Global Forest Journal
Journal homepage: https://talenta.usu.ac.id/gfj

Species composition, structure, and carbon stocks of coffee agroforestry systems in East Java, Indonesia

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ARTICLE INFO
Article history:
Received 18 May 2026
Revised 14 July 2026
Accepted 20 July 2026
Available online 31 July 2026

E-ISSN: 3024-9309

How to cite:
H. Hamdi, M. Ardani, L. Pramukyana, D. N. Hariyanto, Y. S. Kusuma, "Species composition, structure, and carbon stocks of coffee agroforestry systems in East Java, Indonesia," *Global Forest Journal*, vol. 04, no. 02, July 2026.

http://doi.org/10.32734/gfj.v4i2.25875

ABSTRACT
Coffee agroforestry systems (CAF) offer an important opportunity to maintain agricultural productivity while enhancing ecosystem services by integrating shade trees and perennial crops. This study aimed to characterize vegetation composition and structure and to estimate carbon stocks in CAF in Panti District, Jember Regency, East Java. A total of 12 nested plots were established to assess vegetation composition, structure, and carbon stocks. The results showed that 17 species belonging to 13 families were identified. The highest Importance Value Index (IVI) at the seedling and sapling levels was *Coffea canephora*, while at the pole and tree levels, *Hevea brasiliensis* dominated. Species diversity (H′ = 0.60–1.77) and evenness (E = 0.50–0.81) increased from the seedling to tree stages. The regeneration structure and diameter class distribution of the stand exhibited an inverse J-shaped distribution pattern. The total carbon stock was 161.3 Mg C ha^{-1}, equivalent to 591.7 Mg CO_2e ha^{-1}. Shade-tree aboveground biomass represented the largest carbon pool (93.9 Mg C ha^{-1}; 58.2%), followed by soil organic carbon (36.2 Mg C ha^{-1}; 22.4%), while coffee shrubs accounted for only 8.2 Mg C ha^{-1} (5.1%). These findings demonstrate that carbon accumulation in this CAF is predominantly biomass-driven rather than soil-driven.
Keyword: Agroforestry, Carbon Stock, Coffea Canephora, Coffee Agroforestry, Species Diversity

1. Introduction

Agroforestry is a sustainable land management approach that integrates woody perennials with crops and/or livestock within spatially and temporally structured arrangements to enhance land productivity while maintaining ecological functions [1]-[3]. Perennial crops cultivated within agroforestry systems (AFS) have been widely recognized as effective climate change mitigation strategies, as they enhance carbon sequestration in both aboveground Biomass (AGB) and belowground Biomass (BGB) while simultaneously supporting long-term ecosystem stability [4,5]. This dual capacity to support land productivity and mitigate climate change underlies the growing interest in AFS as a land-management strategy.

Coffee (*Coffea* spp.) is among the perennial crops most widely integrated into AFS. Within the 133 known Coffea genus, only *Coffea arabica* L. and *Coffea canephora* Pierre ex *A. Froehner* (robusta coffee) are cultivated on a commercial scale and dominate global coffee markets [6]. Global coffee export markets are dominated by 12 major producing countries, including Indonesia, Peru, Ethiopia, Vietnam, Brazil, Honduras, Mexico, Uganda, Colombia, India, Nicaragua, and Guatemala [6]. As part of the global supply, robusta coffee accounts for approximately 40% of global coffee production [7], reflecting its increasing importance in meeting global demand. Robusta coffee is primarily cultivated in tropical regions, particularly in Vietnam, Brazil, Indonesia, Uganda, and India, where favorable climates support large-scale production [7,8].

In Indonesia, the centers of robusta coffee production are located in Aceh, North Sumatra, South Sumatra, Lampung, and Bengkulu Province [9]-[11]. These provinces account for 70% of total national coffee production [12,13]. Besides Sumatra, East Java is also a major robusta coffee-producing region, with the development of coffee agroforestry systems (CAF) [11]. AFS acts as a multifunctional land management approach that not only supports biodiversity conservation but also improves soil fertility and structure, and maintains microclimate conditions [14]. These systems also provide economic opportunities for farmers and strengthen the resilience and sustainability of the agricultural sector [14,15].

