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Review

Biomass Production and Carbon Sequestration Potential of Different Agroforestry Systems in India: A Critical Review

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Abstract: Agroforestry systems (AFS) and practices followed in India are highly diverse due to varied climatic conditions ranging from temperate to humid tropics. The estimated area under AFS in India is 13.75 million ha with the highest concentration being in the states of Uttar Pradesh (1.86 million ha), followed by Maharashtra (1.61 million ha), Rajasthan (1.55 million ha) and Andhra Pradesh (1.17 million ha). There are many forms of agroforestry practice in India ranging from intensified simple systems of monoculture, such as block plantations and boundary planting, to far more diverse and complex systems, such as home gardens. As a result, the biomass production and carbon sequestration potential of AFS are highly variable across different agro-climatic zones of India. Studies pertaining to the assessment of biomass and carbon storage in different agroforestry systems in the Indian sub-continent are scanty and most of these studies have reported region and system specific carbon stocks. However, while biomass and carbon stock data from different AFS at national scale has been scanty hitherto, such information is essential for national accounting, reporting of C sinks and sources, as well as for realizing the benefits of carbon credit to farmers engaged in tree-based production activities. Therefore, the objective of this study was to collate and synthesize the existing information on biomass carbon and SOC stocks associated with agroforestry practices across agro-climatic zones of India. The results revealed considerable variation in biomass and carbon stocks among AFS, as well as between different agro-climatic zones. Higher total biomass (>200 Mg ha^{-1}) was observed in the humid tropics of India which are prevalent in southern and northeastern regions, while lower total biomass (<50 Mg ha^{-1}) was reported from Indo-Gangetic, western and central India. Total biomass carbon varied in the range of 1.84 to 131 Mg ha^{-1} in the agrihorticulture systems of western and central India and the coffee agroforests of southern peninsular India. Similarly, soil organic carbon (SOC) ranged between 12.26–170.43 Mg ha^{-1}, with the highest SOC in the coffee agroforests of southern India and the lowest in the agrisilviculture systems of western India. The AFS which recorded relatively higher SOC included plantation crop-based practices of southern, eastern and northeastern India, followed by the agrihorticulture and agrisilviculture systems of the northern Himalayas. The meta-analysis indicated that the growth and nature of different agroforestry tree species is the key factor affecting the carbon storage capacity of an agroforestry system. The baseline data obtained across various regions could be useful for devising policies on carbon trading or financing for agroforestry.

Keywords: agroforestry; agro-climatic zones; biomass production; carbon storage; soil organic carbon

1. Introduction

Agroforestry is a collective name for a land-use system and technology whereby woody perennials are deliberately used on the same land management unit as agricultural crops and/or animals in some form of spatial arrangement or temporal sequence. In an agroforestry system there are both ecological and economic interactions between the various components [1]. On the other hand, forest includes natural forests and forest plantations. The term is used to refer to land with a tree canopy cover of more than 10 percent and an area of more than 0.5 ha. Forests are determined both by the presence of trees and the absence of other predominant land uses [2]. The estimated area under natural forest in India is 713,789 km^2 (21.71% of the total geographical area), while the area occupied by trees outside forest, as in agroforestry, is estimated to be 95,748 km^2, which accounts for 2.91% of the country's total geographical area [3].

Agroforestry systems in India include the use of trees grown on farms, community forestry and a variety of local forest management and ethno-forestry practices. The Indian Council of Agricultural Research has classified systems used in different agro-climatic zones as silvipasture, agrisilviculture or agrihorticulture, based on irrigated or rain-fed conditions. The practice of growing scattered trees on farmland is quite old. The trees are used for shade, fodder, fuel wood, food and medicinal purposes. Eucalypts and poplars are also grown in fields or on farm boundaries in the Punjab and Haryana. Traditional agroforestry systems include the practice of growing trees on farmlands used for fodder, fuel wood and vegetables, along with shifting cultivation in northeast India and Taungya cultivation. The Taungya cultivation system is practiced in Kerala, west Bengal, and Uttar Pradesh and to a limited extent in Tamil Nadu, Andhra Pradesh, Orissa, and Karnataka, as well as in the northeastern hill regions. In addition, home gardens, tea plantations, wood lots and alder (*Alnus* spp.)-based agriculture are other kinds of agroforestry systems prevalent in India [3,4].

India has pledged to reduce total projected carbon emissions by up to 1 billion tons by 2030 apart from other ambitious climate change targets agreed in the recently held COP26 summit in Glasgow. Among different mitigation and adaption options available, trees can play a pivotal role in global carbon flux and help store huge quantities of carbon for a long period of time. Agroforestry offers opportunities for delivering negative emissions while providing a variety of economic, social and environmental co-benefits. Although AFS are not fundamentally designed for carbon sequestration, many recent studies confirm, with evidential support, that AFS play a significant role in storing above ground biomass and carbon [5,6], belowground biomass and carbon in soil [7]. The increased production of biomass from AFS, and converting that into energy, has the potential to substantially offset the use of fossil fuels [8]. The area with the greatest potential for yielding biomass energy that could reduce net warming and avoid competition with food production is land that was previously used for agriculture or pasture but that has been abandoned and not converted to forest or urban areas [9].

