in dryland area. Bull Indian Soc Soil Sci 16:92–100

Das A, Yadav GS, Layek J, Lal R, Meena RS, Babu S, Ghosh PK (2020) Carbon management in diverse land-use systems of Eastern Himalayan Subtropics. In: Ghosh P, Mahanta S, Mandal D, Mandal B, Ramakrishnan S (eds) Carbon management in tropical and sub-tropical terrestrial systems. Springer, Singapore, pp 123–142

Datta A, Basak N, Chaudhari SK, Sharma DK (2015) Effect of horticultural land uses on soil properties and organic carbon distribution in a reclaimed sodic soil. J Indian Soc Soil Sci 63(3):294–303

de Stefano A, Jacobson MG (2018) Soil carbon sequestration in agroforestry systems: a meta analysis. Agrofor Syst 92:285–299

Demenois J, Torquebiau E, Arnoult MH, Eglin T, Masse D, Assouma MH, Blanfort V, Chenu C, Chapuis-Lardy L, Médoc JM, Sall SN (2020) Barriers and strategies to boost soil carbon sequestration in agriculture. Front Sustain Food Syst 4:37

Dey SK (2005) A preliminary estimation of carbon stock sequestrated through rubber (*Hevea brasiliensis*) plantation in north eastern region of India. Indian Forester 131:1429–1436

Dhyani SK, Handa AK, Uma (2013) Area under agroforestry in India: an assessment for present status and future perspective. Indian J Agrofor 15(1):1–11

Dollinger J, Jose S (2018) Agroforestry for soil health. Agrofor Syst 92:213–219. https://doi.org/10.1007/s10457-018-0223-9

FAOSTAT (2018) FAOSTAT. Food and Agriculture Organization Corporate Statistical Database. www.fao.org/faostat/en/#home

Forrester DI, Bauhus J, Cowie AL, Jerome K, Vanclay JK (2006) Mixed-species plantations of Eucalyptus with nitrogen fixing trees: a review. For Ecol Manag 233:211–230

Gabrielsson S, Ramasar V (2013) Widows: agents of change in a climate of water uncertainty. J Clean Prod 60:34–42. https://doi.org/10.1016/J.JCLEPRO.2012.01.034

Ganeshamurthy AN, Ravindra V, Rupa TR (2019) Carbon sequestration potential of mango orchards in India. Curr Sci 117(12):2006–2013

Ganeshamurthy AN, Kalaivanan D, Rajendiran S (2020) Carbon sequestration potential of perennial horticultural crops in Indian tropics. In: Ghosh P, Mahanta S, Mandal D, Mandal B, Ramakrishnan S (eds) Carbon management in tropical and sub-tropical terrestrial systems. Springer, Singapore, pp 333–348

Gera M, Mohan G, Bisht NS, Gera N (2006) Carbon sequestration potential under agroforestry in Rupnagar district of Punjab. Indian Forester 132(5):543–555

Ghosh PK, Mahanta SK (2014) Carbon sequestration in grassland systems. Range Manage Agrofor 35(2):173–181

Gupta MK, Sharma SD (2011) Sequestrated carbon: organic carbon pool in the soils under different forest covers and land uses in Garhwal Himalayan region of India. Int J Agric For 1(1):14–20

Haile SG, Nair PKR, Nair VD (2008) Carbon storage of different soil-size fractions in Florida silvopastoral systems. J Environ Qual 37:1789–1797

Haile SG, Nair VD, Nair PKR (2010) Contribution of trees to carbon storage in soils of silvopastoral systems in Florida, USA. Glob Change Biol 16:427–438

Hangarge (2012) Carbon sequestration potential of tree species in Somjaichirai (sacred grove) at Nandghur village, in Bihar region of Pune district, Maharashtra state, India. Ann Biol Res 3(7):3426–3429

Hartmann A, Rothballer M, Schmid M, Hiltner L (2008) A pioneer in rhizosphere microbial ecology and soil bacteriology research. Plant Soil 312:7–14

