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Rudragouda
Central Coffee Research Institute, Coffee Research Station, Chikkamagaluru, Karnataka, India

Girijesh GK
Department of Agronomy, College of Agriculture, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, India

Nagaraja JS
Central Coffee Research Institute, Coffee Research Station, Chikkamagaluru, Karnataka, India

Devagiri GM
Department of Agronomy, College of Agriculture, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, India

Veeranna HK
Department of Agronomy, College of Agriculture, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, India

Nagarajappa Adivappar
Department of Agronomy, College of Agriculture, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, India

Dinesh Kumar M
Department of Agronomy, College of Agriculture, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka, India

Somshekargouda Patil
Central Coffee Research Institute, Coffee Research Station, Chikkamagaluru, Karnataka, India

Corresponding Author:
Rudragouda
Central Coffee Research Institute, Coffee Research Station, Chikkamagaluru, Karnataka, India

Carbon stock and ecosystem benefits of shaded coffee systems in India: Implications for biodiversity and climate resilience

Rudragouda, Girijesh GK, Nagaraja JS, Devagiri GM, Veeranna HK, Nagarajappa Adivappar, Dinesh Kumar M and Somshekargouda Patil

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Abstract
Coffee cultivation in India, particularly in the ecologically sensitive Western and Eastern Ghats, follows sustainable agroforestry practices that integrate shade trees, enhancing biodiversity, soil fertility and carbon sequestration. This review highlights the critical role of shaded coffee systems in maintaining ecological balance, emphasizing the importance of shade trees for soil organic carbon (SOC) enhancement, biodiversity conservation and carbon neutrality. However, evolving practices, including monoculture adoption and reduced shade cover, driven by economic pressures and international regulations like the European Union Deforestation Regulation (EUDR), challenge these systems. The study highlights the socio-economic and ecological significance of shade trees, analyzing their impact on litterfall, soil fertility and carbon storage across diverse pools. By documenting carbon footprints and mitigation strategies, this review advocates for agroforestry systems as a sustainable solution to mitigate climate change and preserve ecosystem services while maintaining coffee production viability.

Keywords: Coffee cultivation, agroforestry, shade trees, Western Ghats, Eastern Ghats

Introduction
Coffee is one of India's most important plantation crops, traditionally grown in agroforestry systems beneath the shade of native tree canopies. This method promotes biodiversity by supporting mixed cropping with crops such as black pepper, orange and banana. It ensures the long-term sustainability of coffee farms while preserving ecological balance and providing numerous environmental benefits. Indian coffee is considered one of the most environmentally sustainable production systems, playing a key role in the preservation of biodiversity, especially in the ecologically sensitive Western and Eastern Ghats.

However, recent trends in coffee cultivation have led to increased deforestation, as growers reduce shade cover, alter management practices and shift towards monoculture farming to intensify production and boost yields. This has been exacerbated by the introduction of the European Union Deforestation Regulation (EUDR), effective from the end of 2025. Under this regulation, operators and traders in industries such as coffee, cattle, cocoa, wood, rubber, palm and soy must ensure that their products comply with new standards, or face substantial penalties. The EUDR stipulates that only products from land that has not been degraded or deforested after December 31, 2020, will be permitted for import or export within the EU market (The Hindu, 2024) [51].

The reduction in shade cover and the shift towards monoculture farming not only threaten biodiversity but also hinder the critical carbon sequestration role played by shade trees. These trees capture carbon from the atmosphere and contribute to mitigating climate change. Additionally, shaded coffee systems enhance the growth of vegetation, which, in turn, positively influences soil organic carbon (SOC) levels. This increase in SOC can lead to carbon neutrality or even carbon negativity by improving soil health and increasing the carbon storage capacity of the land. The preservation of shaded agroforestry systems is thus essential, as it helps enhance vegetation growth, boost soil carbon content and mitigate climate change impacts, making coffee farming more resilient and sustainable in the face of evolving environmental challenges.