India's nationally determined contribution (NDC), to sequester an additional 2.5 to 3 billion ton carbon dioxide (CO_2) equivalent by 2030under the Paris Climate agreement, can be achieved by integrating trees in multiple land uses [10,11]. A slight increase in carbon captured can help achieve India's climate change targets. A comparison of year 2019 to 2021 change in forest carbon stock revealed an increase of 79.4 million tons of carbon [3]. According to the *Restoration Opportunities Atlas of India*, 87 million hectares in area (25% of the total area) has the potential for carbon removal through agroforestry [10]. The role of agroforestry is highlighted as one of the best and cheapest solutions to address land degradation, pollution, climate change and food security and avoid environmental degradation under the Kyoto Protocol and many other international conventions [12].

The carbon sequestration potential (CSP) of agroforestry has been estimated ina number of studies over the years. The global assessment of carbon accumulation in agroforestry varied from 0.29 to 15.2 Mg C ha^{-1} $year^{-1}$ aboveground and 30 to 300 Mg C ha^{-1} $year^{-1}$ for soils down to 1 m depth [13]. Based on areas assessed as suitable for agroforest interventions, a carbon storage potential of 1.1–2.2 Pg. C has been estimated globally [14]. However, carbon stocks in agroforestry differ according to geographical location and climatic zone [15,16]. The biomass, carbon stock and carbon sequestration potential of different AF systems (AFS) in India also shows wide variation across different regions [17–22]. However, these differences in carbon density and carbon sequestration potential (CSP) among AFS are mainly due to climatic conditions and other site factors. India, as a large country, has diverse climatic conditions and, hence, variation in biomass production and carbon sequestration in AFS is very likely. In addition, use of different methodological approaches, such as biomass assessments based on standing tree volume, destructive sampling, allometry and spectral modelling using remote-sensing data, might also lead to differences in estimated biomass carbon values. Nevertheless, quantifying carbon stocks associated with tree growth at different spatial and temporal scales is a very challenging task due to planting geometry on farmlands, soil-edaphic conditions, local climatic conditions, tree management practices and inherent genetic parameters [11]. For instance, trees growing in natural or wild and native conditions have a greater height, a much larger trunk diameter and stronger physical and mechanical properties than trees growing in an agricultural landscape [23,24]. According to the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [25], scanty information is available concerning the biomass, carbon stock/sequestration potential of both natural forest and trees outside forests at national and regional levels.

The underlying goals of this paper are to: (i) review the information pertaining to biomass, biomass carbon, soil organic carbon (SOC) present indifferent AF systems, such as agrisilviculture, agrihorticulture, silvipasture, homegardens, plantation-based agroforestry, block plantations/woodlots and boundary plantations; and (ii) synthesize and furnish a comprehensive account of biomass carbon and SOC present for different agroforestry practices across different agro-climatic regions of India. This information would be useful for researchers and policy-makers as agroforestry is considered a negative emissions technology to tackle global climate change.

2. Materials and Methods

2.1. Data Collection

Data sources on biomass and C stocks in different AF systems practiced across the Indian sub-continent were assembled from studies published between 2000 to 2022. A systematic search identified 153 peer-reviewed studies that reported biomass and carbon, or soil organic carbon (SOC) in AFS. To avoid complications associated with the diverse terms used in AF, we restricted our search to seven major AFS. Sixteen AFS described in the literature were grouped into seven AFSs, namely, agrisilvicultural, agrihorticulture, silvopastoral, boundary planting, homegardens, plantation-crop-based AFS, and woodlots/block plantations. The studies were identified using the databases in Web of Science, Google search, and J-gate. The e-search was limited to papers whose title, abstract, or keywords mentioned the terms, "agroforestry", "boundary plantations", "agrisilviculture", "agrihorticulture", "block plantation", "plantation-crop-based AFS", "silvipasture" or "homegardens", alongwith, "soil", biomass, "carbon" or "SOC". From these studies, we collected information according to AFSs/ location, above ground biomass (ABG), below ground biomass (BGB), total vegetation biomass (TB) and total biomass carbon (TBC) and SOC. If needed, we calculated TB from data on BGB and ABG given in the paper. The database covered five regions, the northern Himalaya, the Indo-Gangetic plains, southern India, eastern and northeastern India, western and central India, covering twenty states, experiencing temperate to hot and humid tropical climates (Figure 1). AFS aged between 3–50 years were considered for analysis as woodlots can accumulate biomass and carbon in a short period of time; hence, three years was taken to be the minimum age.

Figure 1. Grouping of Indian states for evaluation of AFS carbon storage potential.

2.2. Data Analysis

Depending on the data reported in the literature, adjustments were made; for example, in studies which only reported AGB, we calculated BGB by multiplying AGB by a factor of 0.3 [26]. If TB was not reported, AGB and BGB were added with crop biomass to arrive at TB. Since the soil carbon data were found for varying depths, an extra step was performed. In order to enable a standardized analysis compatible with the IPCC guidelines, a quadratic density function (QDF) (Equation (1)) based on Smith et al. [27] was used.

$$\text{qdf}(d) = (22.1 - (33.3d^2)/2 + (14.9d^3)/3)/10.41667 = \text{depth (cm or m)} \quad (1)$$

2.3. Carbon Stock Data Collection, Standardization, and Estimation

Within the soil category, data on soil carbon density (SCD) were found in various forms, including root biomass, microbial biomass, and SOC. In this meta-analysis, we focused on SOC, which remains as a long-term sequestered C pool and is the main driver for various ecosystem health functions.

2.4. Descriptive Meta-Analysis

The mean above-ground biomass and carbon and SOC were calculated for AFS in the five regions identified. In addition, the mean, minimum and maximum biomass (below, above and total), biomass carbon and SOC were calculated for each AFS, in each region. The standard deviation for each AFS was calculated by region:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2}$$

where, s = standard deviation; $\sum$ = sum of values; x_i = value i; $\overline{x}$ = mean of x_i values; n = total number of x_i values.