Hiltner L (1904) Ueberneuere Erfahrungen und Probleme auf dem Gebiete der Bodenbakteriologie und unterbesonderer Ber Ucksichtigung der Grundungung und Brache. Arb Deut Landw Gesell 98:59–78

Howlett D (2009) Environmental amelioration potential of silvopastoral agroforestry systems in Spain: soil carbon sequestration and phosphorus retention. Ph.D. dissertation, University of Florida, Gainesville

Howlett DS, Moreno G, Mosquera-Losada MR, Nair PK, Nair VD (2011a) Soil carbon storage as influenced by tree cover in the Dehesa cork oak silvopasture of central-western Spain. J Environ Monit 13(7):1897–1904

Howlett DS, Mosquera-Losada MR, Nair PKR, Nair VD, Rigueiro-Rodríguez A (2011b) Soil C storage in silvopastoral systems and a treeless pasture in northwestern Spain. J Environ Qual 40:784–790

Ilyas S (2013) Allometric equation and carbon sequestration of Acacia mangium Willd.in coal mining reclamation areas. Civil Environ Res 3(1):8–16

Jaiarree S, Chidthaisong A, Tangtham N, Polprasert C, Sarobol E, Tyler SC (2014) Carbon budget and sequestration potential in a sandy soil treated with compost. Land Degrad Dev 25(2):120–129. https://doi.org/10.1002/ldr.1152

Jana BK, Biswas S, Majumder M, Roy PK, Mazumdar A (2009) Comparative assessment of carbon sequestration rate and biomass carbon potential of young *Shorea robusta* and *Albizzia lebbek*. Int J Hydro-Clim Eng Assoc Water Enviro-Model 1(2):1–15

Janiola MDC, Marin RA (2016) Carbon sequestration potential of fruit tree plantations in Southern Philippines. J Biodivers Environ Sci 8(5):164–174

Jhariya MK, Bargali SS, Raj A (2015) Possibilities and perspectives of agroforestry in Chhattisgarh, pp 237–257. In: Zlatic M (ed) Precious forests-precious earth. InTech, Croatia, 286 pp. https://doi.org/10.5772/60841. isbn:978-953-51-2175-6

Jhariya MK, Banerjee A, Yadav DK, Raj A (2018) Leguminous trees an innovative tool for soil sustainability. In: Meena RS, Das A, Yadav GS, Lal R (eds) Legumes for soil health and sustainable management. Springer, pp 315–345. https://doi.org/10.1007/978-981-13-0253-4_10. eISBN:978-981-13-0253-4 (eBook), ISBN:978-981-13-0252-7 (Hardcover)

Jhariya MK, Banerjee A, Meena RS, Yadav DK (2019a) Sustainable agriculture, forest and environmental management. Springer Nature, Singapore, p 606. https://doi.org/10.1007/978-981-13-6830-1. eISBN:978-981-13-6830-1, Hardcover ISBN:978-981-13-6829-5

Jhariya MK, Yadav DK, Banerjee A (2019b) Agroforestry and climate change: issues and challenges. Apple Academic Press Inc., CRC Press, Tayler and Francis Group, Palm Bay, FL/Oakville, ON, p 335. https://doi.org/10.1201/9780429057274. ISBN:978-1-77188-790-8 (Hardcover), 978-0-42957-274-8 (E-book)

Jhariya MK, Meena RS, Banerjee A (2021a) Ecological intensification of natural resources for sustainable agriculture. Springer Nature, Singapore, p 655. https://doi.org/10.1007/978-981-33-4203-3. eISBN:978-981-334-203-3, Hardcover ISBN:978-981-334-206-6

Jhariya MK, Banerjee A, Meena RS, Kumar S, Raj A (2021b) Sustainable intensification for agroecosystem services and management. Springer Nature, Singapore, p 870. https://doi.org/10.1007/978-981-16-3207-5. eISBN:978-981-16-3207-5, Hardcover ISBN:978-981-16-3206-8

Jhariya MK, Meena RS, Banerjee A, Meena SN (2022) Natural resources conservation and advances for sustainability. Elsevier, Academic Press. https://doi.org/10.1016/C2019-0-03763-6. ISBN:9780128229767