Coffee is one of the country's most important plantation crops. Unlike other places in India, coffee is grown in a traditional agroforestry setting beneath the shade of native tree canopy, allowing for a high degree of diversity (mixed cropping) with black pepper, orange, banana and other plantation crops. This strategy has secured the farm's longevity while also preserving biodiversity and providing a variety of ecological benefits. In short, Indian coffee is the most environmentally benign and sustainable production system, contributing to the preservation of biodiversity in the ecologically vulnerable Western and Eastern Ghats.

During recent years the European Union has passed European Union Deforestation Regulation (EUDR) and it comes into effect from the end of 2025. Operators and traders in the industries of coffee, cattle, cocoa, wood, rubber, palm and soy have until then to ensure their products comply with the legislation, or risk significant penalties (The Hindu, 2024) [51]. It says that only products from land that hasn't been degraded or deforested after December 31st, 2020, will be permitted for import into or exported from the EU market.

Despite its importance and the government's efforts, there has been an increase in destruction on the tree reserve as coffee growers have tended to reduce shade cover, change their management strategies and shift towards monoculture to intensify their cultivation systems and increase yield (Anon, 2011) [5] and such high deforestation rates have had an impact on climate variability and a negative effect on coffee production practice.

Hence, in the review of literature the work done on similar aspects of coffee and shade been reviewed under the following sub headings.

A. Effect of natural shade on quantity of litter fall and soil fertility
B. Socio-Economic Value and Productivity of Shade
C. Shade trees diversity, density and its carbon stock at different pools
D. Tree diversity in agroforestry system
E. Carbon stock in different pools in coffee agroforest ecosystem
F. Estimation of carbon footprint in production and processing stages of value chain

A. Effect of shade trees on litter fall and soil fertility

In coffee farms, shade trees can increase soil fertility in a number of ways. These include improved nitrogen cycling through decomposition, decreased leaching by monitoring runoff and increased nutrient delivery through N-fixation. Shade trees do have a lot of beneficial ameliorative impacts on the soil, including boosting inputs, decreasing losses and improving the physical and chemical processes of the soil. By changing the physical and chemical characteristics of the soil beneath their canopy, shade trees affect soil development. This can be observed by contrasting the soil attributes beneath individual trees with those in the surrounding area that is not covered by trees.

The organic matter and carbon needed by soil organisms are found in the litter that is produced by coffee and shade trees. In addition to improving soil structure and granulation and food web connections, soil organisms also contribute to the carbon cycle and soil nutrients. It is widely acknowledged that trees have a beneficial effect on the nutritional content of soil. Trees, especially those that can fix nitrogen from the air, can supply nutrients to the soil through their litter (Souza *et al.*, 2010) [49].

Shade trees can produce up to 14 Mg ha^{-1} yr^{-1} of litterfall and pruning residues, which include up to 340 kg N ha^{-1} yr^{-1}, as reported by Beer *et al.* (1998) [6]. Leguminous shade trees, however, may fix no more than 60 kg N ha^{-1} yr^{-1} when planted at a density of 100 to 300 trees ha^{-1}.Compared to full sun or open systems, shaded coffee agro-ecosystems are said to have higher total litter biomass and a higher total C stock. Total carbon (C) is regarded as the primary measure of soil quality and agronomic sustainability because of its impact on other physical, chemical and biological variables (Evizal *et al.*, 2013) [17].

Trees provide a network of coarse and fine roots that physically connect the soil and stop erosion. Increased nutrient collection efficiency results from many trees' capacity to use nutrient pools located deeper in the soil than would typically be accessible to crops. Additionally, because coffee roots and shade trees use nutrients from separate soil profile levels, there is far less competition between them for nutrients (Schaller *et al.*, 2003) [46]. These nutrients become available to the crops when they are absorbed into the biomass of the trees and eventually returned to the soil surface through decomposition, mineralization and litter fall (Nair *et al.*, 1999) [32]. Shade trees should be routinely pruned to lessen the likelihood of competition between them and coffee, especially in areas with low soil fertility. Increased organic matter and nitrogen return to the soil would result from this (Dossa *et al.*, 2008) [15].