3. Results

3.1. Biomass Production in Different Regions

Tree biomass assessment is an important facet of ecosystem productivity assessment and carbon budget modeling for national level planning [28]. Our meta-analysis revealed that eastern and northeastern (n = 5) and southern (n = 4) parts of India had a greater number of AFS with the least being found in the Indo-Gangetic region (n = 2) of India (Tables 1 and 2; Figures 2 and 3). The most prevalent agroforestry systems were identified based on published studies of the identified agroforestry systems in different regions. A survey of the peer-reviewed literature showed that the agrisilviculture system (n = 31) was dominant in the northern Himalayas, boundary plantations (n = 24) in eastern and northeastern India, block plantations (n = 71) in western and central India, and coffee plantations (n = 11) in southern India. In the northern Himalayas, studies reported the highest mean AGB in agrisilviculture systems (mean = 54.93 Mg ha^{-1}), and the highest BGB and TB (mean = 19.47 Mg ha^{-1} and 87.52 Mg ha^{-1}, respectively) in silvipasture systems. Similarly, silvipasture systems in the Indo-Gangetic region exhibited higher mean AGB, BGB and TB values (mean = 38.41, 9.32 and 50.32 Mg ha^{-1}, respectively). In eastern and northeastern India, block plantations had the highest accumulation of TB (mean = 220.20 Mg ha^{-1}), whereas the coffee plantations of southern India had the highest TB (mean = 279.2 Mg ha^{-1}). Western and central India had the highest TB in block plantations (mean = 120.09 Mg ha^{-1}). A region-based comparison of TB, irrespective of AFS, revealed lower biomass in the Indo-Gangetic region (mean = 37.28 Mg ha^{-1}) and higher biomass in southern Indian AFS (mean = 196.83 Mg ha^{-1}). The range of standard deviation for TB among AFS was least in the northern Himalayas (41.08 to 50.81) and maximal in the eastern and northeastern Indian regions (3.57–205.92) (Table 1).

Table 1. Variation in biomass components among different agroforestry systems across agro-climatic zones of India.

Agroclimatic Region/States	AFSs (N @)	AGB (Mg ha^{-1})		BGB (Mg ha^{-1})		TB (AGB + BGB + Crop Biomass) (Mg ha^{-1})	
		Range (Mean)	SD	Range (Mean)	SD *	Range (Mean)	SD
Northern Himalayas (Himachal Pradesh, Jammu and Kashmir and Uttrakhand)	Agrisilvicuture (31)	6.7–159.41 (54.93)	42.21	1.58–71.55 (14.87)	14.60	15.94–202.59 (64.67)	43.01
	Agri-horticulture (13)	15.79–137.56 (40.00)	32.90	2.40–34.39 (13.23)	11.20	18.19–171.95 (57.56)	50.81
	Silvipasture (4)	34.49–53.20 (43.85)	13.23	9.01–34.42 (19.47)	10.85	43.51–136.42 (87.52)	41.08
Indo-Gangetic region (Punjab, Haryana, Uttar Pradesh, Bihar)	Agrisilviculture (14)	17.16–62.8 (33.82)	20.25	3.62–3.84 (3.76)	0.10	4.96–137.3 (23.85)	30.64
	Silvipasture (17)	13.57–60.20 (38.41)	13.52	1.17–17.00 (9.32)	4.08	14.74–77.20 (50.72)	16.67

Table 1. *Cont.*

Agroclimatic Region/States	AFSs (N [@])	AGB (Mg ha^{-1})		BGB (Mg ha^{-1})		TB (AGB + BGB + Crop Biomass) (Mg ha^{-1})	
		Range (Mean)	SD	Range (Mean)	SD *	Range (Mean)	SD
Eastern and northeastern India (West Bengal, Odisha, Assam, Sikkam, Meghalaya, Manipur)	Agri-horticulture (14)	0.81–22.50 (5.57)	7.28	1.52–6.28 (3.63)	1.81	2.33–11.79 (6.41)	3.57
	Home gardens (11)	4.72–199.00 (52.54)	75.53	30.60–39.90 (34.69)	4.21	92.58–150.75 (121.67)	41.13
	Plantation-based agroforestry (18)	0.10–141.10 (40.46)	46.96	0.12–38.47 (13.36)	13.53	0.86–245.64 (87.16)	82.55
	Boundary plantation (24)	2.15–104.72 (16.96)	21.39	0.32–15.14 (2.52)	3.11	2.47–119.86 (19.48)	24.50
	Block plantation (13)	23.24–642.32 (186.20)	158.31	2.33–128.46 (25.33)	35.28	25.56–770.78 (220.20)	205.92
Western and central India (Rajasthan, Gujarat, Maharashtra and Madhya Pradesh)	Agrisilviculture (7)	5.63–19.24 (11.91)	6.28	-	-	3.20–89.8 (33.63)	38.38
	Agrihorticulture (19)	0.6–200.5 (81.05)	68.3	0.5–75.2 (24.60)	21.77	1.2–252.6 (78.95)	88.39
	Block plantation (71)	1.11–261.4 (79.24)	77.19	0.96–82.5 (21.84)	23.07	0.1–713.3 (120.09)	168.11
Southern India (Karnataka, Andhra Pradesh, Tamil Nadu, Kerala)	Agrisilviculture (6)	14.42–59.75 (37.37)	19.91	2.85–20.25 (11.87)	5.92	3.90–76.87 (35.96)	27.89
	Plantation crop-based agroforestry (10)	59.96–302.43 (174.96)	90.15	22.14–63.29 (41.29)	17.34	104.14–365.72 (232.38)	105.85
	Block plantation (5)	120.9–233.4 (170.9)	41.4	37.24–104.5 (69.49)	25.8	158.1–332.77 (239.8)	65.25
	Coffee plantation (11)	187.7–252.5 (221.5)	26.84	50.68–68.18 (59.38)	6.57	238.3–320.7 (279.2)	30.91

[@] Number of observations; * SD—Standard deviation.

