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Review

Carbon Sequestration Potential of Commercial Agroforestry Systems in Indo-Gangetic Plains of India: Poplar and Eucalyptus-Based Agroforestry Systems

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Abstract: Climate change, land degradation, and desertification lead to the loss of carbon present in the soil and plants. The carbon dioxide (CO_2) concentration in the atmosphere has reached 412 ppm. This is a rise of 47% since the start of the industrial period, when the concentration was close to 280 ppm. Therefore, the sequestration of carbon from the atmosphere to earth is the need of the hour. Many scientists have suggested agroforestry as a potent instrument for climate change mitigation as well as to fetch lucrative benefits. The Indian government is also promulgating tree-based systems for increasing tree cover up to 33% of the total geographical area to mitigate climate change. Therefore, the expansion of the commercial agroforestry system of fast-growing tree species producing higher biomass could be a sustainable and ecologically benign technique to sequester carbon, increase green cover, and improve the financial status of farmers. This review highlights the commercial agroforestry systems, biomass and carbon sequestration potential, and case studies of poplar and eucalyptus. The species such as poplar (*Populus deltoides*), nilgiri (*Eucalyptus* spp.), subabul (*Leucaena leucocephala*), tree of heaven (*Ailanthus excelsa*), willow (*Salix* spp.), malabar neem (*Melia dubia*), cadamba (*Neolamarckia cadamba*), and white teak (*Gmelina arborea*) are the suitable tree species for carbon sequestration under agroforestry. Among these species, poplar and eucalyptus are major agroforestry tree species that have been adopted by millions of farmers in India since the 1990s. Indo-Gangetic plains are considered the birthplace of commercial or industrial agroforestry, as poplar and eucalyptus are widely planted. This review reports that poplar and eucalyptus have the potential to sequester carbon stock of 212.7 Mg C ha^{-1} and 237.2 Mg C ha^{-1}, respectively. Further, the net carbon sequestration rate in poplar and eucalyptus was 10.3 and 12.7 Mg C ha^{-1} yr^{-1}, respectively. In conclusion, the commercial agroforestry system was very successful in the Indo-Gangetic regions of the country but needs further expansion with suitable compatible crops in different parts of the country.

Keywords: biomass production; climate change; land degradation; litter decomposition

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Citation: Chavan, S.B.; Dhillon, R.S.; Sirohi, C.; Uthappa, A.R.; Jinger, D.; Jatav, H.S.; Chichaghare, A.R.; Kakade, V.; Paramesh, V.; Kumari, S.; et al. Carbon Sequestration Potential of Commercial Agroforestry Systems in Indo-Gangetic Plains of India: Poplar and Eucalyptus-Based Agroforestry Systems. *Forests* **2023**, *14*, 559. https://doi.org/10.3390/f14030559

Academic Editors: Valery P. Kalinichenko, Alexey P. Glinushkin and Saglara S. Mandzhieva

Received: 25 February 2023
Revised: 9 March 2023
Accepted: 9 March 2023
Published: 12 March 2023

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1. Introduction

The phrase "trees for life" has acquired worldwide recognition in recent years. The adoption of woody perennial systems is required to maintain agricultural productivity and way of life due to many catastrophic calamities, including floods, drought, heat and cold waves, and global warming. In practically every terrestrial ecosystem, trees are essential. They provide both urban and rural residents with a wide range of ecosystem services. Agroforestry is the practice of incorporating trees into productive landscapes after natural vegetation is removed for cultivation [1]. The trees on farms are a component of an ancient, traditional agricultural system and are especially important for the survival, nourishment, and preservation of ecological systems. Agroforestry is practiced on nearly one billion hectares of land worldwide, and 1.2 million people rely exclusively on its services and goods [2]. The services of traditional agroforestry are well-received and documented by the scientific community around the world. These systems are fading away due to modern cultivation practices, changes in cropping patterns, and marketing channels. The traditional agroforestry systems were developed to provide the 6Fs (food, fibre, fuel, fruits, floss, fertilizer, and fodder) for the entire family [3]. Due to yield loss, limited land holdings, market rates, and economic returns from the system, these systems are not sufficient to give farmers more revenue, and the adoption rate is falling quickly. According to research by the Indian Planning Commission, the benefit-to-cost ratio of indigenous tree-based systems was estimated to be between 1.09 and 1.80, which is lower than that of conventional agriculture. As a result, farmers are adopting economic methods such as commercial agroforestry and ignoring traditional agroforestry.

In 1970–80, agroforestry science was just born with enigmatic expectations and flourished with time. Reports from the National Commission on Agriculture [4] recommended 'social forestry' on the common lands to provide small timber, fodder, and fuel wood. With this initiation, the project has spread all over the country. These projects promoted the planting of trees in four ways, including (a) farm forestry (tree planting for commercial or subsistence purposes in and around the privately owned farm); (b) agroforestry (planting of trees with a combination of crops on cultivating fields); (c) extension forestry (planting fast-growing trees on government wasteland and degraded forest land, roadsides, canal sides, and railroads) and (d) community forestry (in the form of woodlots on village common land). These types of tree plantations took place in different parts of the country, especially Gujarat, Tamil Nadu, Haryana, Punjab, Maharashtra, and Madhya Pradesh. After the enactment of the National Forest Conservation Act [5] and the National Forest policy [6], tree felling was banned in view of restoring and conserving the fast-decreasing natural forest. These acts and policies advocated forest-based industries to raise their plantations or promote farmers for commercial agroforestry or plantation. After that, to fulfill the requirement of raw materials, wood-based industries such as WIMCO (Western India Match Company) Limited started introductory field trials of *Populus deltoides* in the Indo-Gangetic plain with the help of the Forest Research Institute, Dehradun [7,8]. WIMCO has laid the foundations of a well-known success story of commercial poplar-based agroforestry during the 1990s. "Growing of commercial timber trees for the wood industry on farmlands using irrigation, manuring, plant management technologies, etc., in a harvest cycle of 10–12 years" is how Avtar Singh defines commercial agroforestry. Under-tree intercrops are only given minor significance and only make up a modest portion of the overall income. As a result, crops that prefer or are tolerant of shade are produced to supplement the sale of timber. On the other hand, eucalyptus-based agroforestry systems also gained momentum in 1990–91. Under such circumstances, the scenario of commercial agroforestry systems has changed from traditional and subsistence agroforestry to income generation.

Indian Indo-Gangetic plains (IGP) became the hub of commercial agroforestry, and similar attempts have been made in other places. The poplar and eucalyptus-based agroforestry systems occupy over five lakh hectares (ha) in IGP. With these systems, *Melia composita*, *Gmelina arborea*, *Dalbergia sissoo*, *Bamboo*, and *Leucaena leucocephala* are also adopted by farmers [9]. Similarly, the implementation of the much-needed National Agroforestry Policy (NAP) 2014 [10] of India has been announced with the success of IGP agroforestry models to achieve 33 percent tree cover [3]. The policy mainly focused on: creating a national institutional framework to advance agroforestry under the Ministry of Agriculture's purview; streamlining rules governing the collection, transportation, and felling of trees grown on farmlands; guaranteeing the security of land tenure; building a solid foundation of land records and data to support the increased participation of industries dealing with agroforestry produce; and strengthening marketing information [6]. NAP 2014 identified 20 significant multipurpose agroforestry tree species, including commercial trees such as poplar and eucalyptus, at the national level as being exempt from all limitations on harvesting, transporting, and marketing cultivated under agroforestry systems. NAP 2014 also mentioned public-private partnerships for the spread of agroforestry. Private businesses such as the plywood, matchwood and pulpwood sectors are in great demand for the raw materials that could help farmers practicing commercial agroforestry systems in IGP under the private-public partnership [3,6]. Commercial agroforestry systems have taken a decisive part in achieving these goals and will simultaneously produce a large number of direct and indirect benefits [11]. These systems withstand extreme weather events and provide a huge opportunity to store atmospheric carbon dioxide [12–14]. The adaptation and mitigation potential of commercial agroforestry systems are well accepted by the IPCC (Intergovernmental Panel on Climate Change) and other international treaties to combat climate change [15]. The IGP is the home place of the ever-popular Indian Green revolution. Large-scale land degradation caused by the excessive use of herbicides, insecticides, chemicals, high-yielding cultivars, and other fertilizers in a highly fertile region has generated concerns about the long-term sustainability of natural resources [16,17]. Some of the primary issues that need to be addressed are environmental concerns (such as floods, salinization, pollution, drought and desertification, fast-dwindling water tables, etc.), shrinking landholding sizes, socio-demographic pressure, and other economic variables. Therefore, commercial agroforestry systems are gaining momentum in IGP. It is a paramount and crucial path towards prosperity for people in North-western India, viz., Uttarakhand, Punjab, Haryana, and western Uttar Pradesh, whose lands have been passed by the green revolution [18–20]. These tree-based systems provide an opportunity of sequestrating atmospheric carbon in the wood through the process of photosynthesis [21]. Keeping this in view, the present paper has highlighted an overview of the nature and structure of agroforestry systems and the carbon stock potential of commercial agroforestry systems in the Indo-Gangetic region.