High species density and functional variety shade trees will improve nutrient retention and reduce N losses. Significant gains of up to 10.8 and 2.12 Mg ha^{-1} in soil C and N in the top 20 cm were made possible by tree cutting and litter collection for mulch application (United Nations COP-11 CBD edition, 2012). In the multiple shade system, there was a positive correlation between total N and organic matter. The multiple shade system may be certified as shade or bird-friendly coffee because of its intricate structure and diversity (Romero-Alvarado *et al.*, 2002) [42]. According to research conducted in Indonesia by Van Noordwijk *et al.* (2002) [54], all sun coffee systems may be converted to shade coffee systems while preserving the remaining forest, increasing average landscape level C stocks by 0.5 Mg C ha^{-1} y^{-1} and partially offsetting the loss of forest. The pH, N, P, K, Ca and Mg levels of shaded soil were considerably greater than those of unshaded coffee.

Because coffee agroforestry systems add more organic material to the soil than single crop systems do and because they also promote nutrient recycling within the system, they can help boost the carbon sequestration of agro ecosystems through plant biomass and soil organic matter. Therefore, by improving a favorable microclimate and increasing carbon storage, shadetrees in coffee systems can lessen the effects of climate change (Jeezer *et al.*, 2019) [21].

By using plant biomass and soil organic matter, coffee with shade systems can help increase the C sequestration in agro ecosystems. Coffee agro-ecosystems are potential carbon sinks because they store a lot more carbon in the aboveground woody biomass of shade trees, the litter layer and soil organic matter than unshaded areas (Albrecht and Kandji, 2003) [1]. Under agroforestry coffee production systems, the amount of organic matter in the soil rises over time. This has a significant impact on the physical and chemical properties of the soil, its fertility, plant nutrition and its biological activity (Brady and Weil, 2002) [8].

B. Socio-economic value and productivity of shade

According to empirical data, a large number of Indian coffee growers operate environmentally friendly plantations and grow coffee in areas of the country's Western and Eastern Ghats that are rich in biodiversity. Due to the farmers' extensive expertise planting coffee shade trees, soil fertility has improved, weeds have been suppressed and coffee pest and disease issues have been discouraged. Shade trees also provide carbon sequestration, fuel wood production, timber, fodder, shelter, aesthetic value, bird habitat, wind break, construction, labor opportunity, fresh air, favorable weather conditions, organic material sources, sustainability of coffee production and high-quality yield. Shade trees are also an alternative source of income through crop diversification with other crops like pepper, orange, avocado, etc.

Compared to cultivating coffee without shade, coffee with shade is an agroforestry system that is more environmentally sustainable, commercially feasible and socially acceptable (Rudragouda *et al.,* 2016; Gokavi *et al.,* 2023) [43, 31]. According to Calvo and Platen (1996) [9], shade trees play a significant role in the production of timber, which has a low management cost and is regarded as a "saving account" that can be realized during periods of low prices or when the underlying crop yields fail. Assuring the provision of additional services and promoting the production and sustainability of these systems, shade trees in coffee farms can offer regulatory services like regulating the climate and boosting water penetration (Sebuliba *et al.,* 2021) [47].

C. Tree diversity & carbon stock (AGB, BGB and SOC) in coffee agroforest ecosystem

Shade tree diversity and density are typically high in agroforestry systems (AFS). In addition to offering local and regional ecosystem services, these systems frequently feature a wide variety of plants and animals. The region's ecological versatility and the coexistence of natural habitats with human-modified landscapes are demonstrated by the diverse tree-based landscapes found in Kodagu, which is located in the central Western Ghats. These landscapes range from expansive coffee plantations to lush evergreen forests and mixed species forest plantations (Devagiri *et al.*, 2019) [13]. Forests and trees are now handled as a vital component of sustainable development thanks to special traditional landscape management techniques combined with environmentally friendly farming methods. One of the most varied production systems in the world is the multi-story coffee-based agroforestry system that the farmers created and maintained using their local knowledge (Anon., 2011) [5]. Because of its sufficient and demonstrated capacity to sequester carbon, the coffee-based agroforestry system (CAS) is the most promising mitigation strategy for the rapidly changing climate and has a great potential for biodiversity conservation. Below is a thorough analysis of the literature relevant to the study's goal (tree diversity and carbon stock in various pools in the coffee agroforest ecosystem).