Table 2. Variation in carbon storage between AFS prevalent in different regions of the Indian subcontinent.

Agroclimatic Region/States	AFSs (N [@])	TBC (Tree + Crop Biomass Carbon) (Mg ha^{-1})		SOC (Mg ha^{-1})	
		Range (Mean)	SD	Range (Mean)	SD *
Northern Himalayas (Himachal Pradesh, Jammu and Kashmir and Uttrakhand)	Agrisilviculture (31)	2.16–116.29 (32.61)	34.02	22.28–142.9 (58.07)	33.60
	Agrihorticulture (13)	8.05–81.68 (29.61)	19.77	43.67–151.7 (64.34)	33.33
	Silvipasture (4)	21.75–68.4 (44.59)	17.6	16.2–109.7 (47.63)	34.69
Indo-Gangetic region (Punjab, Haryana, Uttar Pradesh, Bihar)	Agrisilviculture (14)	2.24–19.9 (7.95)	4.96	4.25–48.98 (15.25)	12.52
Eastern and northeastern India (West Bengal, Odisha, Assam, Sikkam, Meghalaya, Nagaland, Manipur, Mizorum)	Home gardens (11)	30.76–140.0 (55.18)	27.74	42.8–119.5 (52.15)	22.27
	Plantation crop-based Agroforestry (18)	0.08–76.16 (26.42)	26.64	30.56–176.74 (96.53)	71.57
	Boundary plantation (24)	1.24–59.93 (9.74)	12.25	48.18–55.73 (51.95)	3.28
	Block plantation (13)	11.41–362.27 (98.99)	97.34	-	-
Western and central India (Rajasthan, Gujarat, Maharashtra and Madhya Pradesh)	Agrisilviculture (7)	1.5–42.9 (10.24)	11.54	4.28–24.13 (12.26)	7.08
	Agrihorticulture (19)	0.82–5 (1.84)	1.77	-	
	Block plantation (71)	0.05–353.2 (38.12)	69.07	0.1–63.80 (14.55)	19.57

Table 2. *Cont.*

Agroclimatic Region/States	AFSs (N [@])	TBC (Tree + Crop Biomass Carbon) (Mg ha^{-1})		SOC (Mg ha^{-1})	
		Range (Mean)	SD	Range (Mean)	SD *
Southern India (Karnataka, Andhra Pradesh, Tamil Nadu, Kerala)	Agrisilviculture (6)	1.57–39.31 (11.93)	10.50	1.23–77.56 (17.08)	26.33
	Plantation crop-based agroforestry (10)	48.95–169.24 (107.95)	49.51	61.26–71.39 (65.82)	3.65
	Block plantation (5)	14.75–152.16 (73.56)	41.13	-	-
	Coffee plantation (6)	112.04–150.74 (131.27)	14.53	78.70–170.43 (125.29)	34.66

[@] Number of observations; * SD—Standard deviation.