Joshi PK, Acharya SS, Chand R, Kumar A (2009) Agricultural sector: status and performance. In: Rai M et al (eds) State of Indian agriculture. National Academy of Agricultural Sciences, New Delhi, pp 1–32

Kareemulla K, Rizvi RH, Singh R, Dwivedi RP (2002) Trees in rainfed agro-ecosystem: a socio-economic investigation in Bundelkhand region. Indian J Agrofor 4(1):53–56

Kaur B, Gupta SR, Singh G (2002) Carbon storage and nitrogen cycling in silvi-pastoral systems on a sodic soil in northwestern India. Agrofor Syst 54:21–29

Kaye JP, Resh SC, Kaye MW, Chimner RA (2000) Nutrient and carbon dynamics in a replacement series of *Eucalyptus* and *Albizia*trees. Ecology 81(12):3267–3273

King KFS (1987) The history of agroforestry. In: Steppler H, PKR N (eds) Agroforestry: a decade of development. International Council for Research in Agroforestry (ICRAF), Nairobi, pp 3–13

Kirby KR, Potvin C (2007) Variation in carbon storage among tree species: implications for the management of a small-scale carbon sink project. For Ecol Manag 246:208–221

Koppad AG, Tikhile P (2014) Role of forest on carbon sequestration in soils of Joida and Karwar Taluka of Uttara Kannada district. Indian Forester 140(3):260–264

Kumar BM (2006) Carbon sequestration potential of tropical homegardens. In: Kumar BM, Nair PKR (eds) Tropical homegardens: a time tested example of sustainable agroforestry. Advance in agroforestry, vol 3. Springer, Dordrecht, pp 185–204

Kumar AK (2010) Carbon sequestration: underexplored environmental benefits of Tarai agroforestry. Indian J Soil Conserv 38:125–131

Kumar S, Satyapria HV, Singh KA (2009) Horti-pasture for nutritional security and economic stability in rainfed area. Progress Hortic 41(2):187–195

Kumar S, Shukla AK, Satyapria Singh HV, Singh KA (2011) Horti-pasture for nutritional security and economic stability in rainfed area. Paper presented in National Conference on Horti Business Linking farmers with Market held at Dehradun from 28–31 May 2011, pp 18–19

Lal R (2005) Forest soils and carbon sequestration. For Ecol Manag 220:242–258

Lal R, Bruce J (1999) The potential of world cropland to sequester C and mitigate the greenhouse effect. Environ Sci Policy 2:177–185

Leakey R (1996) Definition of agroforestry revisited. Agrofor Today 8:1

Lenka S, Lenka NK, Singh AB, Singh B, Raghuwanshi J (2017) Global warming potential and greenhouse gas emission under different soil nutrient management practices in soybean–wheat system of Central India. Environ Sci Pollut Res 24:4603–4612

Majumdar D, Pathak H, Kumar S, Jain MC (2002) Nitrous oxide emission from a sandy loam Inceptisol under irrigated wheat in India as influenced by different nitrification inhibitors. Agric Ecosyst Environ 9:283–293

Makumba W, Akinnifesi FK, Janssen B, Oenema O (2007) Long-term impact of a Gliricidia-maize intercropping system on carbon sequestration in southern Malawi. Agric Ecosyst Environ 118:237–243

Mangalassery S, Dayal D, Meena SL, Ram B (2014) Carbon sequestration in agroforestry and pasture systems in arid northwestern India. Curr Sci 107(8):1290–1293

Manral V, Bargali K, Bargali SS, Jhariya MK, Padalia K (2022) Relationships between soil and microbial biomass properties and annual flux of nutrients in Central Himalayan forests, India. Land Degrad Dev 33(12):2014–2025. https://doi.org/10.1002/ldr.4283

Meena RS, Kumar S, Sheoran S, Jhariya MK, Bhatt R, Yadav GS, Gopinath KA, Srinivasa Rao C, Lal R (2021) Soil organic carbon restoration in India: programs, policies, and thrust areas. In: Lal R (ed) The soil organic matter and feeding the future. CRC Press/Taylor & Francis Groups, Oxfordshire, pp 305–338. https://doi.org/10.1201/9781003102762-13