D. Tree diversity in coffee-based agroforestry system

There are 280 tree species in the shaded coffee agroforestry system (CAS) (Garcia *et al.,* 2010) [18]. *Acrocarpus fraxinifolius* Wt., *Terminalia bellirica* (Gaetn.), *Artocarpus hirsutus* Lam., *Lagerstromia lanceolata* Wight., *Dalbergia latifolia* Roxb., *Aporosa lindleyana* (Wight.) Baill, *Artocarpus heterophyllus* Lam. and *Grevillea robusta* A. are notable shade trees that are frequently seen (Sathish, 2005; Boreux *et al.,* 2016; Maheswarappa *et al.,* 2018) [44, 7, 25].

According to Nath *et al.* (2011) [34], the Kodagu district's traditional shade coffee plantations, located in the southern Indian Western Ghats, are home to a high tree diversity and density. Native biodiversity is valued by local farmers, but they are rapidly replacing the original diverse cover with alien shade trees like *Grevillea robusta*, which grow quickly and are easily exchanged for timber, due to plantation economics and government regulations. Furthermore, in the moist western bioclimatic zone, *G. robusta* develops more slowly. Therefore, it is not advised to plant *G. robusta* in the humid western zone. Instead, native *A. fraxinifolius* is advised for these regions. Tree variety in coffee plantations with different shadow management techniques in Kodagu, Western Ghats, was the subject of a 2009 study by Hareesha. In comparison to a silver oak plantation, the author found that native tree plantations had higher species richness, evenness, beta diversity and Shannon's diversity indices. Additionally, native tree plantations had a greater diversity of avifauna than silver oak plantations. According to the study's findings, many birds may find that native tree coffee farms offer a better alternative habitat than silver oak plantations.

India's coffee AFS are arguably the world's most species-rich coffee systems and one of the most varied agricultural systems. Coffee estates in the Kavery watershed typically have 350 trees per hectare, while devarakadus have 270 trees per hectare. Coffee AFS is home to around 280 distinct tree species. Silver oaks, or *Grevillea robusta*, make up nearly 20 percent of the trees. One of the coffee producing systems with more trees on the planet is the Kodagu coffee plantations. The agronomic qualities of the trees that increase soil fertility and other appropriate microclimates for coffee cultivation and crop diversification are among the reasons for this, as is the necessity to prevent the flower buds from drying up in the event that blossom showers are delayed (Anon., 2011) [5].

Nesper *et al.* (2017) [37] got to an understanding that tree biodiversity in coffee AFS is significantly reduced when the area is intensified from diversified multispecies to *Grevillea robusta*-dominated shade (Shannon's diversity: 2.74 to 0.29). These outcomes were consistent across management approaches (conventional vs. organic farming and irrigation) and a wide rainfall gradient (1060 mm yr^{-1} to 4370 mm yr^{-1}).

In the Cauvery watershed region of Kodagu, Guillemot *et al.* (2018) [19] studied the diversity of trees in natural forests and coffee agroforestry. In native forests and coffee agroforestry, tree diversity was reported to be 44 and 45 species, respectively. Additionally, Manjunatha *et al.* (2017) [26] found that coffee farms with evergreen areas had significantly more tree variety than those with moist deciduous vegetation.