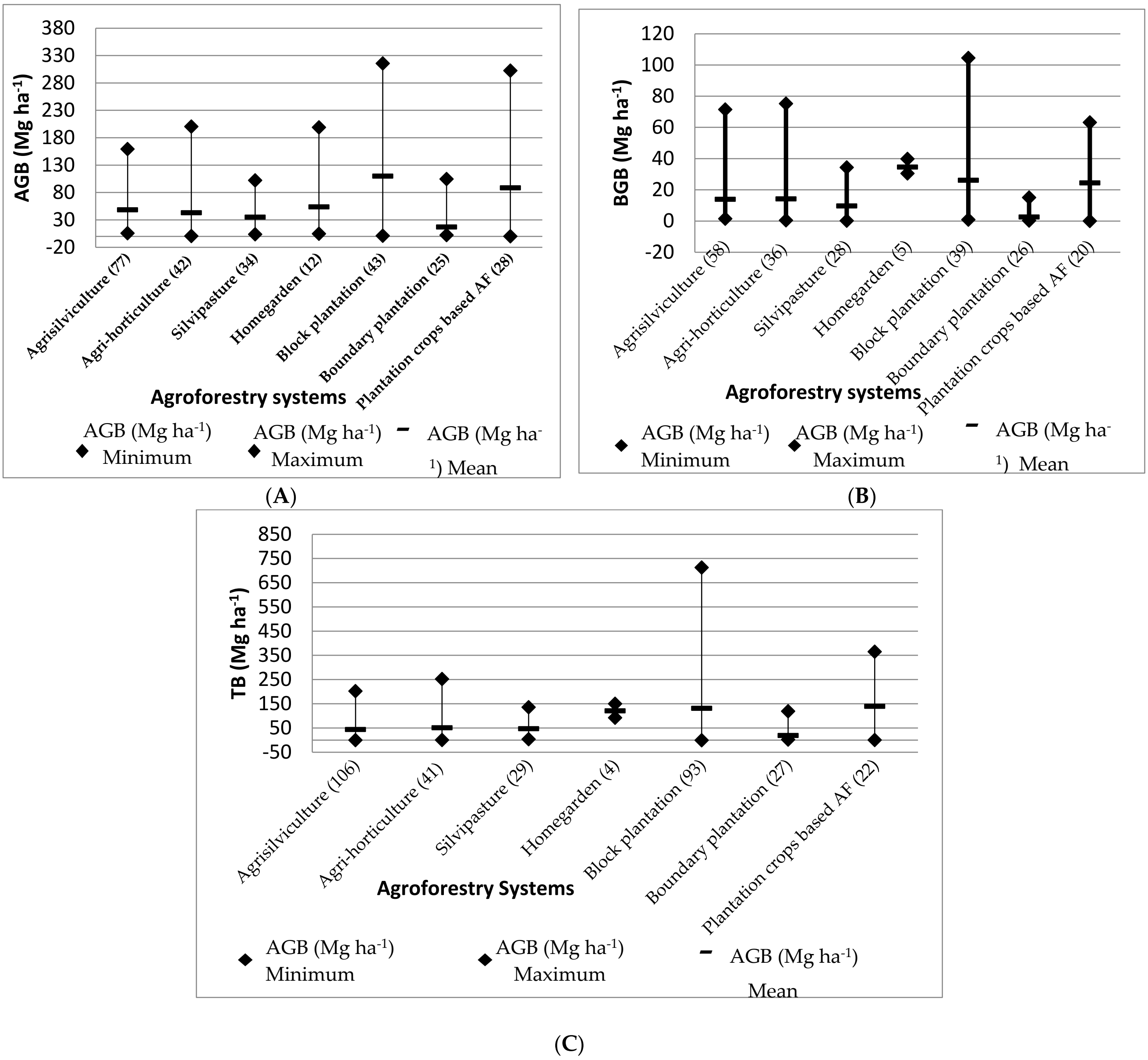
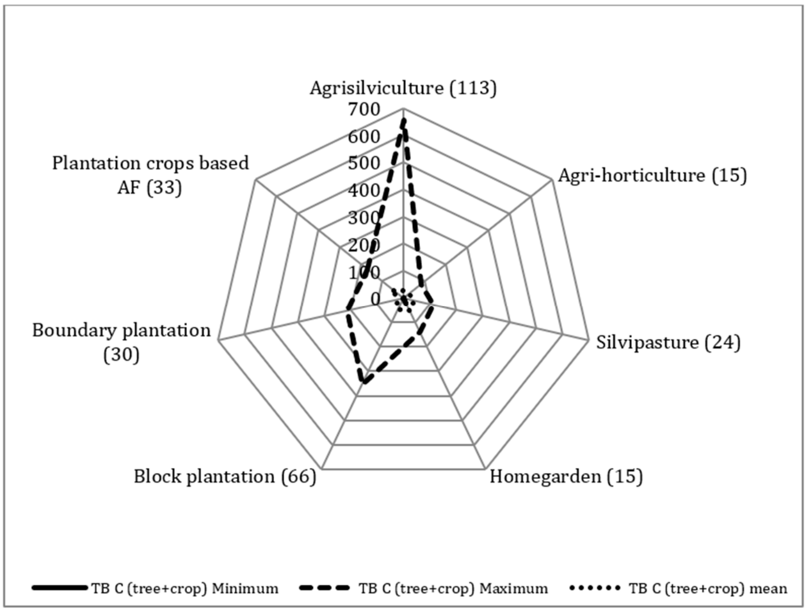
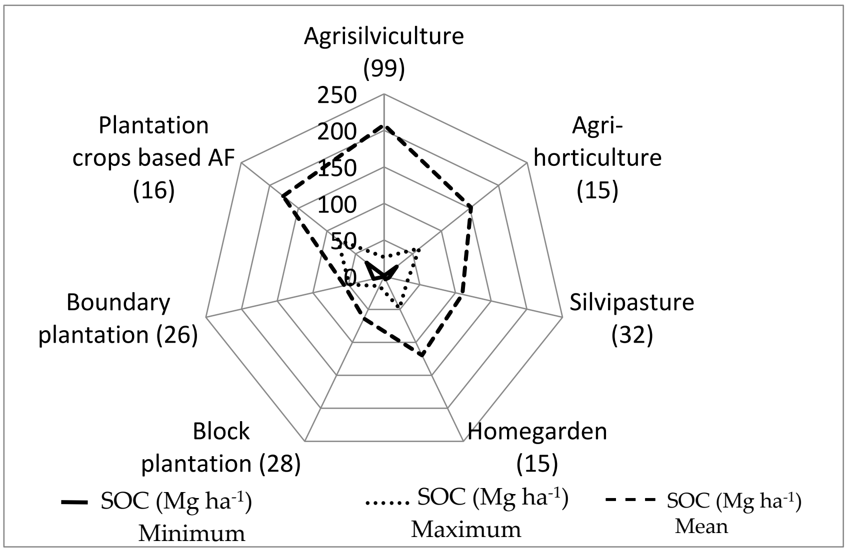


Figure 2. Range (minimum, maximum and mean) of biomass accumulation under different agroforestry systems irrespective of region. (**A**) Above ground biomass (Mg ha^{-1}); (**B**) Below ground biomass (Mg ha^{-1}); (**C**) Total biomass (Tree+crop) (Mg ha^{-1}).



(**A**)



(**B**)

Figure 3. TBC (**A**) and SOC (**B**) in different AFS in India. (**A**) Total biomass carbon (Mg ha^{-1}); (**B**) Soil Organic Carbon (Mg ha^{-1}).

