Carbon Sequestration Potential of Agroforestry Systems in India: A Synthesis

B. Mohan Kumar and T. K. Kunhamu

Abbreviations

AFOLU	Agriculture, forestry, and other land uses
AFS	Agroforestry systems
C	Carbon
CSP	Carbon sequestration potential
GHG	Greenhouse gases
MPT	Multipurpose tree
SCS	Soil carbon sequestration
SOC	Soil organic carbon
SOM	Soil organic matter
UNFCCC	United Nations Framework Convention on Climate Change

Introduction

India is a physiographically diverse and geographically large country with varied ecologies. Rich natural resource endowments in terms of soil, plant, animal, and fish wealth make India and the contiguous areas of South Asia a mega-biodiverse region. The National Bureau of Soil Survey and Land Use Planning (India), based on soil, bioclimatic, and physiographic features (Sehgal et al. 1992), has divided the country into 20 agroecological regions (Fig. 1), which broadly fall under arid, semiarid, subhumid, humid-perhumid, and coastal ecosystems. Land-use systems differ profoundly across these regions but agroforestry dominates in most parts. The Indian

B. M. Kumar (✉)
Arunachal University of Studies, Knowledge City, Namsai, Arunachal Pradesh, India
e-mail: bmkumar@arunachaluniversity.ac.in

T. K. Kunhamu
Department of Silviculture and Agroforestry, College of Forestry, Kerala Agricultural University, KAU (P.O.), Thrissur, Kerala, India
e-mail: kunhamu.tk@kau.in

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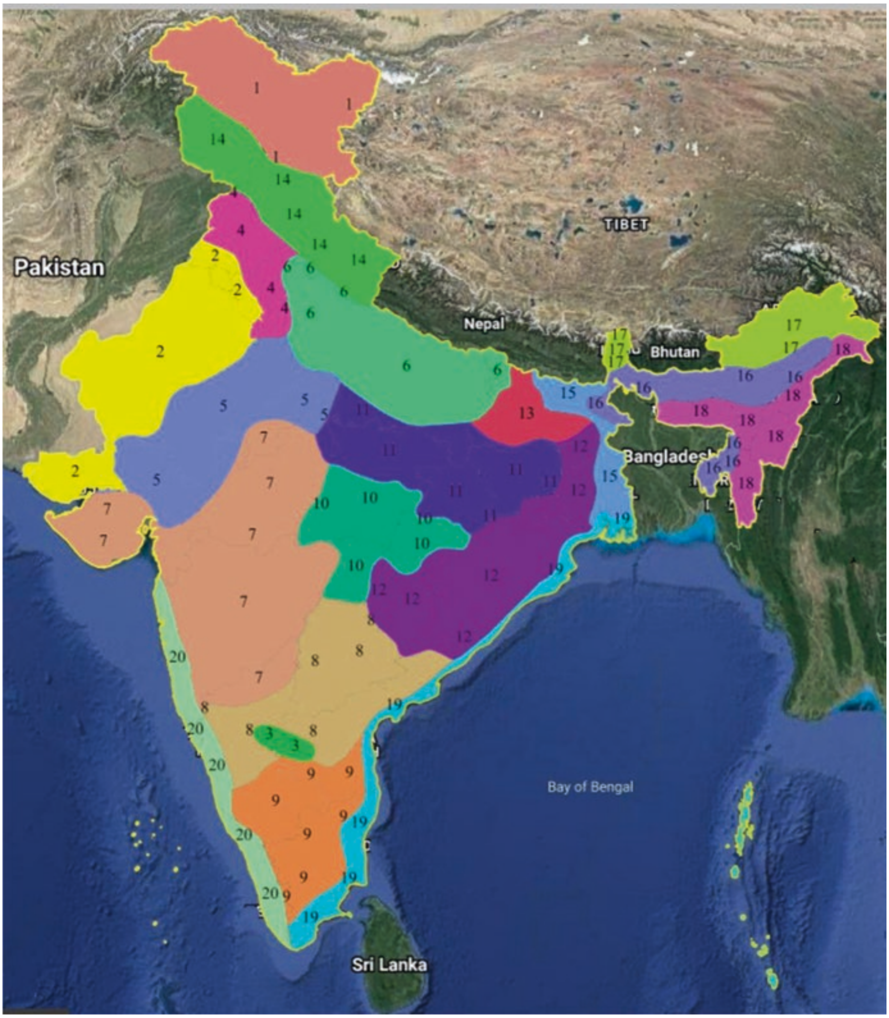

Fig. 1 Agroecological regions of India. 1. Western Himalayas (cold arid), 2. Western Plains and Kutch Peninsula (hot arid), 3. Deccan Plateau (hot arid), 4. Northern Plains (Upper Gangetic; semiarid to subhumid), 5. Northern Plains (Rajasthan Upland and Gujarat Plains; hot semiarid), 6. Northern Plains (Middle Gangetic Plains; hot semiarid to subhumid), 7. Deccan Plateau (Malwa Plateau, Gujarat Plains, and Kathiawar peninsula; hot, semiarid with moderately deep black soils and length of growing period (LGP) 120–150 days), 8. Deccan Plateau (hot semiarid with mixed red and black soils and LGP 120–180 days), 9. Deccan Plateau (hot semiarid with red loamy soils and LGP 150–210 days), 10. Eastern Plateau (Satpura Range and Mahanadi Basin; hot subhumid), 11. Eastern Plateau (Bundelkhand Upland; hot subhumid with red and yellow soils and LGP 120–180 days), 12. Eastern Plateau (hot subhumid with red and lateritic soils and LGP 150–210+ days), 13. Northern Plains (Lower Gangetic; hot, subhumid), 14. Western Himalayas (warm to hot subhumid to humid), 15. Bengal basin (hot, subhumid), 16. Assam and North Bengal Plains (warm humid to perhumid), 17. Eastern Himalayas (warm perhumid), 18. North Eastern hills (Purvanchal; warm perhumid), 19. Eastern Coastal Plains and Islands of Andaman and Nicobar (hot subhumid), and 20. Western Ghats (Coastal Plains and Western Hills; hot humid to perhumid). Reprinted/adapted by permission from the National Bureau of Soil Survey and Land Use Planning, Nagpur (source: http://www.bhoomigeoportal-nbsslup.in/)

Fig. 2 A Kerala homegarden with a multistrata arrangement of coconut palms (*Cocos nucifera*), banana (*Musa* spp.), and other species (photo: BM Kumar)

farmers, as their counterparts elsewhere, have domesticated fruit trees and other agricultural crops over millennia, primarily to meet their subsistence requirements. The tropical homegardens, which represent a complex integration of diverse trees (Fig. 2) with understory crops performing several production and service functions, are a case in point (Kumar et al. 2012). Indeed, the biophysical heterogeneity and climatic variability of the country affect the choice of tree and crop species and their productivity, implying profound variability in the nature and composition of agroforestry practices in India (Tejwani 1994; Puri and Panwar 2007). India is also one of the early countries to launch a national initiative on agroforestry research; indeed, as early as in 1983, it started the All India Coordinated Research Project on Agroforestry (Chinnamani 1993).

Since the late twentieth century, the phenomenon of "climate change" or "global warming" has been attracting global attention at a scale unparalleled in the history of humankind. Scientists, policy makers, and the general public continue to grapple with the adverse impacts of climate change and in figuring out strategies for mitigating the same. It is very likely that climate change may cause unprecedented shifts in global weather patterns producing a range of effects from threats to food security to rising sea levels that increase the risk of catastrophic flooding. India's average temperature has risen by around 0.7 °C during the 1901–2018 period and it is likely to increase further by approximately 4.4 °C by 2100 (relative to the 1976–2005 average; Krishnan et al. 2020). It is widely recognized that climate change is caused by rise in the atmospheric concentrations of the so-called greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The atmospheric concentration of CO_2, a prominent GHG, which accounts for 76% of the total global GHG emissions, has increased at unprecedented rates from the pre-industrial concentration of about 280 ppm to the current level of approximately 410 ppm (https://www.esrl.noaa.gov/gmd/ccgg/trends/gl_trend.html). The principal anthropogenic factors contributing to the increase in atmospheric CO_2 levels include the burning of fossil fuels such as coal, gas, and oil for industrial and other purposes, and agriculture, forestry, and other land uses (AFOLU), including deforestation. The average decadal growth rate of CO_2, which was 2.0 ppm per year in the 2000s, had surged to 2.4 ppm per year during the 2010–2019 period (https://www.co2.earth/co2-acceleration). Significantly, India is the third largest emitter of GHGs and accounts for 7% of total GHG emissions in the world as per the 2018 emission data (https://www.ucsusa.org/resources/each-countrys-share-co2-emissions).

Carbon sequestration is a key strategy for reducing atmospheric concentrations of CO_2, and thereby mitigating global warming. It is a process of storing atmospheric CO_2 or other forms of carbon (C) in long-standing pools. The United Nations Framework Convention on Climate Change (UNFCCC) describes it as "the process of removing C from the atmosphere and depositing it in a reservoir, or the transfer of atmospheric CO_2 to secure storage in long-lived pools" (UNFCCC 2007). Green plants—especially woody perennials—and soil play a central role in this. Dubbed as biological carbon sequestration, plants assimilate atmospheric CO_2 through photosynthesis and store the products of photosynthesis in their parts. The soil also is a major C sink as organic matter can remain in the soil for extended periods. Forestry and agroforestry systems (AFS) play a major role in biological carbon sequestration and stabilization of atmospheric GHG levels. Ever since climate change became a matter of stark global concern, agroforestry has received immense importance as a land management strategy with considerable potential for reducing atmospheric CO_2 levels. The average carbon sequestration potential (CSP) of agroforestry in India has been estimated to be 25 Mg C ha^{-1} over 96 million ha (Sathaye and Ravindranath 1998) and agroforestry figures prominently in the country's climate change mitigation strategies (https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/IndiaFirst/INDIAINDCTOUNFCCC.pdf). There are, however, considerable variations in the CSP of agroforestry across different regions and land-use systems and based on the method of estimation. This chapter examines the range of AFS by agroecological regions of India and their potential to sequester atmospheric CO_2 and thus mitigate global warming. Such information can help focus attention on promising AFS and in adopting appropriate stand management practices including choice of species for enhancing the potential of biological carbon sequestration and for evolving national climate change mitigation strategies, which are cost effective.