Over the past few decades, *Grevillea robusta* has been introduced into the canopies of coffee agroforestry and landscape studies have shown a progressive conversion of privately owned forests into coffee plantations (Elouard *et al.,* 2000; Garcia *et al.,* 2010; Sathish *et al.,* 2022) [16, 18, 45]. Although native trees have greater multipurpose utility and potential economic value, farmers in the Western Ghats are believed to prefer *G. robusta* primarily because of the economic and legal advantages that the current policy framework bestows upon it (Garcia *et al.*, 2010; Nath *et al.*, 2016) [18, 33]. In addition to land conversion, another notable alteration to coffee plantation characteristics is the substitution of *C. canephora*, which needs sparse shade, for *C. arabica*, which was previously planted under good mixed shade cover. This results in a decline in canopy cover and the number of native tree species (Naveen, 2016) [35]. The district's biodiversity is nevertheless higher than that of the majority of coffee-growing regions in the nation and the world, notwithstanding these changes.

According to Muthappa (2000) [29], large plantations contained more diverse tree species than small coffee plantations, despite the fact that tree species were found to be more prevalent throughout all coffee estates. Native trees may have been cut down because the tiny growers needed the extra cash, which suggests that the diversity of native trees on the coffee plantation has changed. Tree species diversity was comparatively larger (0.84) in plantations belonging to the elder age group (40–60 years) than on younger plantations (0.65).

Agroforestry systems are the most promising land use technique for accomplishing conservation objectives and sustaining rural livelihoods at the landscape level, according to Sathish *et al.* (2022) [45]. Native trees provide shade for the sustainably maintained coffee agroforests in India's Western Ghats region. To boost coffee output, the landscape has changed in recent years in terms of shade tree diversity and density. The significance value index of *Grevillea robusta* rose from 36.05 in 2008 to 53.29 in 2017, maintaining its position as the dominating tree species. Tree density dropped dramatically between 2008 (420±349 stems ha^{-l}) and 2017 (274±82 stems ha^{-l}). Nayak *et al.* (2022) [36] identified 50 tree species in Kodagu's neighboring forests and 102 tree species in coffee agroforests. Coffee agroforests had a higher tree density (351±19.35 stems ha^{-1}) than wild forests (287±13.53 stems ha^{-1}). On the other hand, coffee agroforests had a lower basal area (29.54±1.34 m2 ha^{-1}) than natural forests (39.53±0.38 m2 ha^{-1}).

E. Carbon stock in different pools in coffee agroforest ecosystem

Because of its sufficient and demonstrated potential to sequester carbon, the agroforestry system (AFS) is regarded as the most promising mitigation strategy for the rapidly changing climate. Because they are large carbon sinks, tree-based landscapes are essential for reducing the effects of climate change. Any vegetation system's productivity is primarily determined by the biomass production and carbon storage capacity of its many components, which are influenced by the age and kind of plant as well as other biotic, climatic, edaphic and topographic factors. Bole biomass accounted for 28–86 percent of total aboveground biomass in various vegetation systems. For fast-growing tree species, the percentage contributions of bole, branch and leaf were 65–76, 14–19 and 3–12 percent, respectively. Approximately 76 to 80 percent of aboveground biomass was produced by the stem, 11 to 29 percent by the branches and 3 to 14 percent by the leaves in other tree-based systems. On average, a tree devotes 18.11 percent of its biomass below ground and 81.89 percent to above ground biomass (stem, branch, leaves and litter) (Chaturvedi *et al.*, 2016) [11]. Being the greatest terrestrial carbon store, soil organic carbon also has a major impact on the global carbon cycle. Depending on land use and management, soil can either be a source of greenhouse gases (CO_2, CH_4 and N_2O) or a sink of greenhouse gases (CO_2 and CH_4) (Lal, 2013).

The history of coffee farms, ranging from 1 to 40 years from the establishment of shade trees, was examined by De Leijster *et al.* (2021) [12]. They found that the quality of coffee beans, timber volume, habitat provisioningand aboveground carbon stock all followed positive asymptotic trajectories. They discovered recurring positive correlations between epiphyte richness, erosion management and carbon stock. For the first ten years, there was a trade-off between aboveground carbon stock and coffee output; however, over the next ten to twenty years, there was a positive correlation between coffee yield and erosion control. This study showed that ecosystem service supply can be restored by agroforestry. Agroforestry has the potential to produce between 1.1 and 2.2 Pg C through aboveground biomass production over the next 50 years and it also plays a significant role in climate change adoption and mitigation (Solomon *et al.*, 2007) [48].