3.2. Biomass and Soil Organic Carbon in Different Regions

In the northern Himalayan region, the mean total biomass carbon density (TBC) ranged from 29.61 to 44.59 Mg ha^{-1}, being higher in silvipasture systems (Table 2) than other AFS. The SOC was maximum in agrihorticulture systems (mean = 64.34 Mg ha^{-1}) and minimum in silvipasture (mean = 47.63 Mg ha^{-1}). In the Indo-Gangetic region, the mean TBC was 7.95 Mg ha^{-1}, with SOC of 15.25 Mg ha^{-1} in agrisilviculture systems. SOC was the least studied parameter in silvipasture and hence is not reported. In the eastern and north-eastern regions, total biomass carbon was higher in homegardens (mean = 55.18 Mg ha^{-1}), whereas SOC was higher in the plantation-based AF systems (mean = 96.53 Mg ha^{-1}). The block plantations in western and central India had maximum TBC and SOC (mean = 38.12 and 14.55 Mg ha^{-1}, respectively).In the southern peninsular region, coffee plantations had the highest TBC and SOC (mean = 131.27 and 125.29 Mg ha^{-1}, respectively). A region-based comparison showed lower mean TBC in the Indo-Gangetic region (mean = 7.95 Mg ha^{-1})

and higher mean values for AF systems in the southern Indian region (mean = 81.17 Mg ha^{-1}). Measured SOC followed the order: southern India > eastern and northeastern India > northern Himalaya > Indo-Gangetic region > western and central India (Table 2).

3.3. Biomass Production under Different AFS

Comparing prevalent agroforestry systems in India irrespective of region, it was found that AGB was highest in block plantations (mean = 109.8 Mg ha^{-1}), followed by plantation crop systems (mean = 88.49 Mg ha^{-1}), with the lowest AGB observed in boundary plantations (mean = 17.14 Mg ha^{-1}) (Figure 2A). BGB was highest in homegardens (mean = 34.68 Mg ha^{-1}), followed by block plantations (mean = 26.19 Mg ha^{-1}), and lowest in boundary plantations (mean = 2.67 Mg ha^{-1}) (Figure 2B). The total biomass followed the order of: plantation crop-based AF > block plantation > homegardens > agrihorticulture > silvipasture > agrisilviculture > boundary plantations (Figure 2C).

3.4. Biomass Carbon and SOC under Different AFS

Mean TBC among different AFS varied between 25.24 to 52.98 Mg ha^{-1}. The highest mean TBC was in homegardens and the lowest in boundary plantations (Figure 3A). The mean SOC among different agroforestry systems varied from 14.54 to 81.17 Mg ha^{-1}. The mean SOC followed the trend, plantation crop AF > agrihorticulture > boundary plantations > homegardens > silvipasture > agrisilviculture > block plantation (Figure 3B).

3.5. Biomass Production and Carbon Sequestration Potential through AFS in India

In this study, biomass, biomass carbon and SOC of AFSs, irrespective of region and agroforestry system, was estimated. The average AGB, BGB and TB of AFS reviewed were 56.5, 18.01 and 79.65 Mg ha^{-1}, respectively. The mean biomass carbon in TB was 38.44 Mg ha^{-1} and SOC was 44.83 Mg ha^{-1}; thus, total mean AFS carbon in the country was 83.27 Mg ha^{-1}. Considering the *Forest Survey of India* (FSI) [3] report, the area under trees outside forest is 95,748 km^2, thus the estimated carbon sequestration (Indian AFS) is 797.2 million Mg C. The *Restoration Opportunities Atlas of India*, estimates that an area of 87 million hectares (25% of the total area), has potential for carbon removal through agroforestry [10]. Taking an average rate of carbon sequestration of 83.27 Mg C ha^{-1}, as calculated in the present analysis, the potential carbon sequestration through agroforestry in India would be about 7244.49 million Mg C.

4. Discussion

Agroforestry has been popularly practiced in India as it provides a source of livelihoods, diverse goods and ecosystem services. It encompasses a wide range of systems, starting from basic shifting cultivation and Taungya, to complex homegardens, which are practiced almost throughout the Indian sub-continent, except in cold desert regions. The IPCC [29] has identified agroforestry as one of the land-use systems having the highest potential for carbon sequestration by 2040. It has been estimated that the mitigation potential of agroforestry over the next 50 years is of the order of 1.1–2.2 PgC in the form of biomass production and the soil organic pool [30]. At the national level, agroforestry offsets one–third (33%) of total GHG emissions from the agriculture sector per year, and mitigates more than 6% of total GHG emissions [31]. In this paper, the biomass production and carbon sequestration of agroforestry systems, such as agrisilviculture, boundary planting, homegardens, plantation crop-based AFS, agrihorticulture, silvopastoral systems, and woodlots/block plantations under Indian conditions was discussed.

4.1. Biomass Production

The highest numbers of dominant AFS were reported in southern India and the northeastern and eastern Indian regions. These regions of India receive very high rainfall and hence agrobiodiversity is high, which creates opportunities for maintaining varied plant diversity in AFS. The least number of AFS was reported in the Indo-Gangetic region.

This region is the food bowl of India and is highly fertile and highly populated. Farmers prefer cash crops in this region. The main system used in the region is the short rotation *Populus deltoides* and Eucalyptus spp. agrisilviculture system.