Meena RS, Yadav A, Kumar S, Jhariya MK, Jatav SS (2022) Agriculture ecosystem models for CO2 sequestration, improving soil physicochemical properties, and restoring degraded land. Ecol Eng 176:106546. https://doi.org/10.1016/j.ecoleng.2022.106546

Montagnini F, Nair PKR (2012) Carbon sequestration: an underexploited environmental benefit of agroforestry systems. Agrofor Syst 61:281–295

Murthy IK, Gupta M, Tomar S, Munsi M, Tiwari R, Hegde GT, Ravindranath NH (2013) Carbon sequestration potential of agroforestry systems in India. J Earth Sci Climate Chang 4(1):1–7

Nair PKR (2012) Climate change mitigation and adaptation: a low hanging fruit of agroforestry. In: Nair PKR, Garrity DP (eds) Agroforestry: the future of global land use. Springer, Dordrecht, pp 31–67

Nair PKR, Nair VD (2003) Carbon storage in North American agroforestry systems. In: Kimble J, Heath LS, Birdsey RA, Lal R (eds) The potential of U.S. forest soils to sequester carbon and mitigate the green house effect. CRC Press LLC, Boca Raton, pp 333–346

Nair PKR, Kumar BM, Nair VD (2009a) Agroforestry as a strategy for carbon sequestration. J Plant Nutr Soil Sci 172:10–23

Nair PKR, Nair VD, Kumar BM, Haile SG (2009b) Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. Environ Sci Policy 12:1099–1111

Nair PKR, Vimala DN, Kumar BM, Showalter JM (2011) Carbon sequestration in agroforestry systems. Adv Agron 108:237–307

Narain P (2008) Dryland management in arid ecosystem. J Indian Soc Soil Sci 56:337–347

Newaj R, Chaturvedi OP, Handa AK (2016) Recent development in agroforestry research and its role in climate change adaptation and mitigation change adaptation and mitigation. Indian J Agrofor 18:1–9

Niles JO, Brown S, Pretty J, Ball AS, Fay J (2002) Potential carbon mitigation and income in developing countries from changes in use and management of agricultural and forest lands. Philos Trans R Soc 360:1621–1639

Novara A, Minacapilli M, Santoro A, Rodrigo-Comino J, Carrubba A, Sarno M, Venezia G, Gristina L (2019) Real cover crops contribution to soil organic carbon sequestration in sloping vineyard. Sci Total Environ 652:300–306

NRCAF (2007) Perspective plan: vision 2025. National Research Centre for Agroforestry (NCRAF), Jhansi

Oelbermann M, Voroney RP, Gordon AM, Kass DCL, Schlnvoigt AM, Thevathasan NV (2006) Carbon input, soil carbon pools, turnover and residue stabilization efficiency in tropical and temperate agroforestry systems. Agrofor Syst 68:27–36

Ospina C (2016) Carbon sequestration: addressing climate change and food security through sustainable agriculture, pp 1–8

Pant KS, Yewale AG, Prakash P (2014) Fruit trees based agroforestry systems. In: Raj AJ, Lal SB (eds) Agroforestry theory and practices. Scientific Publishers, Jodhpur, pp 564–588

Parrotta JA (1999) Productivity, nutrient cycling and succession in single- and mixed-species stands of *Casuarina equisetifolia*, *Eucalyptus robusta* and *Leucaena leucocephala* in Puerto Rico. For Ecol Manag 124:45–77

Pathak H, Saharawat YS, Gathala M, Mohanty S, Ladha JK (2009) Simulating environmental impact of resource-conserving technologies in the rice-wheat system of the Indo-Gangetic Plains. In: Ladha JK, Yadvinder-Singh, Erenstein O, Hardy B (eds) Integrated crop and resource management in the rice-wheat systemof South Asia. International Rice Research Institute, Los Banos, pp 321–334