According to Panwar *et al.* (2022) [40], the total biomass carbon in coffee agroforests and agri-horticultural systems in western and central India ranged from 1.84 to 134 Mg ha^{-1}. The range of soil organic carbon was 12.26 to 170.43 Mg ha^{-1}, with the highest levels found in south Indian coffee agroforestry. In the Kodagu district, Vaast *et al.* (2010) [53] measured the carbon sequestration of *Coffea arabica* and *Coffea canephora* AFS in relation to nearby reference forest patches. According to the findings, coffee agroforestry using local species sequesters a significant quantity of carbon (190-200 t ha^{-1}), comparable to that of forests. The two main carbon stores are soil and tree biomass, which account for more than 90 percent of the total carbon, whereas coffee plants and litter contribute very little. According to Anon. (2011) [5], coffee AFS made up of Arabica trees shaded by either native or exotic tree species sequestered carbon (183 to 206 t ha^{-1}) at a rate that was comparable to that of the reference forest (196 t ha^{-1}). This also seems to be the case for Robusta AFS shaded with native species (182 t ha^{-1}) and there was a decrease in carbon sequestered in Robusta AFS shaded with *Grevillea robusta* (138 t ha^{-1}).

Similar research was also carried out by Guillemot *et al.* (2018) [19] in native forests and coffee agroforestry in two precipitation zones in the Cauvery watershed region of Kodagu under contrasted management (native versus alien shade trees, robusta versus arabica systems). According to reports, native coffee agroforestry showed high and comparable carbon stocks (228 Mg C ha^{-1} and 234 Mg C ha^{-1}, respectively), even though there was a significant decrease in shade tree cover as compared to forest. According to Kumar (2011), the soil organic carbon concentration was 10.706 Mg ha^{-1} at 15–30 cm soil depth and 17.35 Mg ha^{-1} at 0–15 cm depth. Agroforestry had a carbon content of 131.65 Mg ha^{-1} aboveground and 39.61 Mg ha^{-1} belowground. An investigation of the carbon accumulation in dominating shade trees in coffee farms under two vegetation types was conducted by Manjunatha *et al.* (2017) [26]. According to the study, the top 10 dominant species in evergreen vegetation accounted for 43.3 percent of the total carbon stock, while the top 10 species in moist deciduous vegetation supplied 76 percent. The carbon pool and biomass output from various forest types in the southern and western regions of Karnataka were reported by Devagiri *et al.* (2013) [14]. A maximum above-ground biomass of 250

Mg ha^{-1} and a carbon density of 33 Mg C ha^{-1}was estimated in this study.

The carbon content of biomass, necromass and soil in coffee plantations with three distinct shade levels in three Colombian towns was examined by Andrade and Zapata (2019) [3]. According to reports, 75 percent of the total carbon was stored by the soil (93.9 to 137.7 Mg C ha^{-1} in the upper 30 cm), with trees accounting for 19 percent of the carbon content. The carbon content rose from 23 to 55.8 Mg C ha^{-1} as the number of shade trees increased. With a maximum carbon sequestration value of 7.1 Mg CO_2 ha^{-1} year^{-1} in 30 to 40 percent shade, these coffee plantations fixed an average of 2.3 Mg C ha^{-1} year^{-1}. Coffee plantations were found to have a significant potential for carbon fixation, particularly those with high levels of shade (Yadav and Thokchom, 2014) [56]. Large forest trees on a one-acre shade-grown coffee farm can sequester 70–80 tons of carbon per hectare, roughly similar to the amount of carbon stored in an equivalent area of forest, according to research by Anil Kumar *et al.* (2019) [4]. Less than 10 tons of carbon can be stored by a hectare of coffee that is grown in full sun or outdoors. The potential for carbon stocks in AFS is higher than that of cultivated land use systems. The coffee home garden agroforestry system showed higher carbon store in biomass and soil organic carbon (SOC). The overall ecosystem carbon stores in the woodlot AFS and coffee home garden were 72.9 and 100.4 mg C ha^{-1}, respectively. AFS may be used as a way to mitigate climate change (Mihert Semere, 2019) [28]. A higher rate of carbon fixation in the agroforestry system as opposed to coffee that is cultivated under open condition. The open-grown coffee showed an average of 148.34 Mg ha^{-1}, but the AF had 195.6 Mg ha^{-1}, when taking into account the carbon in the biomass and in the soil up to 0.70 m (Zaro *et al.*, 2020) [57].