Considerable regional variability for biomass production was recorded in this study (Table 1). Higher total biomass (>200 Mg ha^{-1}) was observed in the humid tropics of India, which are prevalent in southern India and northeastern India. Coffee plantations had the highest mean biomass (279.2 Mg ha^{-1}), followed by block plantations/woodlots (239.8 Mg ha^{-1}) and plantation crop-based AF (232.38 Mg ha^{-1}) in southern India, or followed by block plantations/woodlots (220.2 Mg ha^{-1}) in the northeastern part of India. The effectiveness of agroforestry systems in biomass production and carbon storage depends on environmental and socio-economic factors, management regimes, tree growth characteristics and other factors [32]. In a humid tropic climate, the rainfall is abundant, thus water stress does not occur. In this climatic condition, the temperature generally remains between 20–30 °C, which is conducive to plant growth. However, in other regions, such as the northern Himalayas, the temperature descends to subfreezing, while, in western India, the temperature rises above 40 °C during summer, and these conditions hamper plant growth. The higher biomass in the coffee agroforests of southern peninsular India could be a reflection of management practices. Coffee farmers in this region, through intermittent crown pruning, retain large sized trees to provide shade to under-story vegetation [33]. Irrespective of the region, the mean AGB was lowest in boundary plantations followed by silvipasture systems (Figure 2A), and highest in block plantation/woodlots. This is because of the intrinsic nature of AFS, whereby the number of trees per hectare varies. Boundary plantations and silvipastures contain less trees, while block plantations have densely planted trees. The root proportion (read BGB) was higher in homegardens and least in boundary plantations (Figure 2B). Homegardens have different species in different strata (vertical stratification above ground); the roots of these species draw nutrients from different root zones and, hence, occupy a larger surface of the soil profile, resulting in higher root biomass.

Irrespective of the region, the highest total biomass was recorded in plantation crop-based AFS, followed by boundary plantations and homegardens (Figure 2C). This could be attributed to higher tree density and difference in management regimes; for example, in coffee plantations in the western Ghats region, farmers retain native trees in large numbers to provide shade for under-story coffee, and *Grevillea robusta* trees serve as standards for pepper vines. In the homegardens of northeastern and western Ghats, smallholder farmers maintain diverse trees to meet an array of demands. A study in the western Ghats region of peninsular India found that coffee agroforests resembled natural forest and mixed species plantations in terms of tree diversity and biomass production, suggesting that traditional coffee farms can help to protect tree species, sustain smallholder production and offer opportunities for conservation of biodiversity and climate change mitigation [33]. Similarly, another study revealed that coffee agroforests and mixed species plantations were more effective compared to monocultures for conserving biodiversity and storing more biomass [34].

4.2. Carbon Capture

Total mean biomass carbon (TMBC) was in the range of 7.95–81.2 Mg C ha^{-1}, while average SOC varied in the range of 13.3–69.39 Mg C ha^{-1} across different regions. The highest TMBC (81.2 Mg C ha^{-1}) and SOC (69.39 Mg C ha^{-1}) were recorded from the southern peninsular region followed by the eastern and northeastern Indian region, with a TMBC value of 47.58 Mg C ha^{-1} and SOC of 66.88 Mg C ha^{-1}, indicating the higher carbon sequestration potential of AFS from these regions in India. AF systems, such as coffee plantations, plantation crop-based AFS in the southern peninsular region, homegardens in northeastern India and silivipastoral systems in the northern Himalayas were found to have greater potential to sequester carbon in both biomass and soil. When the same AFS were compared between different agroclimatic regions, we found that the agrisilviculture and agrihorticulture systems of the northern Himalayas had greater carbon sequestration potential compared to the Indo-Gangetic and western and central Indian regions. These differences in biomass carbon and SOC across the regions and AFS were observed as the carbon storage capacity of agroforestry systems is dependent upon many biophysical and socio-economic characteristic of the system [35]. Further, the carbon storage potential of AF systems are strongly governed by the structure and functioning of different components within the system. The lowest biomass carbon was observed in agrihorticulture systems in western India (mean = 1.84 Mg ha^{-1}), probably due to the extremely dry and hot climatic conditions. This was also reflected in low SOC, ranging from 12.26 to 14.55 Mg ha^{-1}) (Table 2). In addition, frequent pruning of horticulture crops to enhance fruit production could lead to lower biomass carbon in these systems. Biomass carbon in agrisilviculture systems (mean = 7.95 Mg ha^{-1}) in Indo-Gangetic region (IGR) was also relatively lower. This is because short rotation species are maintained in the region with a rotation age of 5–7 years. The SOC was also less in IGR (mean = 15.25 Mg ha^{-1}) because intensive agriculture is practiced in the region with a cropping intensity of 2.5, with paddy as the main crop; the practice of paddy does not allow buildup of SOC, as, during soil puddling, soil aggregates are broken, leading to loss of SOC.

The south Indian AFS had the highest mean SOC stock in the range of 17.08–125.29 Mg ha^{-1}, followed by eastern Indian AFS, with a mean SOC stock of 51.95–96.53 Mg ha^{-1}. AFS in southern peninsular India showed considerable variation in SOC stock compared to AFS in eastern and northeastern India. The prominent agroforestry systems in the south Indian region were found to be plantation-based systems, in the form of either commercial coffee or forest tree species plantations, which are crucial from the perspective of long-term carbon storage. SOC in AFS other than vegetation, particularly woody species composition, is also influenced by litter quality, age and locality (e.g., climate, soil conditions, topography), geographic position, land use and management systems. Older and relatively undisturbed land use systems generally accumulate higher organic carbon content [36–38]. Relatively, the eastern and northeastern Indian region receives higher rainfall compared to other regions of India with an average annual rainfall of more than 2000 mm; thus, soils are generally acidic and have higher SOC [37,39].