Compared to conventional monoculture systems, CAF enhances carbon sequestration through more complex vegetation structures, increases both AGB and BGB, and improves soil organic carbon (SOC) stocks [16]-[18]. The integration of shade trees also moderates microclimatic conditions, reduces environmental stress, and promotes more stable coffee yields under climate variability. These ecological functions highlight the important role of CAF in enhancing climate resilience while contributing to long-term carbon sequestration and environmental sustainability [19,20]. Despite these recognized ecological and climate-regulating functions, information on vegetation structure, species diversity, and multi-pool carbon storage in CAF in Panti District, Jember Regency, remains limited. To date, no study has comprehensively quantified ecosystem carbon pools, including aboveground carbon (AGC), belowground carbon (BGC), litter carbon (LC), herbaceous carbon (HC), and soil organic carbon (SOC), or examined their relationship with vegetation diversity.

To address this gap, the present study examines species composition, vegetation structure, and carbon stocks in CAFs, providing an integrated assessment of the ecological and climate-mitigation function of CAF in Panti District. We hypothesized that the dominance of shade trees in CAF would result in high AGC accumulation and substantial potential for climate change mitigation. Accordingly, this study aimed to: (1) characterize vegetation structure and species diversity across coffee growth stages; (2) estimate carbon stocks and CO_2-equivalent emissions reductions across multiple ecosystem carbon pools; and (3) compare the carbon stock and carbon pool allocation patterns of CAF in Panti District with those reported in other CAF across tropical and subtropical regions. These findings are intended to inform future landscape-level carbon accounting and support sustainable intensification of CAF in comparable production regions of Indonesia.

2. Methods

2.1. Study area

The study was conducted in Panti District, Jember Regency, East Java, Indonesia. Geographically, the study area is located at 8°10′31.69816″ S and 113°37′8.56927″ E (Figure 1). The district covers approximately 8,317 ha (83.17 km²) and ranges in elevation from 25 to 1,000 m above sea level [21]. The soils in Panti District are predominantly classified as Andosols [22]. The area is characterized by a tropical monsoon climate, with an average daily rainfall of 14.60 mm day^{-1}. The highest daily rainfall was recorded in December (27.82 mm day^{-1}), whereas the lowest rainfall occurred during the dry season from July to September (8.84–0.00 mm day^{-1}) [23]. Panti District is one of the main coffee-producing areas in Jember Regency, where coffee cultivation is predominantly managed under AFS. The total area under coffee cultivation is approximately 155 ha [23,24].

2.2. Data collection

The data were collected from October to December 2025. The woody vegetation data were collected using random sampling across 12 plots established in CAF (Figure 1). The total sample area is equivalent to a sampling intensity of approximately 0.31% of the total coffee cultivation in Panti District. Plots were selected to represent shade-based CAF with relatively uniform stand age (15–20 years), minimizing variation in vegetation structure and Biomass associated with stand development. Each main plot measured 20 × 20 m (400 m²) and was used for tree-level observations (diameter at breast height [DBH] ≥ 20 cm). All plots represented similar AFS management dominated by *C. canephora*. Within each main plot, nested subplots were established: 10 × 10 m for poles (10 cm ≤ DBH < 20 cm), 5 × 5 m for saplings (height ≥ 1.5 m and DBH < 10 cm), and 2 × 2 m for seedlings (height < 1.5 m) [25].