In southwestern Ethiopia, the carbon stocks of coffee-based agroforestry varied from 254.9 t C ha^{-1} in the coffee agroforestry shaded by *Syzygium* to 321.8 t C ha^{-1} in the coffee agroforestry shaded by *Albizia* (Niguse *et al.*, 2022) [38]. In the current coffee-based agroforestry, the average carbon sequestration was 287.1 t C ha^{-1}. In the agroforestry systems, coffee plants sequestered a total of 18.8 t C ha^{-1} in the coffee stratum shaded by *Syzygium* and 48.5 t C ha^{-1} in the coffee stratum shaded by *Albizia*. In the coffee *Albizia* association, the aboveground biomass estimates were 140 Mg ha^{-1} and 32 Mg ha^{-1}, while in the open-grown system, they were 29.7 Mg ha^{-1} and 18.7 Mg ha^{-1}, according to Dossa *et al.* (2008) [15]. In the shaded coffee system, albizia trees accounted for 55 percent of the total root biomass and 87 percent of the total aboveground biomass. More carbon stock was stored in shaded coffee agroforestry (81 Mg C ha^{-1}) than in open coffee (22.9 Mg C ha^{-1}), highlighting the significance of shade trees in delivering many ecosystem services. In the Moist Mid-Highlands of Southern Ethiopia, Tesfay *et al.* (2022) [50] examined the carbon stock, structure and woody species composition of an agroforestry system centered on coffee along an elevation gradient. The density, DBH and height of coffee shrubs and shade trees were found to vary significantly throughout the elevation gradient. Along the elevation gradient, the total aboveground woody biomass carbon store varied between 11.07 and 27.48 Mg ha^{-1}. The range of the soil organic carbon stock was 83.91–89.29 Mg ha^{-1}. Nayak and Associates (2022) [36] reported that in a coffee-based agroforestry system, the quantity of carbon stored was 77.39±3.30 Mg ha^{-1}, compared to 88.84±2.90 Mg ha^{-1} in wild forests.

F. Estimation of carbon footprint in production and processing stages of value chain

In the public debate on responsibility and mitigation strategies against the threat of global climate change, the phrase "carbon footprint" has gained widespread usage (Wiedmann and Minx, 2008) [55]. It's critical to comprehend greenhouse gas emissions from coffee supply chains when assessing the industry's alternatives for mitigating climate change. Many coffee-growing regions' futures hinge on measures that enable the reduction of the adverse effects of climate change. Increasing C-sequestration and reducing carbon footprints are essential components of mitigation and adaptation strategies for climate sensitivity. Below is a thorough analysis of the literature on carbon footprints (CFP)