Agroforestry: A Cardinal Feature of the Indian Landscape

India is regarded as the cradle of agroforestry with diverse kinds of AFS (Kumar et al. 2012). These include the tropical, subtropical, and temperate AFS. India, with a geographical area of 329 million hectares, features 20 diverse agroecological regions each with an array of AFS (Table 1). Many of these are indeed traditional systems, practiced since time immemorial. For instance, homegardening and rearing of silkworm (*Bombyx* spp.) and lac insect (*Kerria lacca*) were practiced in the Indian subcontinent during the epic era of *Ramayana* and *Mahabharat* (7000 and 4000 BCE, respectively; Puri and Nair 2004). The travelogue of *Ibn Battuta* (Persian traveler; 1325–1354 CE) provides the earliest literary evidence of agroforestry from peninsular India and it mentions that in the densely populated and intensively cultivated landscapes of Malabar Coast, coconut (*Cocos nucifera*) and black pepper (*Piper nigrum*) were prominent around the houses (Randhawa 1980). The ecoclimatic situations under which agroforestry is practiced in India are also correspondingly diverse and range from the humid tropical valleys through to the high-elevation temperate regions and from humid tropical forests to the semiarid and arid drylands, including both irrigated and rain-fed ecosystems.

The predominant Indian AFS include agrisilviculture involving poplar (*Populus deltoides*; Fig. 3); *Eucalyptus* spp.; plantation agriculture involving coffee (*Coffea* spp.; Fig. 4), tea (*Camellia sinensis*; Fig. 5), cacao (*Theobroma cacao*), and spices (e.g., black pepper, cardamom, or *Elettaria cardamomum*) in association with a wide spectrum of trees (planted as well as trees in the natural forests); betel vine (*Piper betel* L.) + areca palm (*Areca catechu*); intercropping systems with coconut, Para rubber (*Hevea brasiliensis*), and other trees; commercial crop production under the shade of trees in natural forests (e.g., cardamom; Fig. 6); homegarden systems; and parkland systems. Table 1 provides a detailed account on this, agroecological region-wise. Deliberate growing of trees on field bunds (risers) and in agricultural fields as scattered trees and the practice to utilize open interspaces in the newly planted orchards and forests for cultivating field crops are also widespread in the Indian subcontinent (Singh 1987). In the relatively bigger landholdings of Himachal Pradesh, agri-horticulture is widespread, and in the northern and southern aspects, apple trees (*Malus domestica*) dominate. Growing arable crops in association with alder (*Alnus nepalensis*) is a remunerative AFS in the northeastern hill region of the country. Indeed, alder-based production system is an outstanding example of sustainable land use that stood the test of time in many parts of eastern Himalayas. Kumar et al. (2018) recently reviewed the literature on agroforestry in the Indian Himalayan region.

The traditional land-use systems, however, have been transformed over time—owing to the interplay of socioeconomic and technological factors. In particular, agricultural transformations brought about by market economies in the past, especially the incorporation of exotic commercial crops (e.g., *Hevea brasiliensis*), have led to the decimation of many traditional land-use systems (Kumar 2005). For example, the homegardens that constituted a predominant land-use activity in the

Table 1 Major agroforestry systems and practices in different agroclimatic regions of India

Sl. no.	Agroecological region	Agroforestry systems/ practices	Major tree and crop species
1.	Western Himalayas (cold region)	Agrisilviculture, agri-silvi-horticulture, boundary plantations, fruit tree orchards, silvopasture	**Forest trees**: Banj oak (*Quercus leucotrichophora*), birch (*Betula* spp.), black locust (*Robinia pseudoacacia*), black poplar (*Populus nigra*), brown oak (*Quercus semecarpifolia*), cherry elm (*Ulmus villosa*), Chilgoza pine (*Pinus gerardiana*), sea buckthorn (*Hippophae* spp.), chinar (*Platanus orientalis*), Chinese albizia (*Albizia chinensis*), chir pine (*Pinus roxburghii*), green oak (*Q. dilatata*), Himalayan alder (*Alnus nepalensis*), Himalayan elm (*Ulmus wallichiana*), Himalayan poplar (*Populus ciliata*), Himalayan mulberry (*Morus laevigata*), Indian horse chestnut (*Aesculus indica*), Indian willow (*Salix tetrasperma*), juniper (*Juniperus* spp.), tama bamboo (*Dendrocalamus hamiltonii*), pines (*Pinus* spp.), red cedar (*Toona ciliata*), tree of heaven (*Ailanthus altissima*), tree rhododendron (*Rhododendron arboreum*), West Himalayan alder (*Alnus nitida*), wild olive (*Olea ferruginea*), white willow (*Salix alba*) **Fruit and nut trees**: Almond (*Prunus dulcis*), apple (*Malus pumila*), apricot (*Prunus armeniaca*), citrus (*Citrus* spp.), common pear (*Pyrus communis*), common or European plum (*Prunus domestica*), Indian gooseberry (*Emblica officinalis* syn. *Phyllanthus emblica*), peach (*Prunus persica*), pear (*Pyrus pyrifolia*), pomegranate (*Punica granatum*), walnut (*Juglans regia*) **Crops:** Medicinal and aromatic plants, millets, mustard (*Brassica juncea*), oats (*Avena sativa*), pulses, rice (*Oryza sativa*), vegetables, wheat (*Triticum aestivum*) **Grasses:** Setaria grass (*Setaria anceps*), *Panicum* spp., etc.

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Table 1 (continued)

Sl. no.	Agroecological region	Agroforestry systems/ practices	Major tree and crop species
2.	Western Plains and Kutch Peninsula (hot arid)	Agrisilvicultural system, agri-silvi-horticulture, boundary plantations, parkland systems, silvopasture	**Forest trees:** Babul (*Acacia nilotica*), cactus (*Opuntia* spp.), cassia tree *(Cassia siamea* syn. *Senna siamea*), desert teak (*Tecomella undulata),* horsebean (*Parkinsonia aculeata*), khejri tree (*Prosopis cineraria*), Persian neem (*Melia azedarach*), pongam tree (*Millettia pinnata* syn. *Pongamia pinnata*), sicklebush (*Dichrostachys cinerea*) **Fruit and nut trees**: Ber or Indian jujube (*Ziziphus mauritiana*), date palm (*Phoenix dactylifera*), common fig (*Ficus carica*), jamun (*Syzygium cumini*), phalsa (*Grewia asiatica*) **Crops:** Maize (*Zea mays*), pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*), sesame (*Sesamum indicum*), foxtail millet (*Setaria italica* syn. *Panicum italicum*) **Vegetables**: Cluster bean (*Cyamopsis tetragonoloba)*, cowpea (*Vigna unguiculata*), watermelon (*Citrullus lanatus*), round melon (*Cucumis melo*), long melon (*Cucumis melo* var. *utilissimus*)
3.	Deccan Plateau 7 (hot arid)	Agri-horticulture, agrisilviculture, block planting, boundary planting, silvopasture	**Trees:** Anjan (*Hardwickia binata*), babul, casuarina (*Casuarina equisetifolia*), eucalyptus (*Eucalyptus tereticornis*), jujube (*Ziziphus nummularia*), khejri, mesquite (*Prosopis juliflora*), mahua (*Madhuca longifolia*), neem (*Azadirachta indica*), Persian neem, safed khair (*Acacia ferruginea* syn. *Senegalia ferruginea*), siris tree (*Albizia lebbeck*), white-bark acacia (*Acacia leucophloea* syn. *Vachellia leucophloea*) **Fruits:** Custard apple (*Annona squamosa),* guava (*Psidium guajava*), Indian gooseberry, lotebush (*Ziziphus nummularia*), mango (*Mangifera indica*), tamarind (*Tamarindus indica*) **Crops**: Cowpea, finger millet (*Eleusine coracana*), groundnut (*Arachis hypogaea*), legumes, millets, pigeon pea (*Cajanus cajan*), pearl millet, rice, seasonal grasses, sorghum

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Table 1 (continued)

Sl. no.	Agroecological region	Agroforestry systems/ practices	Major tree and crop species
4.	Northern Plains (Upper Gangetic; semiarid to subhumid)	Agri-horticulture, agrisilviculture, agri-silvi-horticultural system, silvopasture, parkland systems	**Trees**: Arjun (*Terminalia arjuna*), babul, citrus, eastern poplar (*Populus deltoides*), eucalyptus, Indian tree of heaven (*Ailanthus excelsa*), Indian gooseberry, khejri tree, mesquite, miswak (*Salvadora persica*), pongam oil tree, sesban (*Sesbania sesban*), shisham (*Dalbergia sissoo*), *tamarisk* (*Tamarix articulata*) **Crops:** Barley (*Hordeum vulgare*), black gram (*Vigna mungo*), berseem (*Trifolium alexandrinum*), cowpea, cluster bean, green gram (*Vigna radiata*), lentil (*Lens culinaris*), marigold (*Tagetes erecta*), mint (*Mentha piperita*), mustard, oats, pearl millet, pigeon pea, potato (*Solanum tuberosum*), taro (*Colocasia esculenta*), sorghum, sugarcane (*Saccharum officinarum*), rice, sesame, turmeric (*Curcuma longa*), wheat **Fodder crops**: Buffel grass, birdwood grass, blue panic grass (*Panicum antidotale*), butterfly pea (*Clitoria ternatea*), Caribbean stylo, cowpea, Napier grass (*Pennisetum purpureum*), Sewan grass (*Lasiurus scindicus*)
5.	Northern Plains (Rajasthan Upland and Gujarat Plains; hot semiarid)	Agrisilvicultural system, parkland systems, silvipasture	**Trees:** Anjan, babul, ber, banwali (*Acacia jacquemontii* syn. *Vachellia jacquemontii*), casuarina, citrus, common bamboo (*Bambusa vulgaris*), eucalyptus, gum arabic tree (*Acacia senegal* syn. *Senegalia senegal*), Indian gooseberry, jujube, large toothbrush tree (*Salvadora oleoides*), khejri, lotebush, mango, sapota, subabul, umbrella thorn (*Acacia tortilis* syn. *Vachellia tortilis*) **Crops:** Barley, black gram, cluster bean, cowpea, chickpea (*Cicer arietinum*), green gram, mustard, pearl millet, pigeon pea, sesame, sorghum **Fodder species**: Buffel grass, desert grass (*Panicum turgidum*), marvel grass (*Dichanthium annulatum*), Sewan grass
6.	Northern Plains (Middle Gangetic Plain; hot semiarid to subhumid)	Agri-horticulture, agrisilviculture, agri-silvi-horticultural system, silvopasture, parkland systems	**Trees:** Arjun, babul, citrus, eastern poplar, eucalyptus, Indian gooseberry, Indian tree of heaven, khejri tree, mesquite, miswak, pongam tree, sesban (*Sesbania sesban*), shisham (*Dalbergia sissoo*), tamarisk **Crops:** Barley (*Hordeum vulgare*), berseem, black gram (*Vigna mungo*), cowpea, cluster bean, green gram (*Vigna radiata*), lentil (*Lens culinaris*), marigold, mint, mustard, oats, pearl millet, potato, taro (*Colocasia esculenta*), sesame, sorghum, sugarcane, turmeric, wheat **Fodder crops**: Buffel grass, birdwood grass, blue panic grass, butterfly pea, Caribbean stylo, cowpea, Napier grass, Sewan grass