2. Methodology

In order to conduct a comprehensive search for scientific literature, we utilized specific search terms on Google Scholar: “Agroforestry system AND Carbon sequestration”. We selected the articles that met our search criteria, which included studies that focused on the agroforestry system and any of the specified keywords. Additionally, we collected further records from review articles and research articles that met our initial eligibility criteria. We also performed targeted searches on governmental and independent agricultural research organizations in India where medium to large-scale, commercially oriented agroforestry systems are known to occur. To expand the scope of our study, we included all agroforestry systems such as agro-pastoral systems, agro-silvo-pastoral systems, agri-horti, silvipasture, silvi-horti, etc. We also considered studies involving different land holding sizes and both on-farm (farmers’ field) and on-station (research station) trials. Finally, we limited our search to original research, datasets, dissertations, review articles, book chapters, or conference proceedings.

3. Nature and Structure of Agroforestry in Indo-Gangetic Plains

The vast north-central region of the Indian subcontinent is linked to the IGP, which joins the deltas of the Brahmaputra River basin and the Ganges (Ganga) to the Indus River valley in northern India. The region is widely known as the continent’s richest, most fertile, and most densely populated area. The IGP runs parallel to the Himalayas, from Jammu and Kashmir on the western side to Assam on the eastern side and drains most of northern and eastern India [Figure 1]. From west to east, the plain stretches up to 2400 km and covers an area of 700,000 km^2. The IGP was formed by the sedimentation of the Himalayas and is one of the world's most productive areas. According to statistics, it takes up 15.3% of the nation and houses almost 33% of the human population and 35% of the animal population [22]. Due to its abundant alluvial soil, it is referred to as the "food bowl of India." According to Panwar et al. [23], the IGP, which includes Punjab, Haryana, Uttar Pradesh (UP), Bihar, and West Bengal (WB), except the Purulia district and two districts of Rajasthan, produces roughly 50% of the nation's food grains, enough to feed 40% of the people [24]. The area is further classified into 4 meso-level regions [25], viz., trans-, upper, middle, and lower Gangetic plains, and the details of different regions are furnished in Table 1.

Figure 1. Indo-Gangetic plains (Source www.pinterest.com.au, accessed on 10 March 2023) (1 and 2, trans-Gangetic plains; 3, upper Gangetic plain; 4, middle Gangetic plain; and 5, lower Gangetic plain).

The green revolution was mainly implemented in the IGP to feed millions of empty mouths during the late 70s and became unproductive over time due to unscientific cultivation practices. To restore such an ecologically fragile system, the integration of trees could help to obtain ecologically sound, economically profitable, and conservative systems. Traditionally, the IGP consists of many agroforestry systems to maintain the ecological and livelihood security of the region. In these regions, it has been observed that farmers maintain trees on farm bunds for obtaining different products such as timber, fuel wood, fruits, fodder, etc. In the parts of Haryana and Punjab, farmers are maintaining trees such as *Ailanthus excelsa*, *Melia composita*, *Dalbergia sissoo*, *Populus deltoides*, *Eucalyptus* spp., *Mangifera indica*, etc. Farmers in the Tarai region of Uttar Pradesh and Uttarakhand prefer to plant shisham (*Dalbergia sissoo*), jamun (*Syzygium cumini*), and false white teak (*Trewia nudiflora*). In some parts of Uttar Pradesh and Bihar, *Dalbergia sissoo* is commonly planted in a field with other preferred species such as *Tectona grandis*, *Eucalyptus tereticornis*, *Litchi*, *Emblica officinalis*, and bamboos for livelihood (Table 2).

Homestead and home gardens are popular types of agroforestry systems adopted in hilly and lower hills of the Himalayas due to their diversified outputs [26]. These are traditionally distributed in West Bengal, Eastern Uttar Pradesh, and Bihar, where different crops are presented in a multitier canopy configuration [22]. In West Bengal, home gardens occupy 3–4 tiers of coconut (*Cocos nucifera*), areca nut (*Areca catechu*), banana (*Musa paradisiaca*), vegetables, and flowers. Arecanut (*Areca catechu*) is the principal species widely cultivated in the backyard garden of every house but does not prefer being planted in the agricultural fields [27]. In Uttar Pradesh, farmers cultivate vegetable climbers, including pumpkin (*Cucurbita pepo*), round melon (*Citrullus vulgaris*), and bitter gourd (*Momordica charantia*) under *Azadirachta indica*, *Emblica officinalis*, *Tectona grandis*, and *Mangifera indica* for their consumption. Changes in the forest policies have created opportunities to establish plywood and pulpwood agroforestry to meet the increasing demand of wood-based industries (WBI), in addition to satisfying the domestic demands of the farmers [28]. Poplar and eucalyptus became very popular tree species in the region for sustainable land use to enhance farm income in a short period.

Table 1. Physiographic information of Indo-Gangetic plains.

Physiographic Information	Zone of Indo Gangetic Regions			
	Lower Gangetic Plains	**Middle Gangetic Plains**	**Upper Gangetic Plains**	**Trans-Gangetic Plains**
Area	About 6.94 M ha area of West Bengal and Jharkhand consisting of 15 districts	17.03 M ha area from 61 districts covering the eastern part of Uttar Pradesh and northern districts of Bihar	13.87 M ha area of Central and Western (45 districts) Uttar Pradesh	12.50 M ha area of 51 districts of Delhi, Haryana, Punjab, and Rajasthan
Climate	Hot and humid monsoon-type climate with temperatures ranging from 2.2 °C to 21 °C Rainfall ranges from 1150 to 1750 mm	Humid to sub-humid climate. Mean temperature ranges from 8.9 °C to 37.6 °C. Rainfall 1000–1500 mm	Sub-humid with four seasons: hot summer, wet summer, pre-winter transition, and winter. Temperature reaches 0 °C in winter to up to 48 °C in summer. Rainfall: 500 mm in west to 1400 in east	Semi-arid and sub-humid region with three seasons (rainy, winter, summer) Temperature rises more than 45 °C in summer. Rainfall varies from 200 mm to 1200 mm
Crops	*Rice*, *jute*, *wheat*, *mustard*, *mung*, *sorghum*, *colocasia*	Rice, wheat, tuber crops, vegetables and medicinal crops	Rice, sugarcane, wheat, lentils, mustard, vegetables, berseem, chickpea, and bajra	Wheat, cotton, rice, chickpea, lentil, bajra, guar, fodder crops
Vegetation	Trees: *Acacia mangium*, *Gmelina arborea*, *Tectona grandis*, *Eucalyptus* spp., *Dalbergia sissoo and Bamboo* Fruits: *Mangifera indica*, *Litchi chinensis*, *Psidium guajava*	Timber trees: *Anthocephalus cadamba*, *Azadirachta indica*, *Madhuca longifolia*, *Butea monosperma*, *Bamboo* spp. & *Tectona grandis* Fruits: *Mangifera indica*, *Litchi sinensis*, *Psidium guajava*	Timber trees: *Eucalyptus* spp., *Populus deltoides*, *Melia* spp., *Madhuca longifolia*, *Dalbergia sissoo* Fruit Trees: *Mangifera indica*, *Psidium guajava*	Timber trees: *Acacia nilotica*, *Dalbergia sissoo*, *Melia composita*, *Eucalyptus* spp., *Populus deltoides*, *Prosopis cineraria*, *Ailanthus excelsa*, *Terminalia arjuna* Fruits trees: Apple ber, *Psidium guajava*, *magifera indica*, *Agel marmelos*, *Emblica officilis*

Table modified from Pathak et al. [29].