Paudela D, Tiwaria KR, Bajracharyab RM, Rautb N, Sitaulac BK (2017) Agroforestry system: an opportunity for carbon sequestration and climate change adaptation in the Mid-Hills of Nepal. Octa J Environ Res 5:10

Peichl M, Thevathasan NV, Gordon AM, Huss J, Abohassan RA (2006) Carbon sequestration potentials in temperate tree based intercropping systems, southern Ontario, Canada. Agrofor Syst 66:243–250

Prasad R, Saroj NK, Newaj R, Venkatesh A, Dhyani SK, Dhanai CS (2010) Atmospheric carbon capturing potential of some agroforestry trees for mitigation of warming effect and climate change. Indian J Agrofor 12(2):37–41

Prasad R, Jhariya MK, Banerjee A (2021a) Advances in sustainable development and management of environmental and natural resources: economic outlook and opinions I. CRC Press, Taylor and Francis Group, Apple Academic Press Inc., Palm Bay, FL/Oakville, ON. pp. 1–437. Hardcover ISBN:9781774910344

Prasad R, Jhariya MK, Banerjee A (2021b) Advances in sustainable development and management of environmental and natural resources: economic outlook and opinions, vol II. CRC Press, Taylor and Francis Group, Apple Academic Press Inc., Palm Bay, FL/Oakville, ON, pp 1–428. Hardcover ISBN:9781774910368

Rai P, Ajit CPO, Singh R, Singh UP (2009) Biomass production in multipurpose tree species in natural grasslands under semi-arid conditions. J Trop For 25:11–16

Raizada A, Parandiyal AK, Ghosh BN (2003) Estimation of carbon flux through litter fall in forest plantations of India. Indian Forester 129(7):881–894

Raj A, Jhariya MK (2021a) Site quality and vegetation biomass in the tropical Sal mixed deciduous forest of Central India. Landsc Ecol Eng 17(1):1–13. https://doi.org/10.1007/s11355-021-00450-1

Raj A, Jhariya MK (2021b) Carbon storage, flux and mitigation potential of tropical Sal mixed deciduous forest ecosystem in Chhattisgarh, India. J Environ Manag 293:112829. https://doi.org/10.1016/j.jenvman.2021.112829

Raj A, Jhariya MK, Yadav DK, Banerjee A, Meena RS (2019a) Agroforestry: a holistic approach for agricultural sustainability, pp 101–131. In: Jhariya MK, Banerjee A, Meena RS, Yadav DK (eds) Sustainable agriculture, Forest and environmental management. Springer Nature, Singapore, p 606. https://doi.org/10.1007/978-981-13-6830-1. eISBN:978-981-13-6830-1, Hardcover ISBN:978-981-13-6829-5

Raj A, Jhariya MK, Banerjee A, Yadav DK, Meena RS (2019b) Soil for sustainable environment and ecosystems management, pp 189–221. In: Jhariya MK, Banerjee A, Meena RS, Yadav DK (eds) Sustainable agriculture, forest and environmental management. Springer Nature, Singapore, p 606. https://doi.org/10.1007/978-981-13-6830-1. eISBN:978-981-13-6830-1, Hardcover ISBN:978-981-13-6829-5

Raj A, Jhariya MK, Yadav DK, Banerjee A (2020a) Climate change and agroforestry systems: adaptation and mitigation strategies. Apple Academic Press Inc., CRC Press, Tayler and Francis Group, Palm Bay, FL/Oakville, ON, p 383. https://doi.org/10.1201/9780429286759. ISBN:9781771888226

Raj A, Jhariya MK, Yadav DK, Banerjee A (2020b) Forest for resource management and environmental protection. In: Banerjee A, Jhariya MK, Yadav DK, Raj A (eds) Environmental and sustainable development through forestry and other resources. AAP, CRC Press, Toronto, pp 1–24

Raj A, Jhariya MK, Khan N (2022) Forest for soil, food and climate security in Asia. In: Öztürk M, Khan SM, Altay V, Efe R, Egamberdieva D, Khassanov FO (eds) Biodiversity, conservation and sustainability in Asia, vol. 2; South and Middle Asia. Springer, pp 33–52. https://doi.org/10.1007/978-3-030-73943-0_3