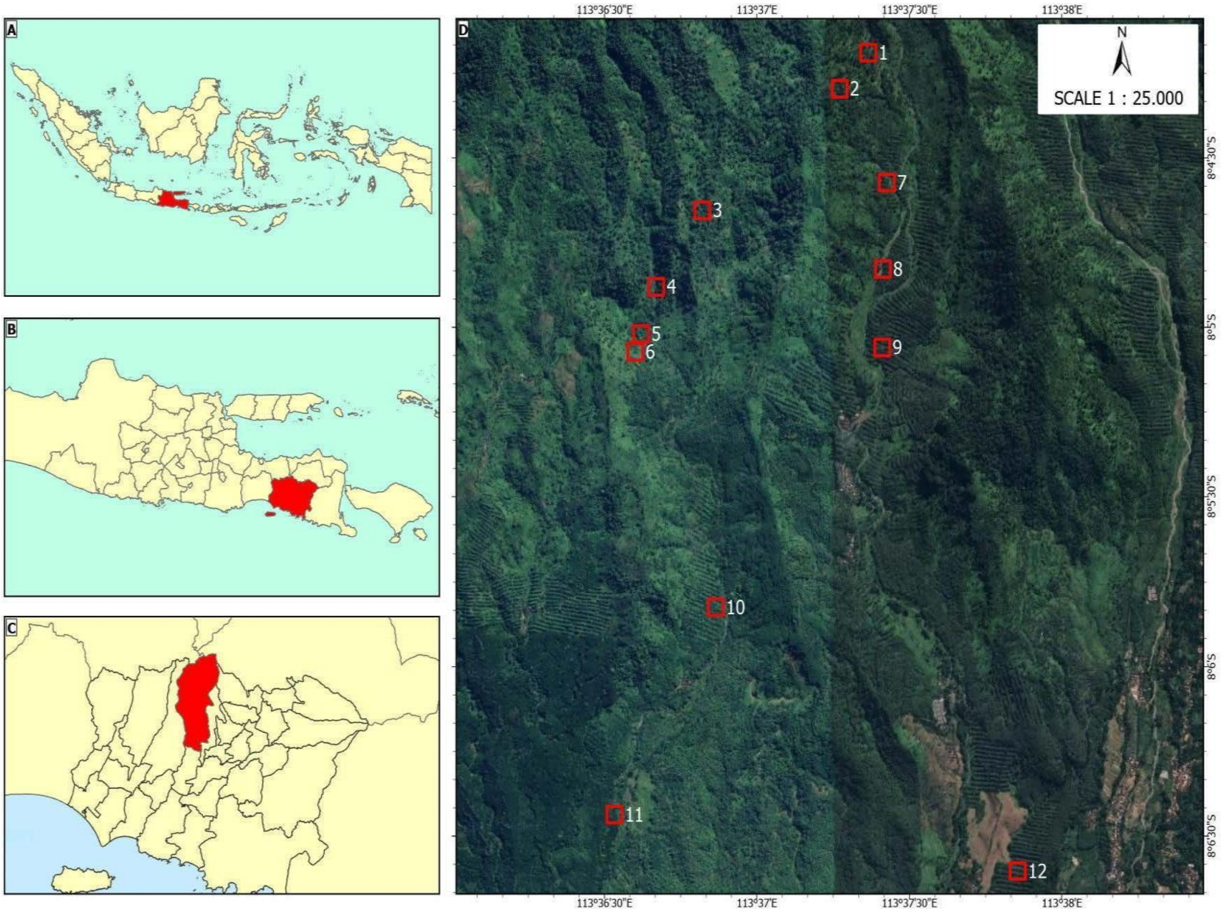


Figure 1. Map of the study area: (a) The location of East Java within Indonesia; (b) Jember Regency; (c) Panti District; and (d) 12 of the sampling plots established for vegetation structure assessment and carbon estimation in agroforestry systems.

An additional 1 × 1 m2 subplots were randomly established within each main plot for understory vegetation and litter sampling. Herbaceous vegetation and litter samples were collected and weighed in the field to obtain fresh Biomass. Subsamples (50 g) of herbaceous vegetation and litter were subsequently oven-dried at 80–85°C until constant weight was achieved to determine dry Biomass [26,27].

Soil samples were collected at 0–30 cm depth following IPCC guidelines for soil carbon assessment, as this layer generally contains the highest concentration of biologically active organic matter and is widely used to estimate SOC stocks in tropical AFS [28]. Several soil subsamples were collected from different points within each main plot measuring 20 × 20 m (400 m²) and combined into a single composite sample, resulting in 12 composite soil samples. Soil samples were analyzed for SOC using the loss-on-ignition (LOI) method, while soil bulk density was measured by oven-drying core samples at 105°C for 24 h and calculating dry mass per unit core volume [29]. For SOC determination, the oven-dried samples were subsequently ignited in a muffle furnace at 360–400°C for ~4 hours, and the percentage weight loss during combustion was used as the loss-on-ignition value to estimate organic carbon content [28,29]. Soil carbon stock was then estimated by combining SOC content with bulk density and sampling depth.

2.3. Data Analysis

2.3.1. Vegetation diversity

Vegetation data were analyzed to evaluate vegetation structure, composition, and species diversity using relative density, relative frequency, relative dominance, the IVI, Shannon–Wiener diversity index, and Pielou's evenness index (Table 1). These indices were applied to quantify patterns of species distribution, dominance, diversity, species richness, and community stability within the CAF.