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Table 1 (continued)

Sl. no.	Agroecological region	Agroforestry systems/ practices	Major tree and crop species
7.	Deccan Plateau (Malwa Plateau, Gujarat Plains, and Kathiawar Peninsula; hot, semiarid with moderately deep black soils and length of growing period (LGP) 120–150 days)	Agrisilviculture, agri-silvi-horticulture, boundary plantations, fruit tree orchards, live fence, horti-silvi-pasture, parkland systems, silvi-horticulture Silvopasture	**Trees:** Anjan, babul, ber, banwali, casuarina, common bamboo, eucalyptus, gum arabic tree (*Acacia senegal* syn. *Senegalia senegal*), henna (*Lawsonia alba*), horsebean, Indian laurel (*Terminalia elliptica*), large toothbrush tree, khejri, lotebush, Manila tamarind (*Pithecellobium dulce*), *Opuntia* spp., palmyra palm (*Borassus flabellifer*), Persian neem, pongam tree, sicklebush (*Dichrostachys cineraria*), siris tree, subabul (*Leucaena leucocephala*), spotted gliricidia (*Gliricidia sepium*), teak (*Tectona grandis*), umbrella thorn **Fruits trees:** Ber, common fig, custard apple, drumstick (*Moringa oleifera*), guava, Indian gooseberry, jamun, mango, orange (*Citrus reticulata*), phalsa, pomegranate, sapota (*Manilkara zapota*), tamarind **Crops:** Black gram, brinjal (*Solanum melongena*), chickpea, cluster bean, cowpea, curry leaf (*Murraya koenigii*), green gram, groundnut, lathyrus (*Lathyrus sativus)*, linseed (*Linum usitatissimum*), long melon, maize, okra (*Abelmoschus esculentus*), pearl millet, pigeon pea, rice, safflower (*Carthamus tinctorius*), sesame, sorghum, soybean (*Glycine max*), sunflower, sunn hemp (*Crotalaria juncea*) **Fodder species**: Buffel grass, desert grass (*Panicum turgidum*), marvel grass (*Dichanthium annulatum*), Sewan grass
8.	Deccan Plateau (hot semiarid with mixed red and black soils and LGP 120–180 days)	Agri-horticultural system, agrisilvicultural system, agri-silvi-horticulture, fruit tree orchards, horti-silvi-pasture, silvi-horticulture, silvopasture	**Trees:** Belliric myrobalan (*Terminalia bellirica*), eucalyptus, Indian laurel (*Terminalia elliptica*), mahua, Persian neem, pongam tree, shisham, subabul, tamarind, teak (*Tectona grandis*) **Fruit trees:** Custard apple, guava, Indian gooseberry, mango, orange (*Citrus reticulata*), sapota, tamarind **Crops**: Black gram, cowpea, curry leaf, finger millet, foxtail millet, groundnut, horse gram (*Macrotyloma uniflorum*), Indian aloe (*Aloe vera* syn. *Aloe barbadensis*), lathyrus, linseed, maize, pearl millet, safflower, rice, sorghum, sunn hemp **Fodder crops**: Hybrid Napier (*Pennisetum glaucum* × *P. purpureum*), stylo (*Stylosanthes guianensis*), desmanthus (*Desmanthus virgatus*)

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Table 1 (continued)

Sl. no.	Agroecological region	Agroforestry systems/ practices	Major tree and crop species
9.	Deccan Plateau (hot semiarid with red loamy soils and LGP 150–210 days)	Agrisilviculture, agri-silvi-horticulture, block plantations, fruit tree orchards, horti-pastural system, horti-silvi-pasture, silvi-horticulture, silvopasture	**Trees:** Agati (*Sesbania grandiflora*), casuarina, coconut (*Cocos nucifera*), East Indian *sandalwood* (*Santalum album*), eucalyptus, gmelina (*Gmelina arborea*), Indian laurel (*Terminalia elliptica*), jackfruit (*Artocarpus heterophyllus*), kapok (*Ceiba pentandra*), Malabar neem (*Melia dubia*), mahua, mulberry (*Morus alba*), palmyra palm, teak (*Tectona grandis*), shisham, silk cotton tree (*Bombax ceiba*), white-bark acacia **Fruit trees/crops:** Custard apple, guava, Indian gooseberry, mango, banana (*Musa* spp.), orange (*Citrus reticulata*), papaya (*Carica papaya*), pomegranate, lemon (*Citrus* spp.), sapota, tamarind **Crops**: Black gram, curry leaf, green gram, horse gram, lathyrus, linseed, maize, pigeon pea, rice, sorghum, sunn hemp **Oilseeds**: Groundnut, sesame, sunflower (*Helianthus annuus*), safflower **Vegetables:** Bitter gourd (*Momordica charantia*), bottle gourd (*Lagenaria siceraria*), ridge gourd (*Luffa acutangula*), snake gourd (*Trichosanthes cucumerina*) **Fodder crops:** African tall maize (*Zea mays*), buffel grass (*Cenchrus ciliaris*), birdwood grass (*Cenchrus setigerus*), Caribbean stylo (*Stylosanthes hamata*), desmanthus, hybrid Napier
10.	Eastern Plateau (Satpura Range and Mahanadi Basin; hot subhumid)	Agri-silvi-horticultural system, agrisilviculture	**Trees**: Anjan, arjun, babul, ber, eucalyptus, flame of the forest (*Butea monosperma*), gmelina, neem, pongam tree, sweet orange (*Citrus aurantium*), white siris (*Albizia procera*) **Fruit trees**: *Citrus* spp., guava, litchi (*Litchi chinensis*), mango, papaya **Crops**: Bottle gourd, fodder species, linseed, lentil, rice, mustard, okra, pointed gourd (*Trichosanthes dioica*)

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Table 1 (continued)

Sl. no.	Agroecological region	Agroforestry systems/ practices	Major tree and crop species
11.	Eastern Plateau (Bundelkhand Upland; hot subhumid with red and yellow soils and LGP 120–180 days)	Agrisilvicultural system, agri-horti-silviculture, boundary planting, homegardens, silvopastoral system	**Trees**: Anjan, arjun, babul, ber, banwali, casuarina, common bamboo, eucalyptus, flame of the forest, gmelina, gum arabic tree (*Acacia senegal* syn. *Senegalia senegal*), Indian gooseberry, large toothbrush tree, khejri, lotebush, neem, pongam tree, shisham, sweet orange, solid bamboo (*Dendrocalamus strictus, D. hamiltonii*), white siris, subabul, umbrella thorn **Fruit trees**: *Citrus* spp., guava, Indian gooseberry, Indian date (*Phoenix sylvestris*), litchi, mango, papaya, sapota **Crops**: Barley, black gram, bottle gourd, chickpea, cluster bean, cowpea, green gram, green pea (*Pisum sativum*), lentil, linseed, mustard, okra, pearl millet, pigeon pea, pointed gourd, rice, sesame, sorghum, wheat **Fodder species**: Buffel grass, desert grass (*Panicum turgidum*), marvel grass (*Dichanthium annulatum*), Sewan grass
12.	Eastern Plateau (hot subhumid with red and lateritic soils and LGP 150–210+ days)	Agri-horticultural system, agrisilviculture, alley cropping, homegardens, silvopasture, lac cultivation, commercial forestry, windbreaks	**Trees:** Agati, Australian wattle (*Acacia auriculiformis*), belliric myrobalan (*Terminalia bellirica*), casuarina, chebulic myrobalan (*Terminalia chebula)*, coconut, eucalyptus, jackfruit tree, gmelina, guava, mangium (*Acacia mangium*), litchi, mango, mahogany (*Swietenia macrophylla*), orange, palmyra palm, papaya, shisham, som (*Machilus bombycina* syn. *Persea bombycina*), teak **Crops:** Arrowroot (*Maranta arundinacea*), black gram, forages, ginger, green gram, groundnut, mango ginger (*Curcuma amada*), mustard, pigeon pea, pineapple (*Ananas comosus*), pulses, rice, turmeric, vegetables, wheat
13.	Northern Plains (Lower Gangetic; hot, subhumid)	Agrisilviculture, agri-silvi-horticultural system, silvopasture, parkland systems, *Hevea*	**Trees:** Arjun, babul, citrus, eastern poplar, eucalyptus, khejri tree, mesquite, miswak, pongam tree, sesban (*Sesbania sesban*), tamarisk **Crops:** Berseem, cluster bean, cowpea, green gram, marigold, mint, mustard, oats, pearl millet, potato, taro, sorghum, sugarcane, turmeric, wheat **Fodder crops**: Buffel grass, birdwood grass, blue panic grass, butterfly pea, Caribbean stylo, cowpea, Sewan grass

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Table 1 (continued)