Rajput BS, Bhardwaj DR, Nazir AP (2017) Factors influencing biomass and carbon storage potential of different land use systems along an elevational gradient in temperate northwestern Himalaya. Agrofor Syst 91:479–486

Rao MR, Ong CK, Pathak P, Sharma MM (1991) Productivity of annual cropping and agroforestry systems on a shallow Alfisol in semi-arid India. Agrofor Syst 15:51–63

Rhoades CC, Eckert GE, Coleman DC (1998) Effect of pasture trees on soil nitrogen and organic matter: implications for tropical montane forest restoration. Restor Ecol 6(3):262–270

Rizvi RH, Dhyani SK, Newaj R, Karmakar PS, Saxena A (2014) Mapping agroforestry area in India through remote sensing and preliminary estimates. Indian Farm 63(11):62–64

Roy A (2011) Requirement of vegetables and fruit. The Daily Star (A English Newspaper), 24 Mar 2011

Roy O, Meena RS, Kumar S, Jhariya MK, Pradhan G (2022) Assessment of land use systems for $CO_2$ sequestration, carbon credit potential and income security in Vindhyan region, India. Land Degrad Dev 33(4):670–682. https://doi.org/10.1002/ldr.4181

Ruiz A, Ibrahim M, Locatelli B, Andrade HJ, Beer J (2004) Fijación y almacenamiento de carbonoensistemassilvopastoriles y competitividadeconómica de fincasganaderasenMatiguás, Nicaragua. Agrofor Am 41–42:16–21

Runyon J, Waring RH, Goward SN, Welles JM (1994) Environmental limits on net primary production and light-use efficiency across the Oregon transect. Ecol Appl 4:226–237

Saha S, Nair PKR, Nair VD, Kumar BM (2009) Soil carbon stocks in relation to plant diversity of home gardens in Kerala, India. Agrofor Syst 76:53–65

Samal B, Singh L, Jhariya MK (2022) Carbon storage, mitigation and sequestration potential of *Haldina cordifolia* and *Mitragyna parvifolia* in tropical dry deciduous environment of Chhattisgarh, India. Ecol Eng 175:106490. https://doi.org/10.1016/j.ecoleng.2021.106490

Sanz MJ et al (2017) Sustainable land management contribution to successful land-based climate change adaptation and mitigation. A report of the science–policy interface. A report of the science–policy interface. United Nations Convention to Combat Desertification (UNCCD), Bonn, 178 pp

Sarvade S, Gautam DS, Upadhyay VB, Sahu RK, Shrivastava AK, Kaushal R, Singh R, Yewale AG (2019) Agroforestry and soil health: an overview. In: Dev I, Ram A, Kumar N, Singh R, Kumar D, Uthappa AR, Handa AK, Chaturvedi OP (eds) Agroforestry for climate resilience and rural livelihood. Scientific Publishers, Jodhpur, pp 275–297

Sharma CM, Gairola S, Baduni NP, Ghildiyal SK, Sarvesh S (2011) Variation in carbon stocks on different slope aspects in seven major types of temperate region of Garhwal Himalaya, India. J Biol Sci 36(4):701–708

Sharrow SH, Ismail S (2004) Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. Agrofor Syst 60:123–130

Sheikh MA, Kumar M, Todaria NP (2015) Carbon sequestration potential of nitrogen fixing tree stands. For Stud Metsanduslikud Uurimused 62:39–47

Shi L, Feng W, Xu J, Kuzyakov Y (2018) Agroforestry systems: meta-analysis of soil carbon stocks, sequestration processes, and future potentials. Land Degrad Dev 29(11):3886–3897. https://doi.org/10.1002/ldr.3136

Shinde SM, Turkhade PD, Deshmukh SB, Narkhede GW (2015) Carbon sequestration potential of some fruit trees in Satara district of Maharashtra India. Ecol Environ ConservEco Env & Cons 21(1):359–362

Shrestha G, Malla G (2016) Estimation of atmospheric carbon sequestration by fruit plants in mid-western terai region, Nepal. Nepal J Agric Sci 14:211–215