Table 2. Important agroforestry systems of the Indo-Gangetic region.

State	Agri-Silviculture	Boundary Plantation	Silvopasture
Punjab	*Populus deltoides*, *Eucalyptus* spp., and *Melia composita* for plywood and pulp purposes Scattered plantations of *Tectona grandis*, *Dalbergia sissoo*, and *Azadirachta indica* for timber and furniture purposes	*Dalbergia sissoo*, *Azadirachta indica*, *Acacia nilotica*, *Ailanthus excelsa* are maintained traditionally on field bunds or scattered. Commercially *Eucalyptus tereticornis* and *Populus deltoides* on a single row or paired row on boundaries.	Grasses or fodder crops are being intercropped with *Eucalyptus tereticornis*, *Populus deltoides*, and *Melia composita*.
Haryana	*Eucalyptus tereticornis*, *Populus deltoides*, *Ailanthus excelsa*, *Melia composita* are the main commercial tree species for industrial purposes	Traditionally, *Ailanthus excelsa*, *Dalbergia sissoo*, *Prosopis cineraria*, *Tecomella undulata* are maintained on boundaries for fuelwood, timber and fodder. Commercially, *Eucalyptus tereticornis* and *Populus deltoides* on a single row or paired row on boundaries	Berseem, lucerne and grasses are being grown with *Ziziphus mauritiana*, *Acacia nilotica*, and *Emblica officinalis.* Irrigated areas such as Yamunanagar, Berseem and sorghum are widely intercropped with *Populus deltoides*.
Tarai region of Uttarakhand	*Populus deltoides*, *bamboo*, and *Eucalyptus* spp. are widely preferred for block plantations to supply raw material for plywood	*Eucalyptus*, *Bamboo* spp. and *Dalbergia sissoo*	Berseem with commercial tree species and under alleys of fruit orchards
Central Uttar Pradesh	*Dalbergia sissoo*, *Mangifera indica*, *Tectona grandis* and *Euclayptus* spp. for timber and plywood. Apart from that, some fruit trees, including *Mangifera indica*, *indica*, *Psidium guajava*, *Zizyphus mauratiana*, *Emblica officinalis*, and *Aegel marmelos*, are widely grown by the farmers	*Acacial nilotica*, *Azadirachta indica*, *Dalbergia sisoo*, *Madhuca longifolia*, and *Bamboo*	Napier, stylo, and *Cenchrus* spp., are grown with Luecaena *leucocephala* and *Albizia amara*
Eastern Uttar Pradesh	*Mangifera indica*, *indica*, *Psidium guajava*, and *Syzygium cumini* grown in orchards	*Dalbergia sissoo*, *Eucalyptus* spp., *bamboo* on field boundaries. Bamboo as live fence	Fodder grasses intercropped with *Emblica officinalis*, *Psidium guajava*, and *Ziziphus mauritiana*
Bihar	*Dalbergia sissoo*, *Tectona grandis*, *Terminalia arjuna*, *Bamboo species* and different *orchards of Mangiferaindica*, *Psidium guajava*, *Emblica officinalis*, and *Litchi chinensis*	*Tectona grandis*, *Dalbergia sissoo*, *Mangifera indica and Bombax ceiba*	*Fodder crops with Dalbergia sissoo*, *Mangifera indica*, *Leucaena leucocephala*, *Tectona grandis*, *Bamboo* spp.
West Bengal	*Terminalia arjuna*, *Acacia mangium*, *Acacia auriculiformis*, *Gmelina arborea* planted in blocks with *Annona squamosa*, *Emblica officinalis*, *Ziziphus mauritiana*, *Punica granatum*, *Madhuca latifolia*, *Syzygium cumini*	*Butea monosperma*, *Tectona grandis* and *Mangifera indica*	*Dicanthium* and *Pennisetum* grasses are grown with *Acacia mangium*, *Tectona grandis*, and fruit orchards

4. Concepts of Carbon Capture and Storage in Agroforestry System

In light of growing worries about a potential global climate emergency, carbon sequestration (also known as carbon capture and storage) is becoming a significant worldwide policy objective. From the 1970s onward, the notion of reducing it through forest management and conservation was studied. However, worldwide action was not started until the

1990s. The United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992 with the primary goals of creating national inventories of greenhouse gas emissions and sinks and decreasing greenhouse gas emissions [30]. The United States and the other participating nations committed to the Kyoto Protocol, also known as the Framework Convention on Climate Change (FCCC) Third Kyoto Agreement, which calls for a reduction in greenhouse gas emissions of at least 5% below 1990 levels by 2012. The process of taking carbon from the atmosphere and depositing it in a reservoir is referred to as carbon sequestration by the UNFCCC. It involves the movement of atmospheric CO_2 and its safe storage in reservoirs with a long lifespan, similar to woody perennials [31]. The process of photosynthesis powers the plant's carbon cycle (Figure 2). It turns carbon dioxide, water, energy, and sunshine into oxygen and glucose through this mechanism. Using their branches, limbs, leaves, roots, and stems, plants may absorb atmospheric carbon dioxide molecules and transform them into useful molecules that are then stored in various plant components [32].

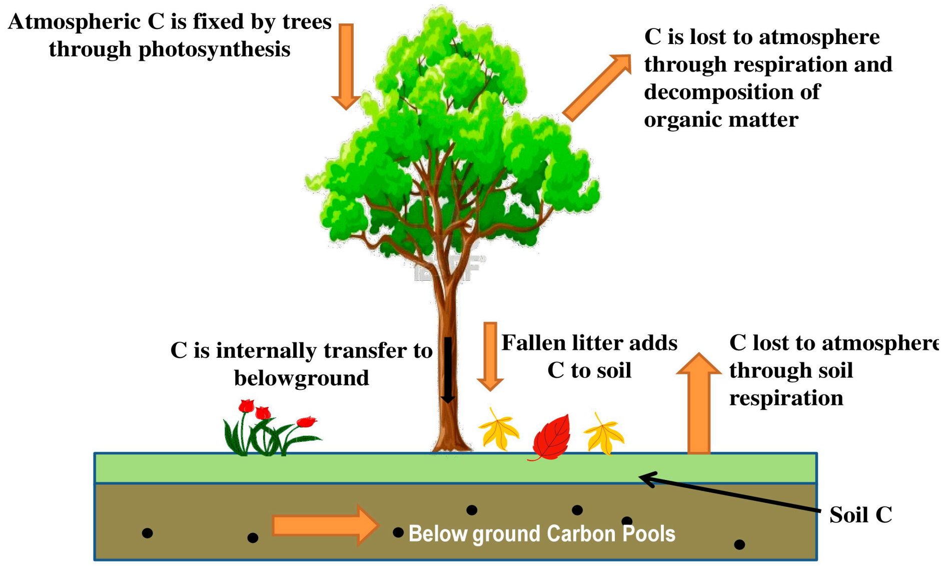

Figure 2. The process of carbon sequestration through trees.