Sl. no.	Agroecological region	Agroforestry systems/ practices	Major tree and crop species
14.	Western Himalayas (warm to hot subhumid to humid)	Agri-silvi-horticulture system, agrisilviculture, agri-horticulture, agri-horti-silviculture, silvopasture	**Trees:** Arjun, axle wood tree (*Anogeissus latifolia*), babul, ber, bihul (*Grewia optiva*), cherry elm, Chinese albizia, chir pine, cutch tree (*Acacia catechu*), eastern poplar, East Indian sandalwood, eucalyptus, haldu (*Adina cordifolia*), Himalayan mulberry, Indian elm (*Holoptelea integrifolia*), Indian gooseberry, Indian willow, Indian tree of heaven, kachnar (*Bauhinia variegata*), kadam (*Neolamarckia cadamba*), lote tree or honeyberry (*Celtis australis*), mulberry, oaks (*Quercus* spp.), Persian neem, red cedar, sesbania (*Sesbania aegyptiaca*), siris tree, shisham, solid bamboo, soapberry (*Sapindus mukorossi*), subabul, teak, wild olive **Horticulture trees**: Apple, citrus, guava, Indian gooseberry, jackfruit, litchi, mango, papaya. **Crops:** Brinjal, cabbage (*Brassica oleracea var. capitata*), cauliflower (*Brassica oleracea var. botrytis)*, chilies (*Capsicum* spp.), French bean (*Phaseolus vulgaris*), green pea, maize, medicinal and aromatic plants, millets, mustard, oats, okra, onion (*Allium cepa*), pulses, potato, radish (*Raphanus sativus*), rice, tomato (*Solanum lycopersicum*), turnip (*Brassica rapa subsp. rapa*), wheat **Grasses:** Green foxtail (*Setaria* spp.), Guinea grass (*Panicum* sp.), Napier (*Pennisetum* spp.), etc.
15.	Bengal basin (hot, subhumid)	Agrisilvicultural system, agri-silvi-horticultural system, homegardens	**Trees:** Akil (*Dysoxylum binectariferum*), areca nut (*Areca catechu*), bamboo (*Bambusa balcooa, B. tulda*), coconut, kadam, Indian laurel (*Litsea glutinosa)*, sal (*Shorea robusta*), solid bamboo, white siris **Fruit trees**: Ber, litchi, guava, mango **Crops:** Banana, bottle gourd, cabbage, cauliflower, ginger (*Zingiber officinale*), groundnut, lentil, mustard, pineapple, pointed gourd, soybean, rice, turmeric

(continued)

Table 1 (continued)

Sl. no.	Agroecological region	Agroforestry systems/ practices	Major tree and crop species
16.	Assam and North Bengal Plains (warm humid to per humid)	Agrisilvicultural system, agri-silvi-horticultural system, homegardens	**Trees:** *Acacia* spp., *Albizia* spp., akil, areca nut, bamboos (*Bambusa balcooa, B. tulda, Dendrocalamus hamiltonii*), belliric myrobalan, chebulic myrobalan, common macaranga (*Macaranga peltata*), *Ficus* spp., gmelina, Indian laurel (*Litsea glutinosa*), kadam, kapok, mulberry, palmyra palm, Persian neem, rubber (*Hevea brasiliensis*), sal (*Shorea robusta*), semul (*Bombax ceiba*), solid bamboo, som, teak, white siris **Fruit trees**: Ber, *Ficus* spp., jackfruit, jamun, guava, litchi, mango, pomegranate, orange (*Citrus* spp.), papaya **Crops:** Banana, black pepper (*Piper nigrum*), betel leaf (*Piper betle*), bottle gourd, brinjal, cabbage, cauliflower, cucumber (*Cucumis sativus*), French bean, ginger, green pea, groundnut, knolkhol (*Brassica oleracea*), lentil, mustard, pineapple, pointed gourd, potato, pumpkin (*Cucurbita pepo*), rice, soybean, radish, sesame, tea (*Camellia sinensis*), tomato, turmeric
17.	Eastern Himalayas (warm per humid)	Agrisilviculture, hedgerow intercropping, and many traditional systems	**Trees**: Agarwood (*Aquilaria malaccensis*), belliric myrobalan, Himalayan alder, Indian tree of heaven, champa (*Michelia champaca*), rubber, southern magnolia (*Magnolia* sp.), bamboos (28 bamboo species) **Medicinal plants**: Galangal (*Kaempferia galanga*), green chirayta (*Andrographis paniculata*), long pepper (*Piper longum*), patchouli (*Pogostemon cablin*), sarpagandha (*Rauwolfia serpentina*), sugandhmantri (*Homalomena aromatica*) **Crops:** Large cardamom (*Amomum* spp.), ginger, maize, pineapple, potato, rice, sweet potato (*Ipomoea batatas*), tea, turmeric, vegetables **Hedgerow species**: Eastern rattlepod (*Crotalaria tetragona*), gliricidia, large-leaf flemingia (*Flemingia macrophylla*), pigeon pea, true indigo (*Indigofera tinctoria*), white tephrosia (*Tephrosia candida*)
18.	North Eastern hills (Purvanchal; warm perhumid)	Agri-silvi-horticulture system, jhum cultivation, upland terrace farming	Trees: Apple, Himalayan alder, coffee (*Coffea arabica, C. canephora*), *Dipterocarps* spp., oak (*Quercus* spp.), orange, peach, pear (*Pyrus communis*), pines (*Pinus* spp.) **Crops**: Banana, chilies, cotton, ginger, large cardamom, maize, medicinal plants, millets, mesta (*Hibiscus sabdariffa*), pineapple, potato, rice, sweet potato, sesame, sugarcane, tea

(continued)

Table 1 (continued)

Sl. no.	Agroecological region	Agroforestry systems/ practices	Major tree and crop species
19.	Eastern Coastal Plains and Islands of Andaman and Nicobar (hot subhumid)	Agrisilviculture system, block planting, silvopasture, horti-pasture system, silvi-horticulture system	**Trees**: Australian wattle, casuarina, coconut, gliricidia, Indian tree of heaven, jackfruit, mangium, mango, white-bark acacia, subabul **Bamboos:** Brandisii bamboo (*Dendrocalamus brandisii*), chivari (*Dendrocalamus stocksii*) **Crops:** Black pepper, cowpea, finger millet, rice **Fodder:** Indian lovegrass (*Eragrostis pilosa*), mulberry (*Morus indica*), calliandra (*Calliandra calothyrsus*), shrubby stylo (*Stylosanthes scabra*), lovegrass (*Chrysopogon* sap), Napier
20.	Western Ghats (Coastal Plains and Western Hills; hot humid to perhumid)	Alley cropping, animal-based integrated farming systems, aquaculture, homegardens, improved fallows, live fences, multipurpose trees, plantation-crop combinations, rotational tree fallows	**Trees:** Areca nut, cacao (*Theobroma cacao*), cashew (*Anacardium occidentale*), coconut, gmelina, guava, Indian coral tree (*Erythrina indica*), jackfruit, Malabar tamarind (*Garcinia gummi-gutta*), mango, mahogany, maharukh (*Ailanthus triphysa*), oil palm (*Elaeis guineensis*), palmyra palm, rubber, subabul, teak, sapota, spotted gliricidia **Crops:** Black pepper, cardamom (*Elettaria cardamomum*), cassava (*Manihot esculenta*), clove (*Syzygium aromaticum*), elephant foot yam (*Amorphophallus paeoniifolius*), galangal, ginger, nutmeg (*Myristica fragrans*), rice, taro, turmeric, yams (*Dioscorea* spp.), vegetables **Fodder:** Mulberry, calliandra, subabul, hybrid Napier, guinea grass, stylo

Note: This list is compiled from various sources including Handa et al. (2019) and Kumar et al. (2018) and only the major species of agroforestry relevance are mentioned here

subcontinent, of late, have been showing symptoms of decline in some localities (Guillerme et al. 2011)—owing to rising population pressure and policies oriented towards land-use intensification to meet the rising demands for food grains (e.g., promoting monospecific production systems).

Environmental concerns such as global warming, land degradation, erosion of biodiversity, loss of wildlife habitats, and increased nonpoint source pollution of ground- and surface water, however, have provided impetus for the development and adoption of agroforestry around the world. Of late, economic incentives to the land managers have also acted as a major driver for promoting agroforestry. The poplar-based agroforestry in northern India, especially in the lowland "Tarai" areas at the base of the Himalayas, is a case in point (Fig. 7). An estimated 317,800 ha has been planted with *P. deltoides* in the country, of which 60% are block plantations and 40% are boundary plantations (National Poplar Commission of India 2012–15). Woodlots of other fast-growing trees such as eucalypts (*Eucalyptus* spp.), leucaena (*Leucaena leucocephala*), casuarina (*Casuarina equisetifolia*), mangium (*Acacia mangium*), Australian wattle (*Acacia auriculiformis*), *maharukh* (*Ailanthus triphysa*), and Malabar neem (*Melia dubia*) are also becoming increasingly popular among farmers in several parts of India.

Fig. 3 Agroforestry systems involving poplar (*Populus deltoides*), turmeric (*Curcuma longa*), mango (*Mangifera indica*; pruned trees), and litchi (*Litchi chinensis)* in Yamunanagar district, Haryana; note the systematic arrangement of different components (photo: BM Kumar)

Fig. 4 Coffee (*Coffea* spp.) agroforestry in Wayanad, Kerala; shade-loving coffee plants are raised in the understory of areca palms (*Areca catechu*) (photo: BM Kumar)

Fig. 5 Tea (*Camellia sinensis*) + silver oak (*Grevillea robusta*) trees (for partial shade) in Idukki district, Kerala (photo BM Kumar). Reprinted/adapted by permission from Springer (South Asian Agroforestry: Traditions, Transformations, and Prospects; Kumar et al. 2012)

Fig. 6 Cardamom (*Elettaria cardamomum*) with diverse kinds of shade trees in Idukki district, Kerala; principal trees include *Vernonia arborea, Artocarpus heterophyllus, Actinodaphne malabarica,* and *Persea macrantha* (photo: BM Kumar)

Fig. 7 Poplar (*Populus deltoides*) trees (leafless during winter) and understory wheat (*Triticum aestivum*) in Pantnagar, Uttarakhand (photo: BM Kumar)

Area Under Agroforestry in India

Although AFS abound in India, precise quantitative estimates on the extent of area under agroforestry are lacking—presumably because of the nonavailability of proper procedures for delineating the area influenced by trees in a mixed stand of trees and crops (Nair et al. 2009a). While in the multistrata systems (e.g., homegardens, shaded perennial systems, and intensive tree intercropping) the entire area occupied by such tree-crop combinations can be reckoned as agroforestry, most other agroforestry systems are rather extensive, where the components, especially trees, are not planted at regular spacing or density; for example, the parkland system and extensive silvopastures in central and northern India. The problem is acute in the case of practices such as windbreaks and boundary planting where the trees are planted at wide intervals or on farm boundaries. In the sequential agroforestry systems such as improved fallows and shifting cultivation, the beneficial effect of woody vegetation (in the fallow phase) on the crops in the sequence (in the cropping phase) may last for a variable length of time (years).