From a comparative point of view, SOC assessment in AFS irrespective of region, indicated that block plantations/woodlots had least SOC (15.54 Mg ha^{-1}), closely followed by agrisilviculture (26.59 Mg ha^{-1}) (Figure 3B). Soil management and soil amendments in woodlots/block plantations are seldom performed in India. These plantations are maintained for a short duration for commercial purposes and, hence, resilience for SOC buildup does not occur. Soil carbon increases during the tree-growing phase; however, crop cultivation after tree harvesting or burning soil carbon stocks is likely to decrease it again [40]. This interpretation is consistent with the observed reduced SOC in agrisilviculture. The IPCC recommends a minimum 20-year period for soil carbon sequestration accounting in national greenhouse gas inventories [41]. The higher SOC in plantation-based AFS (81.17 Mg ha^{-1}) is due to a resilience time of more than 40 years, as coffee, tea, or cocoa plantations have durations of more than 50 years.

The mean biomass, biomass carbon and SOC in India reported in the literature are less compared to that of other countries. For example, ref. [15] reported agrisilviculture systems storing 12–228 Mg C ha^{-1} in the humid tropics and 68–81 Mg C ha^{-1} in the dry lowlands of southeast Asia, whereas in our study, we found a mean of 55.69 Mg ha^{-1} (both TBC + SOC) in agrisilviculture systems. AFS are complex and heterogeneous and, the more the heterogeneity, the more efficiently the carbon is sequestered compared to simpler systems [37,39]. However, the efficiency of AFS as carbon sinks is governed by their size, natural site qualities, choice of species and management practices followed, i.e., carbon sequestered by an AFS depends on its structure and composition modified by environmental and socio-economic factors [42,43]. Moreover, inter- and intra-specific variation in tree diameter, stand age, stand structure and diversity of the system also affect variation in biomass and its carbon [44,45].

Homegardens and block plantation agroforestry systems were reported to have higher carbon contents than other land uses in an agricultural landscape with higher net gains in carbon stocks [46–50]. Developing countries are now adopting agroforestry systems to achieve climate change mitigation as REDD+ strategic options [51–53] due to their financial feasibility, avoidance of deforestation, enhanced soil productivity and permanency of carbon sequestration in agricultural landscapes, along with sustaining the growers [54–57].

Uncertainties in estimates of carbon stocks in different AFS would be expected as each system varies according to site factors, tree species, the density and productivity of shade trees, as well as their longevity and subsequent use in processing systems, the production of litter, the rate of decomposition and its incorporation in the soil matrix as soil carbon, nutrient cycling and soil respiration. In addition, the management regime of each system is also critical as it largely determines the carbon additions and removal from the system. Perhaps more important over the longer term is the resilience of the system in terms of its ability to withstand climatic or other shocks, and, thereby, to retain carbon despite such perturbations. The resilience of agroforestry systems is a function of the diversity and complexity of the agroforest management unit, and the nature of the landscape matrix within which agroforestry systems lie. Indeed, a functional landscape system, as viewed from the perspective of resilience and carbon storage, must be considered as an integrated landscape that includes flows of materials and services across system boundaries, from agroforests to natural forest patches, and more intensive land uses, including plantations and annual crops. Agroforestry plantations require a clear understanding of their tree life history strategies, i.e., the driving mechanisms and magnitudes of biomass allocation and partitioning [58,59]. Unfortunately, this driving mechanism and magnitude remain uncertain [60]. There are also significant uncertainties concerning the quantification of carbon fluxes in and out of systems due to an absence of information on land use and land cover change [61,62].

5. Conclusions

India, as a signatory to the Kyoto Protocol, has committed, as an intended nationally determined contribution, to sequester an additional 2.5 to 3 billion tons of CO_2 by 2030. One of the most important strategies to achieve this target is through the adoption of agroforestry to ensure climate resilient production practices. India, as a large country with a geographical area of 328 million ha, offers wide opportunities for expansion of its area under agroforestry. In addition to the current area of 13.7 million ha, approximately 79% of the country's total geographical area is highly or moderately suitable for incorporation of trees on farmland. However, currently, there is a lack of information on carbon stocks and the potential for C-sequestration from different AFS spread across different agro-climatic zones of India. In this context, the present study sought to collate and synthesize carbon stock data, which is very important for understanding and reporting C-sources and sinks at a national scale. This meta-analysis provides baseline information about biomass and carbon stocks in agroforestry, depending upon the region and agroforestry system in the Indian sub-continent. The information compiled shows that the humid and sub-humid regions of India have significant potential for biomass and carbon storage. Homegardens, plantation crop-based AFS, and block plantations have huge potential for biomass and biomass carbon and SOC accumulation. However, the amount of SOC and carbon storage in Indian AFS is lower than that of other regions of the world, which necessitates developing an understanding of their proper management and diversity. The carbon accumulated in the AFS studied may or may not represent a positive carbon balance as most of the literature reviewed did not consider previous land uses. Barriers to the implementation of agroforestry systems, including felling regimes, transit permits and market availability, should be assessed and analyzed before advising on the implementation of these systems. In this meta-analysis, we recognize that there are uncertainties due to region, species richness, tree density and diversity, rainfall, and people's choices, however, the derived values of biomass, carbon stock and SOC could serve as a yardstick for formulating appropriate policies on carbon neutrality, as well as carbon financing, in the future.

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