5. Agroforestry Systems in IGP

Agroforestry is a desirable alternative for sequestering carbon on agricultural lands since it can do so while using the majority of the area for agricultural production and can absorb and store large amounts of carbon [33]. Agroforestry is essential for reducing atmospheric GHG build-up in both the above-ground and below-ground atmospheres [34]. In agroforestry, the sequestration potential is influenced by the choice of species, soil type, climatic conditions, management practices, and end-use of products [35]. In intricate agroforestry systems such as border planting, hedgerow intercropping, and home gardens, carbon sequestration rates are highly encouraging. Agroforestry systems have the potential and capabilities to sequester carbon in trees/plants, as listed in Table 3. Among different agroforestry systems, agri-silviculture systems are widely practiced and reported to store carbon ranging from 0.87 to 8.92 Mg ha^{-1} yr^{-1}. To mention a few, Leucaena-based systems sequester 0.87 Mg ha^{-1} yr^{-1} [36] in Punjab; 3.4 Mg ha^{-1} yr^{-1} is sequestered in alley cropping of *Leucaena*-based systems in Kanpur, Uttar Pradesh [37]; 4.7 Mg ha^{-1} yr^{-1} is sequestered in teak based systems [38] in West Bengal; 2.06 Mg ha^{-1} yr^{-1} is sequestered in poplar-based systems [39]) in Uttaranchal; 2.74 Mg ha^{-1} yr^{-1} is sequestered in *Pongamia pinnata*-based systems [40]. Poplar based systems sequester 8.92 Mg ha^{-1} yr^{-1} [41] in Punjab; 4.7 Mg ha^{-1} yr^{-1} is sequestered in *Acacia nilotica*-based systems in UP [42]. These variations in the carbon sequestration rate are due to variability in soil, climate, the nature of the plant species, management practices (pruning, thinning and lopping), planting geometry, density, irrigation and fertilizers, type of intercropping, and inputs.

Table 3. Carbon sequestration potential of agroforestry tree species in Indo-Gangetic plains of India.

State	Location	System	Tree Species	No. of Tree (tees ha^{-1})	Age (year)	CSP (Mg C ha^{-1} yr^{-1})	References
Uttarakhand	Tarai region	Agri-silviculture	*Populus deltoides*	200	8	2.06	[39]
		Boundary	*Eucalyptus tereticornis*	-	-	0.88	
		Block	*Populus deltoides*	500	-	0.52	
				500	-	1.96	
		Block	*Populus deltoides*	500	9	2.06	[43]
		Boundary	*Eucalyptus tereticornis*	192	9	0.34	
		Block	*Dalbergia sissoo (block)*	625	10	1.04	
		Boundary	*Populus deltoides*	130	9	0.5	
		Plantation		500	11	6.15	[44]
		Plantation		500	8	2.85	[45]
	Central Himalaya	Agri-silviculture	*Populus deltoides*	500	8	12.0	[46]
	Tarai central division	Silviculture	*Tectona grandis*	570	10	3.74	[47]
				500	20	2.25	
				494	30	2.87	
	Budali	Agroforestry MPTs	Mixed tree species	1000	-	3.83	[48]
	Manjokot			950		1.95	
	Manao			940		2.99	
	Dungripanth			1230		2.66	
	Chamdaar			1560		8.2	
	Keshu			1310		6.52	
	Northern India	Agri-silviculture	*Dendrocalamus hamiltonii*	1000	7	15.9	[49]
	Tarai	Plantation	*Dalbergia sissoo*	1825	10	6.46	[50]
			Eucalyptus hybrid	1010	8	7.88	

Table 3. *Cont.*

State	Location	System	Tree Species	No. of Tree (tees ha^{-1})	Age (year)	CSP (Mg C ha^{-1} yr^{-1})	References
	Pantanagar	Agri-silviculture	*Populus deltoides*	1000	8	9.02	[51]
				500	8	6.76	
				333	8	4.94	
				250	8	4.02	
				200	8	3.46	
Haryana	Kurukshetra	Silvopasture	*Acacia nilotica*	-	-	2.81	[52]
			Dalbergia sissoo	-	-	5.37	
			Prosopis juliflora	-	-	6.5	
		Plantation	*Eucalyptus tereticornis*	925	8	11.4	[53]
		Agri-silviculture	*Populus deltoides*	-	6	0.36	[54]
	Yamunanagar	Agri-silviculture		500	7	10.6	[55]
		Agri-silviculture				9.42	[56]
		Boundary plantation				3.86	
	Chandigarh	Agri-silviculture	*Leucaena leucocephala*	10,666	6	10.4	[36]
	Hisar	Strip plantation	*Eucalyptus tereticornis*	200	5.4	2.87	[57]
		Boundary		200	8	3.37	[58]
		Agri-silviculture		1111		20.7	
		Boundary	*Populus deltoides*	200	8	4.8	
		Agri-silviculture		500		14.0	
		High-density energy plantation	*Eucalyptus tereticornis*	2500	8	6.16	[42]
			Leucaena leucocephala	2500	8	7.31	
			Acacia nilotica	2500	8	4.64	
Uttar Pradesh	Kanpur	Alley cropping	*Leucaena leucocephala*	-	-	3.4	[59]
	Saharanpur	Agri-silviculture	*Populus deltoides*	500	7	11.8	[56]
		Boundary plantation		200		4.56	

Table 3. *Cont.*

State	Location	System	Tree Species	No. of Tree (tees ha^{-1})	Age (year)	CSP (Mg C ha^{-1} yr^{-1})	References
Punjab	Ludhiana	Agri-silviculture (A + B)	*Populus deltoides*	493	6	6.21	[60]
		Agroforestry MPTs	*Acacia catechu*	555	3	1.84	[61]
			Acacia nilotica			1.53	
			Acrocarpus fraxinifolius			3.75	
			Anthocephalus cadamba			2.73	
			Bombax ceiba			1.28	
			Dalbergia sissoo			2.17	
			Eucalyptus tereticornis			3.12	
			Gmelina arborea			2.08	
			Melia azedarach			1.32	
			Populus deltoides			3.58	
			Terminalia arjuna			1.89	
			Toona ciliata			1.39	
		SRF plantation	*Acacia catechu*	630	10	4.78	[62]
			Dalbergia sissoo	690	10	4.58	
			Melia azedarach	640	10	3.94	
			Terminalia arjuna	690	10	9.54	
	Taran	Plantation	*Populus deltoides*	714	5	18.5	[63]
			Eucalyptus tereticornis	4444		130	
			Tectona grandis	625		5.55	
	Ladhowal	SRF	*Eucalyptus* spp.	258	8	11.8	[40]
			Pongamia pinnata	258	8	2.75	

Table 3. *Cont.*

State	Location	System	Tree Species	No. of Tree (tees ha^{-1})	Age (year)	CSP (Mg C ha^{-1} yr^{-1})	References
Jharkhand	Ranchi	Orchard	*Mangifera indica*	400	10	0.38	[64]
			Litchi	200	10	0.18	[65]
West Bengal	Tista valley range	Plantation	*Tectona grandis*	400	47	2.9	[38]
	Pankhabari range			800	24	4.35	
	Bagdogra range			848	24	2.73	

The agroforestry system of IGP has distributed over 12,540 km^2 with 176.4 million m^3 of growing stock and 42.5 million Mg of carbon stock [43,44]. The agroforestry in Upper Gangetic plains and Trans-Gangetic plains come out to be 0.27 and 0.14 of the total geographical area (2.87 and 3.32 M ha), respectively [66]. Table 4 represents the area and growing stock of forest under the IGP. In the Upper Gangetic region, commercial agroforestry systems dominated by *Eucalyptus*, *Poplar*, *Melia*, *Leucaena*, *Bamboo*, *Dalbergia*, etc., are very popular among the farmers due to their fast growth, adaptability in agriculture, easy establishment, and lucrative market benefits. As per the ICAFRE-Country Report [67], the area under poplar cultivation in India is estimated to be 2, 70,000 ha consisting of monoculture plantations as well as agroforestry. In the case of eucalyptus, being the main species in the trees outside forests, it constitutes 12.1% to 23.7% of the total growing stock in India [68,69]). Eucalyptus is planted over 4 m ha in various parts of the country for timber, fuel wood, pulp, bio drainage, and environmental amelioration and avenue plantations. Chavan et al. [3] reported that about 6.57 lakh ha area is under commercial agroforestry in India. The Central Agroforestry Research Institute, Jhansi, under the NICRA project, computed the total biomass and carbon storage of existing agroforestry systems at the farmer's field by using the CO_2FIX model (Figure 3). Newaj et al. [14] reported that baseline standing biomass in the total biomass (tree-crop) varied from 11.1 to 17.5 Mg ha^{-1} in the IGP. The tree density on farmers' fields varied from 5.60 trees ha^{-1} in the Lower Gangetic region to 12.5 trees ha^{-1} in the Trans-Gangetic regions. The total carbon sequestration potential was 5.01 Mg ha^{-1} yr^{-1} (Table 3).