Given the diversity of AFS in India and the complexity of its components, it is a formidable task to determine the area under agroforestry. Nonetheless, some attempts have been made in this direction. Dhyani et al. (2013), using the databases of agricultural, horticultural, and forestlands of the country, deduced the area under agroforestry as 25.32 m ha, or 8.2% of the total geographical area of India with Maharashtra, Gujarat, and Rajasthan ranking high among the states. In another attempt, Rizvi et al. (2014), using geospatial techniques, estimated the area under agroforestry in India as 14.46 m ha and the potential area as 17.45 m ha. Forest Survey of India (FSI 2013), using digital interpretation of remote sensing data, however, estimated it as 11.54 m ha. Given the lack of consistency among the available estimates and the need to evolve climate change mitigation strategies through land-use management, it is imperative to estimate the area under agroforestry in India more precisely; however, such efforts are still rudimentary.

Agroforestry for Climate Change Mitigation and Adaptation

Agroforestry provides an excellent opportunity for combining the twin aims of climate change mitigation (technological changes and substitution that reduce GHG emissions by averting emissions and sequestering GHGs) and adaptation (evolving approaches to reduce the harmful effects of climate change). In addition to its potential for reducing atmospheric CO_2 levels, AFS play an important role in reducing vulnerability of agricultural production systems to climate change (i.e., imparting increased resilience); they also increase livelihood security of the dependent populations. Given such advantages, the importance of promoting agroforestry in the country cannot be overemphasized. In particular, there is scope for conversion of wastelands and grasslands to agroforestry, which according to IPCC (2007) has huge potential to absorb CO_2 from the atmosphere. There are about 120 million hectares of degraded lands in India (ICAR-NAAS 2010) and a significant chunk of that could probably be converted into agroforestry. While the potential for agroforestry in India is enormous, there are also challenges such as dearth of quality planting materials, lack of credit and marketing facilities, meager insurance cover, and weak extension, which hamper the adoption of AFS. To capitalize on the ecological and production functions of agroforestry, the Government of India launched the landmark National Agroforestry Policy in 2014 (http://www.indiaenvironmentportal.org.in/content/389156/national-agroforestry-policy-2014/), which aims to mainstream tree growing on farms and meet a wide range of developmental and environmental goals.

Vegetation Carbon Sequestration Potential of AFS in India

Agroforestry systems, which occur under diverse ecological conditions in India, offer immense scope for enhancing carbon stocks in the terrestrial ecosystems. During photosynthesis, atmospheric CO_2 is fixed as C in vegetation, detritus, and soil pools for “secure” storage. Vegetation carbon pools include those long-lasting products derived from biomass such as timber and belowground biomass such as roots. Nair et al. (2009a, 2010) reviewed the global literature on CSP of AFS and highlighted that aboveground CSP of AFS is tremendously variable, ranging from 0.29 to 15.21 Mg ha^{-1} $year^{-1}$. Dhyani et al. (2016) reviewed the Indian literature on this topic and found that the CSP values (aboveground) range from 0.25 to 19.14 Mg C ha^{-1} $year^{-1}$ for the tree components; and for bamboo-based systems, it may be as high as 21.36 Mg C ha^{-1} $year^{-1}$ (Nath and Das 2012). A perusal of the data in Table 2, which summarizes the relatively recent studies on this, echoes the gross variability in CSP values of Indian AFS: aboveground C sequestration ranges from 0.23 to 23.55 Mg C ha^{-1} $year^{-1}$ and belowground (root) C sequestration varies from 0.03 to 5.08 Mg C ha^{-1} $year^{-1}$. Given the diverse nature of tree components involved, besides variations in ecoclimatic conditions, site quality, and stand management practices adopted, this is not unusual. The following section provides a brief account of the major factors influencing aboveground CSP of AFS.

Agroforestry Systems and the Nature of Components

As mentioned, the diverse range of ecoclimatic conditions and the disparate array of agroforestry systems and practices in India representing profound variability in species and management regimes result in enormous variability of CSP values. In general, woodlots of bamboos, *Acacia auriculiformis*, *A. mangium*, and *Populus deltoides* are characterized by relatively high CSP (Table 2). Likewise, boundary plantation of 8-year-old *P. deltoides* had lower carbon stocks (4.51 Mg ha^{-1}) than block plantations (28.67 Mg ha^{-1}) in the Central Himalayan region (Kanime et al. 2013) with carbon sequestration rates of 0.43 and 2.75 Mg C ha^{-1} $year^{-1}$, respectively. Mangalassery et al. (2014) found that silvopastoral systems involving *Acacia tortilis* and *Azadirachta indica* and grasses such as *Cenchrus ciliaris* and *C. setigerus* showed higher sequestration potential compared with systems containing only trees or pastures in the arid northwestern India.

While most AFS (e.g., multipurpose trees, silvopasture, energy plantations) have great potential for C sequestration, homegardens are unique in this respect. They not only sequester C in biomass and soil, but also conserve agrobiodiversity (Kumar 2006). Tilman et al. (1997) and Kirby and Potvin (2007) have suggested that plant assemblages with high species diversity may promote more efficient use of site resources compared with those of lesser diversity. It signifies that "biodiverse" systems such as tropical homegardens can maintain greater net primary production and consequently higher CSPs than AFS with fewer species. In a case study from peninsular Indian homegardens, Kumar (2011) found that average aboveground standing stock of C ranged from 16 to 36 Mg ha^{-1}. Structural attributes such as size of the homegardens, however, may alter the carbon sequestration rates; for example, small homegardens in the reported study showed higher C stocks on unit area basis than large- and medium-sized ones.

Table 2 Biomass (aboveground + roots) carbon sequestration potentials of some agroforestry systems in India

Agroforestry/ land-use system	Major system components	Stand characteristics	Method of estimation	Carbon sequestration potential[a] (Mg ha^{-1} $year^{-1}$)			Source
				Aboveground	Roots	Total	
Agri-horticulture, Tarai region, Central Himalaya	*Mangifera indica* + wheat (*Triticum aestivum*)	278 trees ha^{-1}, 15 years old[b]	Allometric equation	5.48	1.37	6.85	Adhikari et al. (2020)
	Populus deltoides + wheat	400 trees ha^{-1}; 8 years old		6.07	1.62	7.69	
Agrisilviculture, Chhattisgarh (humid and subhumid)	*Gmelina arborea* + soybean (*Glycine max*)	1000–2500 trees ha^{-1}; 4 years old	Destructive sampling	0.28–1.13	0.17–0.24	0.46–1.36	Swamy et al. (2003)
	Gmelina arborea + eight field crops	592 trees ha^{-1}; 5 years old	Destructive sampling	1.00	0.26	1.26	Swamy and Puri (2005)
Agrisilviculture: multipurpose tree and black pepper (*Piper nigrum*), Kerala (humid tropics)	*Casuarina equisetifolia*	1111 trees ha^{-1}; 22 years old	Destructive sampling	6.12	0.77	6.89	Kunhamu et al. (2018)
	Macaranga peltata			2.83	0.91	3.75	
	Ailanthus triphysa			2.68	0.52	3.20	
	Artocarpus heterophyllus			4.91	1.19	6.09	
	Acacia auriculiformis			5.66	1.37	7.03	
	Grevillea robusta			6.35	1.35	7.69	
Agrisilviculture/ silvoarable systems, arid western Rajasthan	*Prosopis cineraria* + crops	45 trees ha^{-1};19 years old	Allometric relationships			0.46	Tanwar et al. (2019)
	Hardwickia binata + crops	145 trees ha^{-1}; 19 years old	Allometric relationships			0.56	
Homegarden, Mizoram	Mixed-species stand	Young (<20 years) and old (>20 years) homegardens	Allometric relationships			2.46–4.11	Singh and Sahoo (2018)
Horticultural plantations, Central Himalayan Tarai region, Uttarakhand (Indo-Gangetic region)	*Litchi chinensis*	100 trees ha^{-1}; 7 years old	Nondestructive method			1.20	Kanime et al. (2013)
	Mangifera indica	100 trees ha^{-1}; 15 years old	Nondestructive method			1.80	
	Prunus salicina	400 trees ha^{-1}; 5 years old	Nondestructive method			1.61	

Hortipasture, arid western Rajasthan	*Ziziphus mauritiana* + grass	120 trees ha^{-1}; 19 years old	Allometric relationships			0.28	Tanwar et al. (2019)
Mine spoil reclamation, dry tropical region (Singrauli coalfield), Madhya Pradesh	*Dendrocalamus strictus* plantation	3999 green culms ha^{-1}; 3 years old	Harvest method	2.73	5.08	7.81	Singh and Singh (1999)
		10,854 green culms ha^{-1}; 5 years old		2.61	4.86	7.47	
Plantation forests, Himachal Pradesh (Northwestern Himalaya)	*Quercus leucotrichophora*	2320 trees ha^{-1}; 32 years old	Allometric relationships			3.47	Devi et al. (2013)
	Pinus roxburghii	1875 trees ha^{-1}; 32 years old				2.78	
	Acacia catechu	1342 trees ha^{-1}; 32 years old				0.97	
	Acacia mollissima	1217 trees ha^{-1}; 32 years old				2.9	
	Albizia procera	1603 trees ha−1; 32 years old				4.42	
	Alnus nitida	459 trees ha^{-1}; 32 years old				4.68	
	Eucalyptus tereticornis	2233 trees ha^{-1}; 32 years old				3.76	
	Ulmus villosa	1617 trees ha^{-1}; 22 years old				4.6	
Plantation forests, Chhattisgarh (humid and subhumid)	*Gmelina arborea*	625 trees ha^{-1}; 5 years old	Destructive sampling	1.57	0.38	1.95	Swamy and Puri (2005)
Plantations of bamboo, Barak Valley, Assam	Mixed patch of *Bambusa cacharensis*, *B. vulgaris*, and *B. balcooa*	Total density 11,030 culms ha^{-1}	Allometric relationships	18.93–23.55	–	–	Nath and Das (2012)

(continued)

Table 2 (continued)