Table 1. Formulas for analyzing vegetation structure, composition, and diversity indices

No	Formula	Definition
1	$RD = \frac{n_i}{\sum n} \times 100\%$	Relative density (RD, %) indicates the percentage contribution of species i to the overall abundance of all recorded species, where n_i refers to the number of individuals belonging to species i, and ∑n denotes the total number of individuals across all species [30].
2	$RF = \frac{F_i}{\sum F_i} \times 100\%$	Relative frequency (*RF*, %) describes the distribution of a species based on its occurrence across all sampling plots, where F_i is the number of plots containing species *i* and $\sum F$ is the total frequency of all species [30].
3	$RDm = \frac{BA_i}{\sum BA_i} \times 100\%$	Relative dominance (*RDm*, %) indicates the degree of space occupation by a species, calculated using basal area (*BA*), where BA_i is the basal area of species *i* and $\sum BA$ is the total basal area of all species [30].
4	$IVI_s = RD + RF$ $IVI = RD + RF + RDm$	Importance Value Index (*IVI*) is calculated as the sum of *RD, RF*, and *RDm* for trees and poles, while for seedlings and saplings (IVI_s) it is based on *RD* and *RF* [30].
5	$H' = -\sum (p_i \ln p_i)$	Shannon–Wiener diversity index (*H′*) where $p_i = n_i / N$, n_i is the number of individuals of species *i*, and *N* is the total number of individuals. Higher values indicate greater species diversity [31].
6	$E = \frac{H'}{ln\ ln\ (S)}$	Pielou's evenness index (E) was calculated using species richness (S) and the Shannon diversity index (H′). Values approaching 1 indicate a more even distribution of individuals among species [32].

2.3.2. Biomass, Carbon Stock, and CO_2 Estimation

AGB and BGB were estimated using species-specific allometric equations and root-to-shoot ratio approaches (Table 2). AGB estimation was based on DBH, tree height, and wood density variables. Herbaceous Biomass, litter biomass, SOC, carbon stock, and carbon dioxide equivalent (CO_2e) were calculated using the equations presented in Table 3.

Table 2. Allometric equations for aboveground and belowground biomass estimation

No	Species	Allometric equations	References
	Aboveground Biomass		
1	Branched trees	$AGB = 0.11\ \rho\ D^{2.62}$	[33]
2	Unbranched trees	$AGB = (\pi/40)\ \rho\ H\ D^2$	[34]
3	Coffea spp.	$AGB = 0.2811\ D^{2.0635}$	[33,34]
4	Theobroma cacao	$AGB = 0.1208\ D^{1.98}$	[35]
	Belowground Biomass		
1	General vegetation	$BGB = 0.2 \times AGB$	[36]
2	Coffea spp.	$BGB = 0.28 \times AGB$	[37]

Carbon stock was estimated from all ecosystem carbon pools, including tree biomass, understory vegetation, litter biomass, and SOC. Biomass values were converted to carbon stock using a carbon fraction of 0.47, as described in [38]. Carbon stock values were subsequently converted into carbon dioxide equivalent (CO_2e) using the [28] conversion factor of 3.67.

Table 3. Equations used for estimating herbaceous and litter Biomass, soil organic carbon stock, biomass carbon stock, and carbon dioxide equivalent.

No	Formula	Definition
1	$B_h = \frac{DW_s}{FW_s} \times FW_t$	Herbaceous Biomass (B_h, kg) is calculated as the ratio of dry sample weight (DW_s, kg) to fresh sample weight (FW_s, kg), multiplied by total fresh herbaceous Biomass (FW_t, kg) [39].

2	$B_l = \frac{DW_l}{FW_l} \times TFW_l$	Litter biomass (B_l, kg) is calculated as the ratio of dry sample weight (DW_l, kg) to fresh sample weight (FW_l, kg), multiplied by total fresh litter biomass (TFW_l, kg) [40].
3	$SOCS = \frac{D \times BD \times SOC}{100}$	Soil organic carbon stock ($SOCS$, g cm^{-2}) is calculated based on soil depth (D, cm), bulk density (BD, g cm^{-3}), and soil organic carbon content (SOC, %), divided by 100 for percentage conversion [40].
4	C = B × 0.47	Biomass carbon stock (Mg C ha^{-1}) was estimated by multiplying total dry Biomass (B) by a carbon fraction coefficient of 0.47 [41].
6	CO_2 = C × 3.67	Carbon dioxide equivalent (Mg CO_2e ha^{-1}) was calculated from carbon stock (C) using the IPCC conversion factor of 3.67 [41].