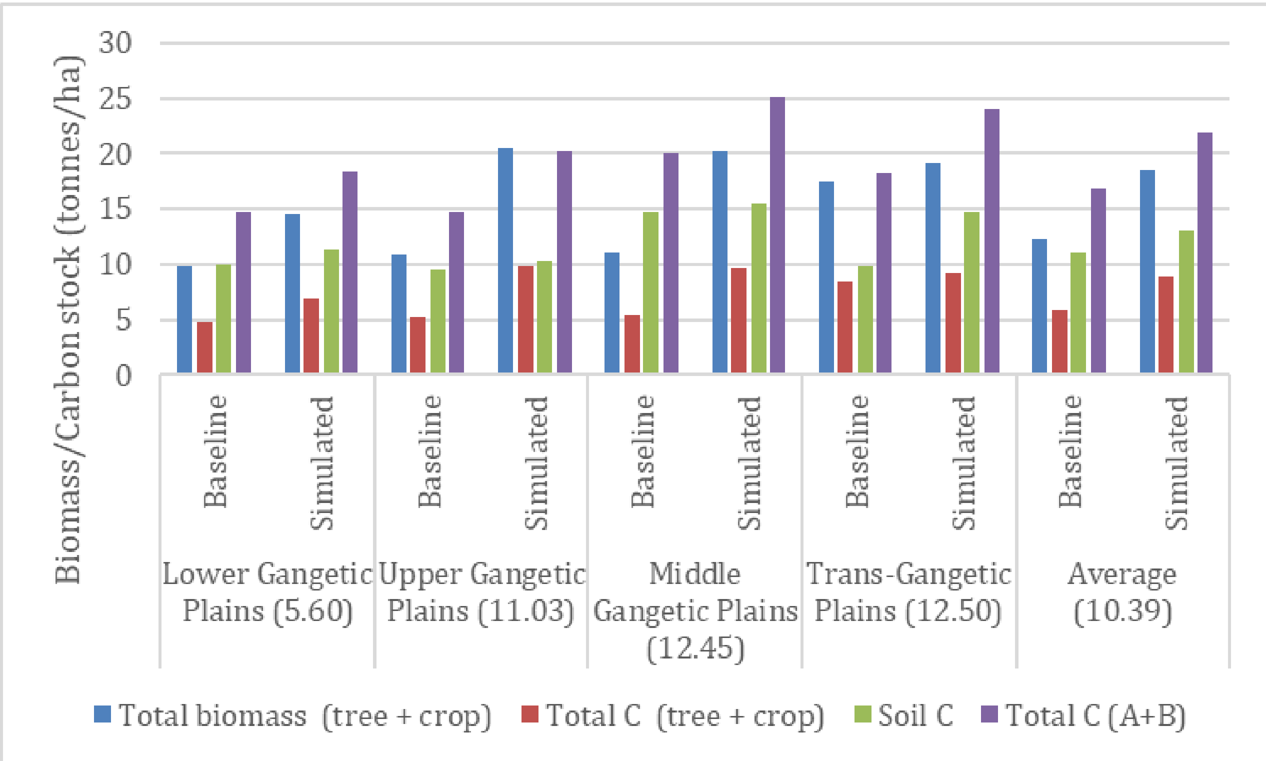

Figure 3. Biomass, soil carbon, and carbon stock available in agroforestry systems existing on farmer's fields. Note: Baseline, 2013 and simulated for 30 years (2042). Parenthesis is tree density per hectare [70].

Table 4. Tree cover area, growing stock, and carbon stock in the Indo-Gangetic Region.

States	Geographical Area (sq. km)	Forest Area (sq. km)	Tree Cover (sq. km)	Growing Stock (million cub m)	Carbon Stock (million t)
West Bengal	88,752	16,808	2088	37.6	8.72
Bihar	94,163	7288	2182	37.2	9.75
Uttar Pradesh	240,928	14,461	7044	80.1	18.3
Haryana	441,212	1584	1355	15.3	3.45
Punjab	50,362	1771	1544	18.1	4.03
Delhi	1483	18,877	111	1.15	0.06
Northern Plains	295,780	-	7912	99.5	22.6
Eastern Plains	223,339	-	4628	76.8	19.8
India	3,287,262		92,572	1573	279.8

5.1. Poplar-Based Agroforestry

Populus deltoides-based agroforestry systems have transformed traditional subsistence-based tree farming into industrial agroforestry. In the last three decades, poplar farming has been widely spread among farmers of the IGP. The appropriate crop combinations (such as sugarcane, wheat, turmeric, and medicinal crops) with suitable spacing have been adopted for the planting of poplar. The modern technologies and scientific management of poplar agroforestry produce average biomasses of around 50–60 Mg ha^{-1}. The huge potential of wood production and intercropping of different crops make poplar-based agroforestry a very profitable business, which provides a benefit-cost ratio of 1:2.13 [6]. Haque [71] reported that an average height of 18 m and girth of 90 centimetres, under a 6-year rotation cycle, generated 180 Mg ha^{-1} and recorded an income of INR 0.72 million ha^{-1}, earning a sale price of INR 4000 per tonne. Poplar has grown in popularity as one of the fastest-growing industrial softwoods in the world that can be harvested in only 5–8 years [72]. Apart from higher income, this system helps to increase the soil's organic carbon with various nutrient enrichments. A possible source of organic inputs through biogeochemical nutrient cycling, or decomposition, is the litter fall in poplar trees. A study by Das and Chaturvedi [73] recorded nitrogen (Kg ha^{-1}) in the range of 37.3–146.2, phosphorus (Kg ha^{-1}) of 5.6–17.9, and potassium (Kg ha^{-1}) of 25.0–66.3 in 3 and 9-yr old plantations, respectively. Another study carried out at CCS Haryana Agricultural University, Hisar, showed that an eight-year-old poplar-based agroforestry system could add 6.2, 4.6, and 2.5 Mg ha^{-1} leaf litters in 5 × 4, 10 × 2, and 18 × 2 × 2 m spacings, respectively [74]. Additionally, Sirohi and Bangarwa [75] reported organic carbon (0.77%), N (234.3 kg ha^{-1}), P (20.1 kg ha^{-1}), and K (241.3 kg ha^{-1}) in 5 × 4 m spacing under poplar plantation. In the era of climate change, carbon sequestration through biomass production in agroforestry is one of the attractive and easy strategies to mitigate CO_2 concentration in the atmosphere [76]. The evolving carbon trading and the market will provide a new feasible avenue for farmers provided that carbon prices must be profitable for farmers, making growing trees a worthwhile investment, especially on small farms, and the procedures must be simplified for easy documentation and trade [72]. Poplar-based agroforestry through boundary plantations, windbreaks, and block plantations has sequestered a considerable amount of carbon stock in wood and soil. Annually, about 50 million poplars covering 30,000 ha yield approximately 3.6 million cubic meters of wood annually [77]. In contrast to solitary cropping systems, Benbi et al. [78] highlighted the potential and contribution of poplar-based intercropping systems in lowering the ambient CO_2 concentration. Several researchers have published scientific figures regarding the potential and ability of poplar in carbon sequestration, as enlisted in Table 4 [79,80].