Agroforestry/ land-use system	Major system components	Stand characteristics	Method of estimation	Carbon sequestration potential[a] (Mg ha^{-1} $year^{-1}$)			Source
				Aboveground	Roots	Total	
Shifting agriculture, Mizoram	Mixed-species stand	Young (<5 years) and old (>5 years) fallows	Allometric relationships			2.50–2.77	Singh and Sahoo (2018)
Silvopasture in arid western Rajasthan	Silvopasture: *Colophospermum mopane* + grass	19-year-old trees; 98 trees ha^{-1}	Allometric relationships			0.28	Tanwar et al. (2019)
Silvopasture, Kerala (humid tropics)	Coconut + *Calliandra calothyrsus*	Calliandra stand 17,777–27,777 plants ha^{-1}; 3 years old	Destructive sampling	1.49–2.06	0.19–0.24	1.68–2.29	Joy et al. (2019)
		Coconut: 173 palms ha^{-1}; 25 years old	From bole volume and density; destructive sampling of bunches and fronds	1.32–1.33	—	–	
	Coconut + mulberry (*Morus* spp.)	Mulberry 27,777–49,382 plants ha^{-1}; 3 years old	Destructive sampling	1.11–2.12	0.69–1.18	1.80–3.30	John et al. (2019)
		Coconut: 173 palms ha^{-1}; 25 years old	From bole volume and density; destructive sampling of bunches and fronds	1.25–1.30	–	–	

Silvopasture, Kurukshetra, sodic soils, semiarid region	*Acacia nilotica, Dalbergia sissoo, Prosopis juliflora* + grasses (*Desmostachya bipinnata* and *Sporobolus marginatus*)	1250 trees ha^{-1}; 6 years old	Allometric relationships	0.23–2.55	0.03–0.80	0.26–3.35	Kaur et al. (2002)
Silvopasture, hot semiarid Rajasthan	*Hardwickia binata* + *Cenchrus setigerus*	333–666 trees ha^{-1}; 30 years old	Allometric relationships			0.75–1.06	Gupta et al. (2019)
Silvopasture, arid northwestern India, Gujarat	*Acacia tortilis*	278 trees ha^{-1};10 years old	Harvest method	0.5	0.10	0.6	Mangalassery et al. (2014)
	Azadirachta indica			0.29	0.07	0.36	
	Acacia tortilis + *Cenchrus ciliaris*			0.51	0.18	0.69	
	A. tortilis + *C. setigerus*			0.49	0.12	0.61	
	A. indica + *C. ciliaris*			0.35	0.14	0.49	
	A. indica + *C. setigerus*			0.37	0.12	0.49	

(continued)

Table 2 (continued)

Agroforestry/ land-use system	Major system components	Stand characteristics	Method of estimation	Carbon sequestration potential[a] (Mg ha^{-1} year^{-1})			Source
				Aboveground	Roots	Total	
Woodlots, humid tropics, Kerala	*Acacia auriculiformis*	Block plantations; 2500 trees ha^{-1}; 9 years old	Destructive sampling	19.11	0.99	20.10	Kumar et al. (1998)
	Ailanthus triphysa			2.67	0.41	3.08	
	Artocarpus heterophyllus			5.12	0.56	5.69	
	Artocarpus hirsutus			3.89	0.62	4.51	
	Casuarina equisetifolia			5.62	0.31	5.93	
	Leucaena leucocephala			1.44	0.18	1.62	
	Paraserianthes falcataria			10.96	0.77	11.72	
	Phyllanthus emblica			4.52	0.70	5.22	
	Pterocarpus marsupium			4.08	0.41	4.48	
	Acacia mangium	625–5000 trees ha^{-1}; 12 years old	Destructive sampling	4.17–8.97	1.37–3.71	5.55–12.68	Rocha et al. (2017)
	Grevillea robusta	460 trees ha^{-1}; 21 years old	Destructive sampling	1.49	0.38	1.87	Thakur et al. (2015)
	Acacia mangium	625–5000 trees ha^{-1}; 6.5 years old	Allometric equation	5.53–10.22	0.83–2.37	6.37–12.59	Kunhamu et al. (2011)
Woodlot, arid western Rajasthan	*Acacia tortilis*	Farm forestry; 116 trees ha^{-1}; 19 years old	Allometric relationships			1.65	Tanwar et al. (2019)
Woodlots, bamboo, Assam	*Schizostachyum dullooa*	Block plantation; 4 years old	Allometric relationships	0.9			Singnar et al. (2017)
	Pseudostachyum polymorphum	Block plantation; 4 years old		0.9			
	Melocanna baccifera	Block plantation; 4 years old		2.05			

Woodlot, Central Punjab (Trans-Gangetic plains)	*Populus deltoides*	Block plantation, 500 trees ha^{-1}; 6 years old	Allometric relationships	11.0	–		Gera et al. (2011)
		Boundary planting, 250–290 trees ha^{-1}; 6 years old		6.2	–		
Woodlot, Tarai Uttarakhand (Western Himalayan foothills)	*P. deltoides*	500 trees ha^{-1}; 11 years old		8.19			Arora et al. (2014)
Woodlots, Central Himalayan Tarai region, Uttarakhand (Indo-Gangetic region)	*P. deltoides*	Block plantation, 500 trees ha^{-1}; 8 years old	Destructive method			3.58	Kanime et al. (2013)
		Boundary planting; 70 trees; 8 years old				0.56	
	Eucalyptus tereticornis	Boundary planting; 120 trees ha^{-1}; 10 years old				1.05	
	Dalbergia sissoo	Block plantation, 1666 trees ha^{-1}; 10 years old				4.34	
Woodlot, Pantnagar, Uttarakhand	*P. deltoides*	200–1000 trees ha^{-1}; 8 years old	Allometric equation	3.63–8.99	–		Pingale et al. (2014)

(continued)

Table 2 (continued)

Agroforestry/ land-use system	Major system components	Stand characteristics	Method of estimation	Carbon sequestration potential[a] (Mg ha^{-1} year^{-1})			Source
				Aboveground	Roots	Total	
Woody perennial plantation agriculture, Northeast India	Para rubber (*Hevea brasiliensis*)	Monoculture; 714 trees ha^{-1}; 30 years old	Allometric equation	4.22	0.27	4.49	Brahma et al. (2018)
	Areca (*Areca catechu*)	Monoculture; 1560 palms ha^{-1}; 30 years old		0.73	0.17	0.90	
	Betel vine (*Piper betle*)-*jhum* (slash and mulching) agroforestry	Support trees: *Oroxylum indicum*, *Artocarpus chama*, *Mangifera indica*, *Areca catechu*, *Syzygium cumini*, *Musa* sp., and *Terminalia chebula*; 1350 trees ha^{-1}; 30 years old		4.02	1.02	5.04	

[a]Wherever biomass values had been reported, the C stocks were deduced as 50% of the biomass stocks

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

Ecoregions and Site Quality

Agroforestry systems on humid and tropical sites have higher potential to sequester carbon than those on arid, semiarid, and temperate sites. For example, AFS in the Western Himalayan and humid tropical regions showed higher CSP than those in the arid and semiarid regions (Table 2). Ajit et al. (2017a) using the dynamic carbon accounting model, CO2FIXv3.1, simulated the CSP of extant AFS in 26 districts of 10 selected states in India over a 30-year period. Comparisons across districts indicate that CSP ranged from 0.05 to 1.03 Mg C ha^{-1} year^{-1} with a mean value of 0.21 Mg C ha^{-1} year^{-1}. In another study involving the CO_2FIX model, these authors (Ajit et al. 2017b) showed that the CSP (tree, crop, and soil) of the extant AFS in Kupwara district of Kashmir valley involving species such as *Malus* (33.75%), *Populus* (29.91%), *Salix* (14.32%), *Juglans* (6.68%), and *Robinia* (4.7%) was 0.88 Mg C ha^{-1} year^{-1}. The CSP of an AFS, apart from the nature of the species involved (section "Species and Stand Age"), is driven by stand management (section "Silvicultural Management") and the prevailing ecological quality of the site (site quality). In spite of the potential benefits of site-specific ecological conditions in enhancing stand growth, there are no studies addressing the impacts of site quality on CSP of AFS.

Altitudinal ranges as reported by some authors significantly influence carbon density (amount of carbon per unit area for a given ecosystem or vegetation type). For example, Rajput et al. (2015) showed that biomass carbon density in Kullu valley (Northwestern Himalayas) increased from 1000 to 1600 m altitude and declined thereafter, presumably because of the lower cropping intensity and shorter growing period prevailing in the upper altitudinal zones, which depress carbon density. As a result, carbon stocks/density may decline in the aboveground biomass and woody debris at high elevations (>1600 m). However, the soil organic carbon (SOC) may increase with elevation, albeit modestly, owing to the lower organic matter decay rates prevailing at higher altitudes, offsetting any net change in total carbon density (vegetation + soil) with increasing elevation.

Species and Stand Age

Choice of species is an important criterion that determines the carbon stocks of AFS. Fast-growing species such as bamboos, acacia (*A. mangium*; *A. auriculiformis*), poplar, eucalypts, and leucaena are generally characterized by high CSPs (Table 2). Dhyani et al. (2016) also reported similar results. Russell and Kumar (2019) using the CENTURY model showed that inclusion of trees with traits that promoted C sequestration such as lignin content, along with the use of best management practices, resulted in higher biomass (and therefore higher CSP), suggesting that the nature of tree components, besides the tree and stand management practices, holds the key in this respect. While evaluating the carbon sequestration in an age series of *P. deltoides*, a short-rotation plantation crop in Tarai region of central Himalaya, Arora et al. (2014) found that the C sequestration rate (in wood products and by substitution of biomass for coal) in mature plantations (7–11 years) varied from 5.8 to 6.5 Mg C ha^{-1} $year^{-1}$. They also showed that aboveground carbon stocks increased from 0.5 Mg ha^{-1} in 1-year-old stands to 90.1 Mg ha^{-1} at 11 years of age, implying the dominant role of stand age in determining carbon stocks. Due to fast growth rate and adaptability to a range of environments, short-rotation plantations, in addition to high carbon storage, produce biomass for energy and contribute to reduced greenhouse gas emissions (Kaul et al. 2010). They also reported that high net annual carbon sequestration rates were achieved for fast-growing short-rotation poplar (8 Mg C ha^{-1} $year^{-1}$) and eucalyptus (6 Mg C ha^{-1} $year^{-1}$) plantations compared to the moderately fast-growing teak (*Tectona grandis*; 2 Mg C ha^{-1} $year^{-1}$) and the relatively slow-growing (long-rotation) sal (*Shorea robusta*) forests (1 Mg C ha^{-1} $year^{-1}$).