Singh NR, Jhariya MK (2016) Agroforestry and agrihorticulture for higher income and resource conservation. In: Narain S, Rawat SK (eds) Innovative technology for sustainable agriculture development. Biotech Books, New Delhi, pp 125–145. isbn:978-81-7622-375-1

Singh HP, Malhotra SK (2011) Horticulture for food, nutrition and healthcare- a new paradigm. Indian Hortic 56(2):3–11

Singh B, Singh G (2015) Biomass production and carbon stock in a silvi-horti based agroforestry system in arid region of Rajasthan. Indian Forester 141(12):1237–1243

Sreejesh KK, Thomas TP, Rugmini P, Prasanth KM, Kripa PA (2013) Carbon sequestration potential of Teak (*Tectona grandis*) plantations in Kerala. Res J Recent Sci 2:167–170

Sun Y, Cao F, Wei X, Welham C, Chen L, Pelz D, Yang Q, Liu H (2017) An ecologically based system for sustainable agroforestry in sub-tropical and tropical forests. Forests 8(4):102

Swamy SL, Puri S (2005) Biomass production and C-sequestration of *Gmelina arborea* in plantation and agroforestry system in India. Agrofor Syst 64:181–195

Takimoto A, Nair PKR, Nair VD (2008) Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel. Agric Ecosyst Environ 125:159–166

Thakrey M, Singh L, Jhariya MK, Tomar A, Singh AK, Toppo S (2022) Impact of disturbance on biomass, carbon, nitrogen storage in vegetation and soil properties in tropical dry deciduous forest in Chhattisgarh, India. Land Degrad Dev 33(11):1–11. https://doi.org/10.1002/ldr.4263

The World Bank Report (2012) Carbon sequestration in agricultural soils. https://openknowledge.worldbank.org/bitstream/handle/10986/11868/673950REVISED000CarbonSeq0Web0final.pdf?sequence=1&isAllowed=y

Tonucci RG, Nair PKR, Nair VD, Garcia R, Bernardino FS (2011) Soil carbon storage in silvopasture and related land-use systems in the Brazilian cerrado. J Environ Qual 40(3):833–841. https://doi.org/10.2134/jeq2010.0162

Trexler MC, Haugen C (1994) Keeping it green: tropical forestry opportunities for mitigating climate change. World Resource Institute, Washington, DC

Verchot LV, Dutaur L, Shepherd KD, Albrecht A (2011) Organic matter stabilization in soil aggregates: understanding the biogeochemical mechanisms that determine the fate of carbon inputs in soils. Geoderma 16:182–193

Viswanath S, Peddappaiah RS, Subramoniam V, Manivachakam P, George M (2004) Management of *Casuarina equisetifolia* in wide-row intercropping systems for enhanced productivity. Indian J Agrofor 6(2):19–25

Waldron A, Garrity D, Malhi Y, Girardin C, Miller DC, Seddon N (2017) Agroforestry can enhance food security while meeting other sustainable development goals. Trop Conserv Sci 10:1–6. https://doi.org/10.1177/1940082917720667

Wang Q, Li Y, Alva A (2010) Cropping systems to improve carbon sequestration for mitigation of climate change. J Environ Prot 1:207–215

White RA III, Rivas-Ubach A, Borkum MI, Köberl M, Bilbao A, Colby SM, Hoyt DW, Bingol K, Kim YM, Wendler JP (2017) The state of rhizospheric science in the era of multi-omics: a practical guide to omics technologies. Rhizosphere 3:212–221

Yadav RP, Bisht JK, Pandey BM (2015) Above ground biomass and carbon stock of fruit tree based land use systems in Indian Himalaya. Ecoscan 9(3&4):779–783

Yadav VS, Gupta SR, Yadav SS, Meena RS, Lal R, Sheoran NS, Jhariya MK (2022) Carbon sequestration potential and $CO_2$ fluxes in a tropical forest ecosystem. Ecol Eng 176:106541. https://doi.org/10.1016/j.ecoleng.2022.106541