Chavan [58] estimated biomass production under poplar-based agroforestry systems. Under 8-year-old poplar trees, the average proportional contribution of various tree sections to the overall biomass production was as follows: stems, 67.90%; stump roots, 15.5%; branches, 11.3%; leaves, 4.43%; and fine roots, 0.80%. Singh and Lodhiyal [46] quantified that stems accumulated 74.4% of total biomass, followed by branches (12.6%), twigs (4%), and leaves (8.6%). Stems contribute more than 60% of total tree biomass in poplar [81]. A total of 23.57 Mg ha^{-1} of poplar lumber included carbon, with an equal proportion coming from the tree's roots, leaves, and bark [41]. In seven years, branches contributed 24% of the total 62.48 t of poplar biomass (carbon storage). Hence, it is proved that the structure of agroforestry components shows an impact on the source and sink relationship in the tree. Biomass allocation is one of the important aspects of carbon sequestration as it decides the end-use of products and long-term storage of carbon. In the case of boles/stems, they have numerous uses, including as plywood, beams, furniture, paper, and timber, and carbon is thus locked in them for at least 20 years; however, in branches and leaves, which are used for fuel wood or decomposition, carbon stored in the trees is thus emitted. Carbon allocation in above- and below-ground components were 78.6% and 21.3% [46] in poplar, as delineated in Table 5. The amount of carbon stored in any agroforestry system grows with planting age, and the main contributions come from the timber, roots, and litter (37.30 mg/ha after six years) [60]. At the age of six years, the poplar's greater wood carbon content was calculated to be 28.3 Mg ha^{-1}, compared to 5.67 Mg ha^{-1} from the roots, leaves, and bark. If the branches (1 to 6 years) are applied to the soil rather than being burned for fuel, they might additionally fix 10.22 Mg ha^{-1} of carbon. Another study by Chauhan et al. [82] noted that poplar stored more carbon using the block planting approach (21.9 Mg ha^{-1}) than the border plantation approach (10.4 Mg ha^{-1}). Block plantations with intercrops were projected to have a carbon sequestration capacity of 9.24 Mg ha^{-1} yr^{-1}, whereas boundary plantation systems absorbed carbon at a rate of 5.54 Mg ha^{-1} yr^{-1}, which was greater than that of typical crop rotation (5.20 Mg ha^{-1} yr^{-1}) (provided straw is used as fuel instead of fodder). As the IGP is considered the food bowl of India, the integration of trees in the farm's reduced yield due to shade can be a barrier to the adoption of agroforestry; thus, more research on standard tree-crop combination and management practices is needed [11,12]. Chavan et al. [12] suggested that boundary planting of *Populus deltoides* in the E-W direction (LER of 1.67) is more profitable than the north-south direction (LER of 1.23).

Table 5. Allocation of carbon in different components of poplar tree (kg/tree).

Location	Age/Density	ABG				BG	Total	Reference
		Stem	Leaves	Branches	Total	Roots		
Punjab	3 (555)	18.92	8.60	5.76	32.28	8.56	74.1	[19]
Uttarakhand	8 (500)	109.1	21.82	20.43	151.4	41.02	192.4	[49]
Uttarakhand	10 (500)	50.3	7.41	27.11	85.55	-	85.5	[44]
Bihar	9 (500)	74.3	9.25	5.33	88.94	34.5	109.8	[79]
Haryana	9 (500)	151.7	1.27	22.04	175.0	28.2	203.2	[58]

5.2. Eucalyptus-Based Agroforestry

Eucalyptus is an exotic fast-growing tree widely planted throughout the globe. It consists of 625 species and sub-species with different varieties and hybrids planted on various agricultural lands both as monoculture and as a component of agroforestry programs due to its ease of cultivation and ability to grow in adverse conditions. Eucalyptus was introduced in India about 200 years ago in the Nilgiris Hills of Tamil Nadu during the 18th century from Australia. A hybrid eucalyptus known as "Mysore gum" started to gain popularity in Mysore around 1956. Additionally, large-scale plantings were started in Uttar Pradesh. The introduction of *Eucalyptus grandis*, which has become the most significant species for pulpwood plantations in Kerala, was originally intended for the afforestation of high-range grasslands in Kerala. The other eucalyptus species that are grown in India are *E. tereticornis*, *E. citriodra*, *E. globulus*, and *E. grandis*. Over 6 M ha of eucalyptus plantations have been established throughout the world in more than 60 countries. Another 50 countries have small-scale plantations, either for trial or ornamental purposes. Brazil is the leading country in eucalyptus planting in the world, with an area of 10, 52,000 hectares under eucalyptus plantations [83].

The popular eucalyptus grows to a height of 30–45 m and a diameter of one to two meters in India. The tree's trunk, which makes up half of its height, is often straight. Through extension initiatives by the state forest departments, eucalyptus planting in India began to take on a new form in the late 1960s and early 1970s. All of India eventually saw an increase in its visibility, although Punjab, Haryana, western Uttar Pradesh, Gujarat, Tamil Nadu, North Bengal, and Andhra Pradesh had the greatest increase. The most often used tree to grow on the bunds of agricultural fields is the eucalyptus, which looks to be well-integrated and accepted in agroforestry in many regions of India [20]. Eucalyptus makes up 71.6% of all the trees planted in agricultural forestry. In Punjab, eucalyptus was grown on more than 3% of the land within a decade [84]. Gujarat farmers planted 195 M trees between 1983 and 1984, exceeding their goal by four times. Between 1979 and 1984, farmers in Uttar Pradesh planted 350 million more seedlings than their intended goal of eight million [85]. As shown in Table 6, the FAO has also recorded the area of productive eucalypt plantings by nation, species, and age group.

Table 6. Area of productive eucalyptus plantations by country, species, and age class.

Country	Area (1000 ha) by Age Class (Years)					Subtotal Area (1000 ha)	Percentage (%)
	0–5	5–10	10–20	20–30	30–40		
India	43.0	64.4	103.2			210.6	2.86
China	683.0	576.4	982.7	154.4		2396.5	32.6
Sudan	118.2	189.1	165.5	8.0		480.8	6.54
Australia	131.2	260.1	48.7	1.1	0.4	441.5	6.00
Brazil	2118	756.5	121.0	30.3		3025.9	41.1
Argentina	15.8	32.6	34.5	11.8	3.9	98.6	1.34
Chile	353.4	204.1	85.4	7.2	2.0	652.1	8.87
Myanmar	1.1	2.1	2.2	1.1	0.5	7.0	0.095
Total area						7348.3	100

(Source: FAO 2006 [30] and Raj et al. 2016 [83]).

According to the research, the percentage area of the eucalypt plantation fell in the following sequence with rising age class: 0–5 years: 47.27%; 5–10 years: 28.45%; 10–20 years: 21.04%; 20–30 years: 2.98%; and 30–40 years: 0.02% (more than 40 years). The largest area planted with eucalyptus species is in Brazil (41.17%), followed by China (32.61%), Chile (8.87%), Sudan (6.54%), Australia (6.47%), India (2.86%), Argentina (1.34%), and Myanmar (0.09%). In Punjab, Haryana, and western Uttar Pradesh, eucalyptus is the most preferred species under agroforestry plantations. Depending on the decision and resources available, the tree density ranged from 100 trees per hectare in border plantations to 2500 trees in a block of an agri-silviculture system (Table 7). In irrigated agroforestry plantings, two-row strips on a broader, soil-worked ridge 1.5 m wide, 30–45 cm high, and planting in a row at 1 m escapements are the most typical practices used. Depending on the method of growing, the space between strips is maintained at 4 or 6 m. Another spacing that has gained popularity is 4 × 2.5 m, where crops are grown on a four-year cycle. The most common spacing in Indo-Gangetic plains is 3 m × 3 m, 6 m × 1.5 m, and 3 m × 2 m [74]. Eucalyptus plants have variability, which reduces biomass output. In a plantation of seedling origin, it has been discovered that 33% of the superior trees give 67% of the volume, whereas 67% of the inferior trees generate just 33% of the overall volume.