Silvicultural Management

Carbon sequestration being a function of tree growth and productivity, stand management practices (stand density regulation through thinning or through controlling initial planting density, pruning, fertilization, and weeding), apart from increasing the quality and quantity of production, may also promote C sequestration. In general, fast-growing tropical conifers and broad-leaved species respond favorably to silvicultural treatments. Information on the effect of planting density, crown pruning, and other management practices on the C accumulation potential, however, is scarce in the Indian context. In one such study, Kunhamu et al. (2011) found that biomass C stock of *A. mangium* trees was significantly altered by planting density and pruning treatments. The total tree (aboveground + roots) C sequestration was higher for the 5000 trees ha^{-1} treatment (81.82 Mg ha^{-1}) than that for the 625 trees ha^{-1} (41.39 Mg ha^{-1}) at 6.5 years of age. Rocha et al. (2017) using the same experimental stand reported that CSP ranged from 5.55 to 12.68 Mg ha^{-1} $year^{-1}$ at 12 years of age with denser stocks having substantially higher values (Table 2). In another study involving a 30-year-old *Hardwickia binata*-based AFS in the hot semiarid environment of Rajasthan, Gupta et al. (2019) also reported a significant impact of tree population density on carbon sequestration. Average biomass carbon sequestered per tree (118.44 ± 50.26 kg C $tree^{-1}$) was significantly more (44.5%) in the low-density (333 tree ha^{-1}) stand compared to the high-density (666 tree ha^{-1}) system. However, the total biomass carbon sequestered per hectare was significantly more (40.8%) in the high-density stand (31.6 ± 12.6 Mg C ha^{-1}), implying the silvicultural trade-off between maximization of individual tree growth and maximization of stand growth.

Soil Carbon Sequestration

Soil carbon pool refers to the relatively stable forms of organic and inorganic C in the soil, which account for about two-thirds of the total C sequestration. Biomass such as plant residues that is not removed from the site is eventually incorporated into the soil as soil organic matter (SOM). Apart from plant residues, tree roots (both coarse roots and fine roots), which represent about one-fifth to one-fourth of the total living biomass, signify another important input of organic matter into the soil. SOM plays a vital role in determining C storage in terrestrial ecosystems and in regulating atmospheric CO_2 fluxes. Soil C sequestration (SCS), therefore, is a significant greenhouse gas removal strategy (Lal 2008). However, literature on SCS potential of AFS in India, as it is generally the case elsewhere, is very scanty. Yet another problem is that many of the reported studies lack the required rigor (e.g., low sampling intensity, inadequate sampling depth, and/or inappropriate analytical procedures employed: section "Measurement and Estimation of C Sequestration in Agroforestry Systems"), making generalizations somewhat difficult.

Reviewing the global literature on SCS in AFS, Nair et al. (2009a) reported that the estimates vary greatly across systems, ecological regions, and soil types. The "best-bet estimates" ranged from 5–10 kg C ha^{-1} in about 25 years in extensive tree-intercropping systems on arid and semiarid lands to 100–250 kg C ha^{-1} in about 10 years in species-intensive multistrata shaded perennial systems and homegardens of the humid tropics (Nair et al. 2009b). In the Indian context, soil carbon stocks in AFS (0–100 cm depth) varied from 10.02 Mg C ha^{-1} for *Ziziphus mauritiana* + grass system in the arid western Rajasthan to as high as 229.5 Mg C ha^{-1} in the homegarden systems of Mizoram (Table 3). Like vegetation carbon stocks (Table 2), SCS potential was relatively low for the AFS in the arid and semiarid ecosystems compared to that of the humid tropical ecosystems (e.g., homegardens and woodlots; Table 3), which is consistent with the global trends mentioned above. Indeed, Saha et al. (2010) reported that soil carbon stocks of multistrata homegardens in central Kerala were next only to the adjacent tropical moist deciduous forest ecosystems. Despite the generally low SCS potential of the arid northwest Indian ecosystems, silvopastoral systems were found to be promising. For example, Mangalassery et al. (2014) reported that the SOC and net carbon sequestered were greater in the silvopastoral system in the arid parts of Gujarat, which had 36.3–60.0% more total SOC stock compared to the tree system and 27.1–70.8% more SOC than the pasture system.

The influence of AFS on SCS generally depends on the quantity and quality of biomass inputs provided by the tree and non-tree components of the system, besides soil attributes such as soil structure and aggregation. Taxa of the multipurpose tree (MPT), stand age, and stand density are key factors in this regard. Dhyani et al. (2020) reported that MPTs like *Alnus nepalensis*, *Parkia roxburghii*, *Michelia oblonga*, *Pinus kesiya*, and *Gmelina arborea* with high ground surface cover, constant leaf litterfall, and extensive root systems have huge potential for augmenting SOC levels and for enhancing soil aggregate stability. Silvicultural management of

Table 3 Recent reports on soil carbon stocks of agroforestry systems in India

Agroforestry system	Species	Stand age (year)	Location	Soil depth (cm)	Soil C (Mg ha^{-1})	Reference
Agri-horticulture	Apple (*Malus pumila*) + field crops, 1900–2170 m altitude	25	Kinnaur district, Himachal Pradesh (high-altitude dry temperate region)	0–100	146.52	Chisanga et al. (2018)
	Apple + field crops, 2170–2440 m altitude	20			122.79	
	Apple + field crops, 2440–2710 m altitude	18			186.0	
	Ziziphus mauritiana + crops	19	Arid western Rajasthan	0–100	11.49	Tanwar et al. (2019)
Agri-horti-silviculture	*Robinia* sp. (40 years) + Apple (25 years), *Ailanthus altissima* (40 years), *Salix tetrasperma* (50 years) + field crops, 1900–2170 m altitude	–	Kinnaur district, Himachal Pradesh (high-altitude dry temperate region)	0–100	122.22	Chisanga et al. (2018)
	Robinia sp. (40 years), apple, *Populus ciliata*, *Cedrus deodara* + field crops, 2170–2440 m altitude	–			128.31	
	Cedrus deodara + apple, *Pinus gerardiana* + field crops, 2440–2710 m altitude	–			125.58	
Agri-horti-silviculture	Mango (*Mangifera indica*) + teak (*Tectona grandis*) + okra (*Abelmoschus esculentus*)	–	Navsari, Gujarat	0–30	27.22	Singh et al. (2019)

Agrisilviculture	*Gmelina arborea* + soybean (*Glycine max*)	5	Raipur, Chhattisgarh	0–60	27.4	Swamy and Puri (2005)
	Mixed-species stands	–	Thane, Maharashtra	0–90	85.24	Newaj et al. (2017)
		–	Nasik, Maharashtra		80.82	
		–	Chittoor, Andhra Pradesh		55.84	
		–	Tumkur, Karnataka		62.57	
		–	Bellary, Karnataka		51.54	
		–	Mandi, Himachal Pradesh	–	22.28	Ajit et al. (2017b)
		–	Ludhiana, Punjab	–	9.12	
		–	Faizabad, Uttar Pradesh		4.6	
		–	Nawada, Bihar		16.67	
		–	Upper Gangetic plain, Hisar, Haryana		10.31	
		–	Gujarat plains and hills, Dahod, Gujarat		24.13	
		–	Desert arid and hot, Sikar, Rajasthan		4.28	
Agrisilviculture	Teak + sugarcane (*Saccharum officinarum*)	–	Navsari, Gujarat	0–30	23.81	Singh et al. (2019
Agrisilviculture/ silvoarable systems	*Prosopis cineraria* + crops	19	Arid western Rajasthan	0–100	10.33	Tanwar et al. (2019)
	Hardwickia binata + crops	19		0–100	10.82	

(continued)

Table 3 (continued)

Agroforestry system	Species	Stand age (year)	Location	Soil depth (cm)	Soil C (Mg ha^{-1})	Reference
Homegarden	Mixed species	–	Kerala (humid tropics)	0–100	103.32–119.30	Saha et al. (2010)
	Young (<20 years) and old (>20 years) homegardens	–	Mizoram	0–100	144.6–229.5	Singh and Sahoo (2018)
Homegarden	Multispecies	–	Navsari, Gujarat	0–30	31.03	Singh et al. (2019)
Horticulture	Apple (*Malus domestica*), 1900–2170 m altitude	25	Kinnaur district, Himachal Pradesh (high-altitude dry temperate region)	0–100	151.15	Chisanga et al. (2018)
	Apple, 2170–2440 m altitude	20			145.91	
	Apple, 2440–2710 m altitude	18			124.47	
	Litchi chinensis	7	Central Himalayan Tarai region, Uttarakhand (Indo-Gangetic region)	0–30	36.30	Kanime et al. (2013)
	Mangifera indica	15			40.70	
	Prunus salicina	5			36.97	
Horti-pasture	*Ziziphus mauritiana* + grass	19	Arid western Rajasthan	0–100	10.02	Tanwar et al. (2019)
Multipurpose tree-based black pepper system	*Casuarina equisetifolia*	22	Kerala (humid tropics)	0–100	63.62	Kunhamu et al. (2018)
	Macaranga peltata				68.64	
	Ailanthus triphysa				65.56	
	Artocarpus heterophyllus				64.42	
	Acacia auriculiformis				71.39	
	Grevillea robusta				61.26	

Silvopasture	Coconut + mulberry (*Morus* spp.)	3	Kerala (humid tropics)	0–40	32.88–54.65	John et al. (2019)
	Coconut + *Calliandra*	5		0–100	90.83–103.43	Joy et al. (2019)
	Pinus gerardiana, *Artemisia indica* (50 years) + *A. brevifolia* + grasses, 1900–2170 m altitude		Kinnaur district, Himachal Pradesh (high-altitude dry temperate region)	0–100	127.33	Chisanga et al. (2018)
	Pinus gerardiana + *A. brevifolia* (60 years) + grasses, 2170-2440 m altitude				95.35	
	Cedrus deodara + *A. brevifolia* + *Lespedeza gerardiana* + grasses, 2440-2710 m altitude				106.61	
	Colophospermum mopane + grass	19	Arid western Rajasthan	0–100	9.78	Tanwar et al. (2019)
	Hardwickia binata + *Cenchrus setigerus*	30	Hot semiarid environment, Rajasthan	0–30	22.94–23.25	Gupta et al. (2019)
Shifting agriculture fallows	Young (<5 years) and old (>5 years) fallows	–	Mizoram	0–100	102.6–144.3	Singh and Sahoo (2018)
Tropical moist deciduous forest	Mixed species	–	Southern Western Ghats	0–100	176.6	Saha et al. (2010)
Tropical wet evergreen forest	Mixed stand	–	Barak Valley region, Assam	0–100	133.08	Brahma et al. (2018)