The carbon footprint for 1 kg of fresh coffee cherries was between 0.26 and 0.67 kg CO_2e for conventional management systems and between 0.12 and 0.52 kg CO_2e for organic management systems, according to a 2011 study conducted at the farm level in Costa Rica and Nicaragua that assessed greenhouse gas emissions in coffee grown with varying input levels under conventional and organic management (Noponen *et al.*, 2012) [39]. This study concluded that the inputs of both organic and inorganic nitrogen were the primary sources of GHG emissions. According to Hergoualc'h *et al.* (2012) [20], growing coffee in shaded areas can boost carbon stock by up to 32 t CO_2 eq ha^{-1} and decrease carbon footprint by up to 56 percent. Additionally, a coffee area can become a carbon sequestration site by using agroforestry techniques for coffee cultivation, rather than a carbon emitter (Andrade *et al.*, 2014) [2]. According to Killian *et al.* (2013) [22], green coffee has a total carbon footprint of 4.82 kg CO_2e kg^{-1} along the supply chain. The carbon footprint of the methods used to manufacture one kilogram of green coffee in Costa Rica is 1.77 kilograms of CO_2e, while the techniques used in Europe produce 3.05 kilograms of CO_2e per kilogram of green coffee. According to Martins *et al.* (2018) [27], statistics for Brazilian coffee farms show that the Southeast area has larger carbon footprints (19.791 million t CO_2-equivalent), which translates to a moderate (about 5 percent) value for greenhouse gas emissions. Furthermore, if we consider the carbon sequestration on the biomass of coffee trees, we may be able to further reduce the carbon footprint by 92 percent.

As reported by Nab *et al.* (2020) [30], the average carbon footprint of Arabica coffee from bean to cup in Brazil and Vietnam was 3.51 (±0.13) kg CO_2e kg^{-1} for sustainable coffee production and 15.33 (±0.72) kg of carbon dioxide equivalent per 1 kg of green coffee (kg CO_2e kg^{-1}) for conventional coffee production. Exporting coffee beans via cargo ship instead of freight jet and using less agrochemical inputs, sustainable coffee production reduced its carbon footprint by 77 percent when compared to conventional production. Additional reductions could be achieved by using agrochemicals as efficiently as possible, using less packaging, boiling water more efficiently, using renewable energy, roasting beans before exporting and offsetting carbon emissions. By properly implementing these suggestions through certification programs, additional environmental effects of coffee production may be lessened.

For coffee cherries, roasted coffee and ground coffee, the CFP was 0.40±0.12 kg CO_2e kg^{-1}, 0.55±0.08 kg CO_2e kg^{-1} and 0.56±0.08 kg CO_2e kg^{-1}, respectively. The use of chemical fertilizers accounted for about 70 percent of GHG emissions, with LPG used in roasting and electricity used in grinding coming in second and third. The CFP of coffee cherries was significantly impacted by crop management and planted area size. In large-scale planted areas, co-cultivation with other fruits may considerably lower the CFP. As suitable mitigating strategies for the decline in CFP, optimal fertilizer application, co-cultivation with fruit trees, rejuvenation and the use of a high energy efficiency burner during roasting were recommended (Ratchawat *et al.*, 2020) [41].

In line with Cerri (2022) [10], implementing good practices in coffee growing results in greater carbon sequestration since, in comparison to traditional management, which is already "carbon negative," even more CO_2eq is kept in the soil and in the plant than is released into the atmosphere. The average of the properties evaluated revealed a negative carbon balance of 10.5 tons of CO_2eq per hectare annually, taking into account the shift from traditional to more conservationist management. This balance is calculated by subtracting the 1.74 t CO_2eq/ha/year emitted from the use of fuels, electricity and lime, as well as the 12.25 t CO_2eq/ha/year retained in the soil and plant biomass.

Conclusion

The findings reiterate the indispensable role of shaded coffee agroforestry systems in promoting biodiversity, enhancing soil health and serving as significant carbon sinks. Shade trees not only improve soil organic carbon but also provide socio-economic benefits such as diversified income streams and ecosystem services. The replacement of traditional native shade trees with exotic species, alongside monoculture practices, threatens these benefits, making the preservation and restoration of shaded systems imperative. By leveraging agroforestry's potential to sequester carbon and reduce greenhouse gas emissions, Indian coffee production can align with global sustainability goals while adhering to evolving regulatory frameworks like the EUDR. To this end, policy interventions, farmer incentives and research on optimal shade tree management are essential to sustain the ecological and economic integrity of coffee farming.

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