Table 7. Range of espacement for eucalyptus hybrid (adopted from Luna [86]).

Objective of Planting	Planting Spacing	Tree Density	Harvesting Period (yr)	Dry Biomass (ha^{-1})	Remark
Firewood	1 m × 1 m to 1.5 m × 1.5 m	10,000 to 4444	5	200–250	Higher bark percentage and lower under bark diameters expected
Pulpwood and poles	2 m × 2 m 3 m × 2 m	1667 2500	4–5	60–70	Low bark percentage
Saw logs	3 m × 3 m	1110	10–20	70–100	
Windbreaks and shelterbelts	1 m × 1 m to 1.5 m × 1.5 m	400 533	10–15	20–30	One row; two rows

Krishnkumar et al. [87] reported that eucalyptus can produce about 25–30 m^3 ha^{-1} at a rotation of 6–7 years. This was realized through seed-raised plantations during the early 1990s, but the clonal introduction increased the yield up to 60–70 m^3 ha^{-1} in six years of rotation. Selective genetic improvement has helped to enhance productivity. In Bhadrachalam, the clone's productivity increased from 6 to 10 Mg ha^{-1} yr^{-1} to 20 to 58 mg ha^{-1} yr^{-1} [88]. However, by producing a record yield of 50 m^3 ha^{-1} yr^{-1}, several eucalyptus growers have redefined productivity criteria. Bargali and Singh [89] found that while the biomass production of a 25-year-old eucalyptus plantation was two times higher than that of an 8-year-old plantation (126.7 Mg ha^{-1}), the primary productivity values were nearly identical. *Eucalyptus* + *Casuarina*, *Casuarina* + *Leucaena*, *and Eucalyptus* + *Leucaena* had soil carbon-sequestration potential of 61.9, 56.6, and 61.7 Mg ha^{-1} at 4 years, respectively [90]). Singh and Gill [91] studied biomass production in a seven-year *eucalyptus*-based agroforestry system spaced at 5 m × 4 m in Punjab. The seven-year-old *eucalyptus* produced 114 Mg ha^{-1} above-ground biomass and 31 Mg ha $^{-1}$ below-ground biomass. The biomass productivity of 9.99–21.69 Mg ha^{-1} was reported in *Eucalyptus tereticornis* grown in a three-year-old short rotation under a dry tropical environment [92]. The higher allocation of above-ground biomass follows the order of boles (60.4%–63.3%), branches (including twigs) (12.0–14.5%), and foliage (4.1%–4.8%). In moist regions, *Eucalyptus tereticornis* biomass production ranged from 11.9 Mg ha^{-1} in 3-year-old plantations to 146 Mg ha^{-1} in 9-year-old plantations [93], whereas it ranged from 5.65 Mg ha^{-1} in 5-year-old plantations to 135.5 Mg ha^{-1} in 9-year-old plantations in dry tropical regions. Kidanuet al. [94] reported the effect of the field boundary aspect on crop and tree biomass in Ethiopian highland Vertisols. Wood production rates of eucalyptus ranged from 168 kg ha^{-1} yr^{-1} (4-years old) to 2901 kg ha^{-1} yr^{-1} (12-years old). Dhyani et al. [95] reported biomass production of *Eucalyptus tereticornis* on deep soils and riverbed boundary lands of doon valley, India, and predicted that below-ground root production was 7.51 Mg ha^{-1} and 11.4 Mg ha^{-1} on these respective sites. Carbon stock in eucalyptus-based agroforestry systems was estimated in the Saharanpur district of Uttar Pradesh. The average tree height (m) and diameter at breast height (dbh) was found to be 7.15 m and 5.87 cm at the age of 2–years, which increased to 19.26 m and 16.70 cm at 6 years and further increased up to 28.41 m and 24.77 cm, respectively, at the age of 10 years. The average wood volume, wood biomass, and carbon stock were estimated to be 0.13 m^3 tree^{-1}, 13.6 Mg ha^{-1}, and 6.12 Mg ha^{-1} at 6 years of age; 0.25 m^3 tree^{-1}, 26.4 Mg ha^{-1}, and 11.91 Mg ha^{-1} at 8 years of age; and 0.35 m^3 tree^{-1}, 33.81 Mg ha^{-1}, and 16.65 Mg ha^{-1} at 10 years of age of plantation at the density of 200 trees ha^{-1} [80]. In Punjab, the total carbon sequestration potential per tree ranged between 13.62 in the girth class of 25–30 cm and 387.4 kg in the girth class of 106–110 cm as per the study by [96]. The carbon sequestration per tree in different girth classes was compared using two studies [96,97] in Table 8. Zhao et al. [98] also suggested the inclusion of tree components in park development to promote carbon neutrality.

Table 8. Girth class-wise comparisons of growth and carbon sequestration in eucalyptus trees were recorded by [97,98] in Punjab.

Girth Class (cm)	Tree Height (m)		Carbon Sequestered (kg tree^{-1})	
	[96]	[97]	[96]	[97]
36–40	14.67	15.00	25.7	26.6
46–50	15.77	17.00	45.6	45.6
51–55	20.83	20.00	75.6	66.7
61–65	20.00	20.00	111	91.8
76–80	21.53	22.00	171	154
91–95	25.17	24.00	252	236

5.3. Case Study: Carbon Stocking in Poplar and Eucalyptus in Haryana

Carbon emission and sequestration are the burning issues of the century and the most talked about issue from the 2000s. Many international and national initiatives are taking place to reduce the carbon footprint of different countries. As of today, agroforestry is well-proven as a costless practice recommended for the adaptation and mitigation of climate change. Supporting this statement, the mitigation potential of agroforestry is well-reported and documented throughout the world. The carbon sequestration in tree and intercrop components is the function of biomass production by the individual components (stems, boles, branches, leaves, litter, etc.). It is further distributed as above and below-ground biomass. An experiment was carried out by the Forestry Department, CCS Haryana Agricultural University, Hisar (Haryana), on poplar and eucalyptus-based agroforestry to understand the potential of carbon stocking at rotation age. The study consisted of five spacing geometries of poplar (5 m × 4 m, 10 m × 2 m, 18 m × 2 m × 2 m, north-south, and east-west boundary) and eucalyptus plantation (3 m × 3 m, 6 m × 1.5 m, 17 m × 1 m × 1 m, north-south, and east-west boundary).

The component-wise biomass and carbon were quantified through destructive sampling from the selective harvesting of trees under various spacing. A repertoire of 140 trees of poplar and eucalyptus were harvested from all spacing using standard methodology. The relative contribution of biomass in different components was 68% in the stems, 11% in the branches, 5% in leaves, 16% in the roots of poplar, and 64% in the stems, 9% in the branches, 6% in the leaves, and 21% in roots of eucalyptus. The highest system carbon stock was recorded in poplar (212.75 Mg C ha^{-1}) in 5 m × 4 m (Figure 4) and eucalyptus (237.27 Mg C ha^{-1}) in 3 m × 3 m (Figure 5). The net carbon sequestration rate in poplar and eucalyptus was 10.31 and 12.79 Mg C ha^{-1} yr^{-1}, respectively, in five spacing geometries. The following figures provide a simple understanding of the component-wise accumulation of carbon stock under three carbon pools, i.e., trees, crops, and soil, in agroforestry. The integration of poplar and eucalyptus in agriculture increased the total carbon stock by 2.3 and 2.8 times over sole cropping, respectively. A region-specific study of carbon stock is required to portray a national wide picture of the carbon mitigation potential capacity of tree species under climate change scenarios.