(continued)

Table 3 (continued)

Agroforestry system	Species	Stand age (year)	Location	Soil depth (cm)	Soil C (Mg ha^{-1})	Reference
Woodlots (block plantations)	*Acacia tortilis*	19	Arid western Rajasthan	0–100	13.50	Tanwar et al. (2019)
	Grevillea robusta	21	Kerala (humid tropics)	0–100	77.56	Thakur et al. (2015)
	Acacia mangium	6.5		0–15 cm	27.02–34.64	Kunhamu et al. (2011)
	Quercus leucotrichophora	32	Himachal Pradesh (Northwestern Himalaya)	0–100	165.0	Devi et al. (2013)
	Pinus roxburghii	32			165.0	
	Acacia catechu	32			18.0	
	Acacia mollissima	32			195.0	
	Albizia procera	32			163.0	
	Alnus nitida	32			213.0	
	Eucalyptus tereticornis	32			164.0	
	Ulmus villosa	32			207.0	
	Gmelina arborea	5	Raipur, Chhattisgarh	0–60	36.1	Swamy and Puri (2005)
	Populus deltoides	11	Central Himalayan Tarai region, Uttarakhand (Indo-Gangetic region)	0–90	200.35	Arora et al. (2014)
	Populus deltoides	8		0–30	42.17	Kanime et al. (2013)
	Dalbergia sissoo	10			48.99	
Woodlots (boundary plantations)	*Populus deltoides*	8		0–30	41.83	
	Eucalyptus tereticornis	10			37.23	
Woody perennial plantation agriculture	Coconut (*Cocos nucifera*)	30	Kerala (humid tropics)	0–100	91.7	Saha et al. (2010)
	Para rubber (*Hevea brasiliensis*)	50			119.2	
	Coconut	25		0–40	41.81	John et al. (2019)
	Rubber	30	Barak Valley region, Assam	0–100	101.95	Brahma et al. (2018)
	Areca (*Areca catechu*)				96.18	
	Betel vine (*Piper betle*)- *jhum* (slash and mulching) agroforestry				115.85	

stands may also increase SOM prompting improved productivity, besides providing climate change mitigation effects—signifying a win-win situation. Very little, however, is known about the changes in soil C storage of MPT stands under differing stand density management regimes. In a solitary study, Kunhamu et al. (2011) reported that high stand densities (5000 and 2500 trees ha^{-1}) promoted SCS in 6.5-year-old *A. mangium* stands (31.79 and 34.64 Mg C ha^{-1}, respectively) in the top (0–15 cm) layer of the soil profile. Intense pruning (up to 50% of tree height), however, depressed overall tree growth and soil C stocks at high (5000 tree ha^{-1}) and low (625 tree ha^{-1}) stand densities, while at intermediate densities (2500 and 1250 tree ha^{-1}), pruning exerted a beneficial effect, signifying the need to maintain optimal stand densities, besides adopting appropriate tree management practices, for reaping carbon sequestration benefits.

The association between biodiversity (especially plant diversity) and SCS has become a topic of considerable scientific interest. Saha et al. (2009) reported that the soil C stock was directly related to plant diversity of homegardens. They found that homegardens with higher species richness and tree density than monocultural systems had greater soil carbon stocks, especially in the top 50 cm of soil. Overall, within the 1 m profile, soil C content ranged from 101.5 to 127.4 Mg ha^{-1}. Furthermore, small-sized gardens (<0.4 ha) that had higher tree density and plant species diversity had relatively more soil C per unit area (119.3 Mg ha^{-1}) than large-sized (>0.4 ha) gardens (108.2 Mg ha^{-1}).

Higher species richness of tropical homegardens may also ensure greater stability of the SOM fractions, especially at lower soil depths. Undeniably, SOM represents a significant carbon store and can remain in the soil for extended periods as a part of soil aggregates. The recalcitrant fraction of SOM is "protected" from further rapid decomposition by biochemical recalcitrance, chemical stabilization, and physical protection (Christensen 1996; von Luetzow et al. 2008). Biochemical recalcitrance occurs when the chemical composition of SOM involves aromatic polymers and other structures that are difficult for microbes to break down (Christensen 1996). A familiar example is lignin, one of the main constituents of woody plants. Russell and Kumar (2019) in the modeling study mentioned earlier indicated that inclusion of trees with traits that promoted C sequestration such as lignin, along with the use of best management practices, resulted in higher soil C storage. Studies on aspects of SCS and factors leading to aggregate formation and stability are scarce in the Indian context.

Measurement and Estimation of C Sequestration in Agroforestry Systems

Yet another factor that determines the magnitude of soil and vegetation carbon sequestration is the methods employed for estimating vegetation CSP and SCS. Biomass is often taken as a surrogate of total C and the aboveground CSP values are typically the direct spin-offs of biomass measurements made either through destructive procedures or by employing allometric equations (Table 2). To derive carbon stocks, the amount of harvested and standing biomass is summed up assuming that 50% of the biomass comprises C, which however is variable depending on tissue types. Whole-tree harvest procedures for biomass estimation are also cumbersome. General allometric equations (Brown 1997; Piccard et al. 2012; Chave et al. 2014) are, therefore, widely employed in forestry, and are recommended by UNFCCC (2006) for tree biomass estimation in AFS also. Biomass estimation equations, however, vary with species, age, bole shape, and/or bole wood density. This has created the dilemma of whether to use the generalized equation for tree biomass estimation in AFS or not. Clearly, there is a need to develop a robust generic allometry that accounts for the heterogeneity of tree diversity throughout the landscape (Kuyah et al. 2012a).

As mentioned, often equations built for predicting biomass of forest trees are used in AFS. Variations in tree management, however, can be a concern, which limit the use of standard allometric equations developed for forests in agroforestry; for instance, trees in AFS may be pruned depending on management objectives or may have different growth forms due to differences in spacing compared to natural (forest) systems (Nair et al. 2009a). The determination of biomass production from AFS, therefore, is a challenging task and makes extrapolation from one system to others difficult and sometimes unrealistic (Nair 2012). Biomass regression equations, generalized for a geographic region, have been developed in a few cases to minimize errors in estimated biomass that result from such variability in sampled trees (e.g., Kumar et al. 1998). However, such location-specific allometric equations are not available for many agroforestry tree species.

In addition to aboveground biomass fractions, belowground net primary productivity (biomass) is a major pool of C. However, belowground biomass is difficult to measure and only very few Indian studies have characterized that. Root-to-shoot ratio is commonly used to estimate belowground living biomass. The ratios, however, differ substantially among species and across ecological regions, posing a serious problem in estimating belowground C sequestration in living biomass. Allometric equations for predicting root biomass have been constructed internationally (e.g., Kuyah et al. 2012b), but they are yet to gain popularity.

Apart from the root biomass, organic C occurs in soils as microbial biomass, and as SOM in labile and recalcitrant forms. The intricate interactions among these different forms make the measurement of SCS also a formidable task. The Walkley-Black (WB) procedure (Walkley and Black 1934) has been parsimoniously employed for SOC determination in India and elsewhere; it involves digestion of organic matter in the sample through oxidation with potassium dichromate. Although fast, convenient, and inexpensive, it is semiquantitative in nature and does not completely recover the organic carbon in soil (Abraham 2013). In fact, complete oxidation of SOC does not take place and variable levels of carbon recoveries have been reported (e.g., 60–86%: Nelson and Sommers 1996), implying that underestimation of SOC is in the WB procedure. The problem of incomplete digestion of the organic matter in the WB method, however, has been partially resolved by supplying external heat during sample digestion in the modified WB protocol (Nelson and Sommers 1996). Dry combustion methods, widely used for routine laboratory analysis, are considered to be the "gold standard" and superior to wet digestion (Nayak et al. 2019). Spectroscopic techniques for sensing of SOC are also evolving rapidly; nevertheless, the conventional methods will continue to be used in the near future despite their limitations (Nayak et al. 2019). Another major issue is the lack of uniformity in soil sampling, especially the depth of sampling (see Table 3). Although this problem is universal in nature (Nair 2012), it is more acute in the Indian context. Most soil studies are restricted to the surface soil layers, i.e., to 20 or 30 cm depth. In view of the fact that tree roots extend to deeper soil horizons, and the role of subsoil in long-term stabilization of C, the need for sampling the deeper layers of the soil profile cannot be overemphasized. Overall, a uniform set of methods and procedures are not available for estimating C sequestration in AFS. Wide variations also exist in the procedures used for soil sampling and analysis, which can greatly affect the conclusions made when comparing the differences under various management practices, soils, environments, and social conditions (Nair 2012).

Concluding Remarks

Agroforestry systems abound in India with profound variability in the nature of components and their dynamics. Biological carbon sequestration (in vegetation and soil) is an intrinsic feature of agroforestry. Being a low-cost strategy, it has immense scope in the national climate change mitigation debate. In general, AFS with multistrata canopy architecture are characterized by higher CSP (aboveground) than those with simpler canopy structures. Likewise, AFS in the humid regions have higher aboveground CSPs than those in the arid and semiarid regions. Aboveground CSP values of Indian AFS reported in the literature range from 0.23 to 23.55 Mg C ha^{-1} $year^{-1}$. More than half of the C assimilated is also transported belowground via root growth and organic matter turnover processes (e.g., fine root dynamics, rhizodeposition, and litter dynamics), which enrich the soil organic carbon pool. Species diversity (especially plant diversity), stand age, and stocking levels, besides depth of sampling, are key determinants of SCS. Soil carbon stocks (0–100 cm depth) varied from 10.0 Mg C ha^{-1} to as high as 229.5 Mg C ha^{-1}, signifying great variability in SCS among the various ecoregions and AFS of India. Older, densely stocked (e.g., block plantations) and biodiverse AFS (e.g., multistrata homegardens) are more efficient in SCS. Much like the aboveground CSP, AFS in the arid and semiarid regions showed much less potential for SCS than those in the humid regions. Proper choice of AFS involving rapidly growing multipurpose tree species and adopting appropriate stand management practices are, therefore, key to enhancing the prospects of biological carbon sequestration and evolving national climate change mitigation strategies, which are cost effective.

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