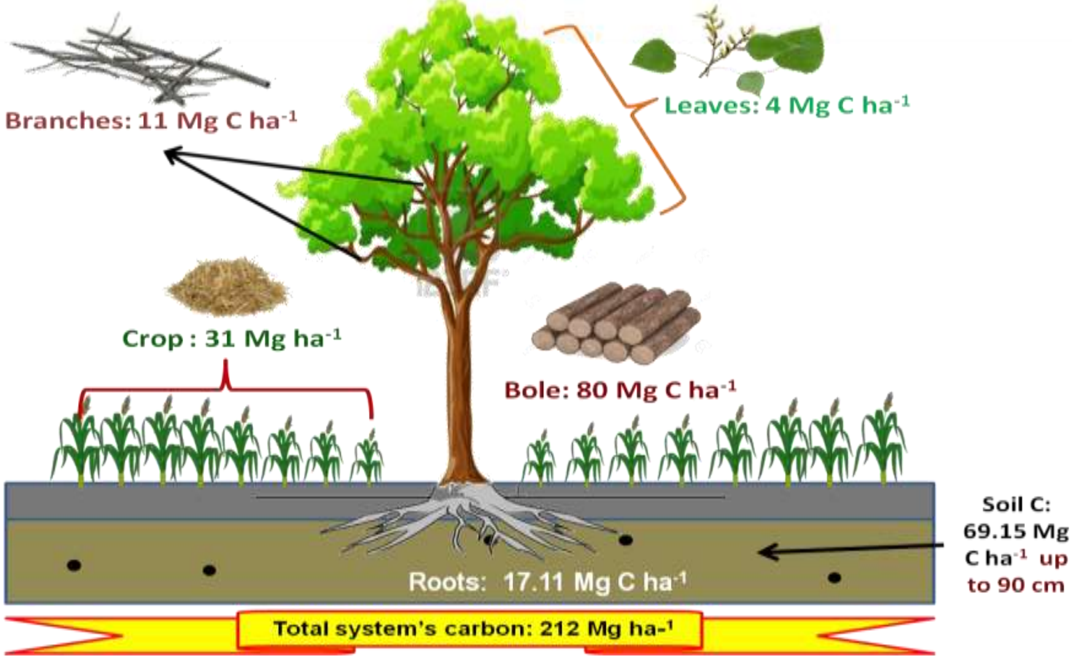

Figure 4. Total carbon stock of sorghum-berseem crop rotation in poplar (5 × 4 m) over a complete rotation of 8 years.

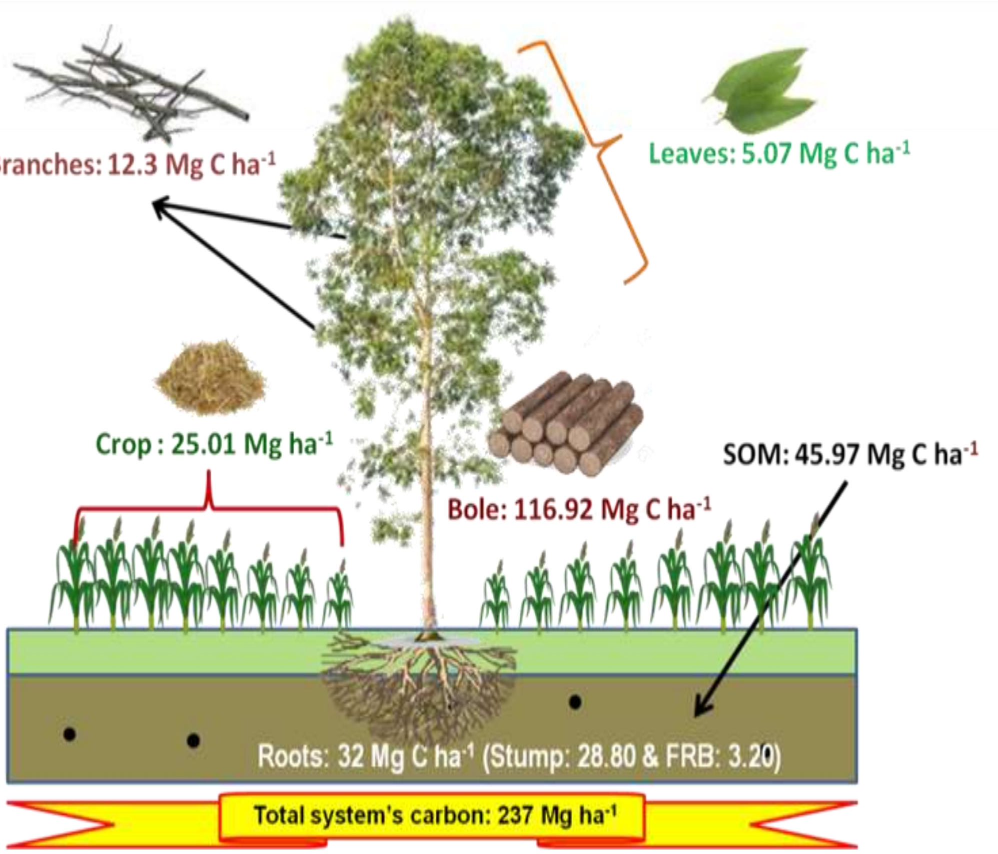

Figure 5. Total carbon stock (Mg ha^{-1}) of Dhaincha–barley crop rotation in eucalyptus-based agroforestry system (3 m × 3 m) over a rotation of 8 years.

6. Conclusions

The agriculture system is under pressure due to climate change, and this poses a hurdle in achieving food, income, and environmental security. Agriculture and related sectors contribute approximately 24% of total global anthropogenic greenhouse gas emissions, which is equivalent to 12.7 GT of carbon dioxide annually, from agriculture covering an area of around 22.2 million km^2. Growing food crops under such circumstances is not sustainable or economically viable. In response, the agroforestry system has emerged as a practical and eco-friendly solution for mitigating climate change. This system involves the cultivation of tree species along with food crops, allowing for the storage of carbon in the terrestrial ecosystem and the rehabilitation of degraded lands. The present paper reviews almost 30 studies on 26 different agroforestry species grown in the Indian Gangetic Plains (IGP). The average carbon sequestration potential for these species is 5.05 Mg C ha^{-1} yr^{-1} for tree densities ranging from 100–10,000 trees. *Poplar deltoides*, for example, produces 180 Mg ha^{-1} of biomass and generates an income of INR 0.72 million ha^{-1} in a 6-year rotation cycle. The paper concludes that incorporating tree components into agricultural land not only improves farm income but also enhances soil health, alters microclimates, and mitigates climate change. Additionally, including tree species tolerant to biotic and abiotic stresses can aid in the reclamation of degraded lands, the enhancement of ecosystem services, and the creation of income and employment opportunities, particularly for small and marginal farmers in India. To make commercial agroforestry more attractive, strengthening research and development, implementing price-support mechanisms for timber and value chains, and establishing decentralized institutions can popularize these systems in the IGP and encourage their adoption by farmers.

Author Contributions: Conceptualization, methodology, S.B.C., R.S.D. and A.R.U.; software, validation, formal analysis, S.B.C., V.K., S.K., C.S. and D.K.Y.; investigation, resources, data curation, S.B.C., R.S.D. and A.R.U.; writing—original draft preparation, S.B.C., D.J. and V.P.; writing—review and editing, visualization, S.B.C., D.J., A.R.C., V.P., H.S.J., V.D.R. and T.M.; supervision, project administration, funding acquisition, S.B.C., V.K., S.K., C.S., D.K.Y. and A.R.C. All authors have read and agreed to the published version of the manuscript.

Funding: Not applicable.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Authors would like to recognize the support of the Ministry of Science and Higher Education of the Russian Federation (no. FENW-2023-0008) and by the Strategic Academic Leadership Program of the Southern Federal University ("Priority 2030").

Conflicts of Interest: The authors declare no conflict of interest.

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