3. Results and Discussion

3.1. Vegetation Diversity

Vegetation structure analysis of CAF revealed a total of 17 woody plant species distributed across 13 families, encompassing all recorded growth stages. A total of 3 species were recorded at the seedling stage, while the sapling, pole, and tree stages consisted of 8, 8, and 9 species, respectively. The species composition at each growth stage is presented in Table 4.

Table 4. Importance value index of woody species across vegetation growth stage in the coffee-based agroforestry system

Growth stage	Species	BA (m^2 ha^{-1})	RD (%)	RF (%)	RDm (%)	IVI (%)
Seedling	*Coffea canephora* Pierre ex A.Froehner	-	84.00	0.67	-	164
	Theobroma cacao L.	-	8.00	0.08	-	18
	Ficus ampelos Burm.f.	-	8.00	0.08	-	18
Total IVI of Seedling						200
Sapling	*Coffea canephora* Pierre ex A.Froehner	-	61.76	50.00	-	111.76
	Persea americana Mill.	-	8.82	13.64	-	22.46
	Gliricidia sepium (Jacq.) Kunth	-	10.29	9.09	-	19.39
	Durio zibethinus L.	-	2.94	9.09	-	12.03
	Hevea brasiliensis (Willd. ex A.Juss.) Müll.Arg.	-	7.35	4.55	-	11.90
	Syzygium aromaticum (L.) Merr. & L.M.Perry	-	5.88	4.55	-	10.43
	Syzygium cumini (L.) Skeels	-	1.47	4.55	-	6.02
	Alstonia scholaris (L.) R.Br.		1.47	4.55	-	6.02
Total IVI of Sapling						200
Pole	*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg.	5.57	56.67	63.69	29.41	149.77
	Coffea canephora Pierre ex A.Froehner	0.94	18.33	10.76	29.41	58.50
	Swietenia mahagoni (L.) Jacq.	1.29	11.67	14.76	5.88	32.30
	Durio zibethinus L.	0.36	5.00	4.07	11.76	20.83
	Persea americana Mill.	0.19	3.33	2.22	5.88	11.44
	Citrus hystrix DC.	0.21	1.67	2.43	5.88	9.97
	Parkia speciosa Hassk.	0.10	1.67	1.10	5.88	8.65
	Annona muricata L.	0.09	1.67	0.97	5.88	8.52
Total IVI of Pole						300

Growth stage	Species	BA (m^2 ha^{-1})	RD (%)	RF (%)	RDm (%)	IVI (%)
Tree	*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg.	2.08	36.36	13.56	19.23	69.16
	Ficus sp.	5.62	3.64	36.71	7.69	48.04
	Swietenia mahagoni (L.) Jacq.	1.15	23.64	7.48	15.38	46.50
	Durio zibethinus L.	1.69	14.55	11.05	19.23	44.82
	Ficus ampelos Burm.f.	1.93	7.27	12.62	11.54	31.43
	Pometia pinnata J.R.Forst. & G.Forst.	2.20	3.64	14.34	7.69	25.67
	Parkia speciosa Hassk.	0.30	5.45	1.98	7.69	15.12
	Persea americana Mill.	0.20	3.64	1.32	7.69	12.65
	Tabernaemontana macrocarpa Jack	0.14	1.82	0.94	3.85	6.60
	Total IVI of Tree					300

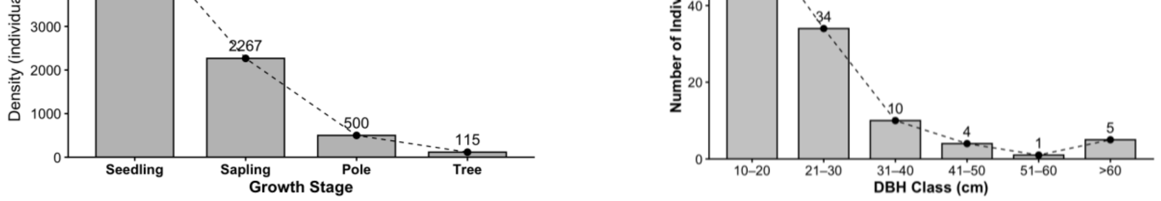
Note: BA = basal area, RD = relative density, RF = relative frequency, RDm = relative dominance, and IVI = importance value index.

IVI analysis indicated distinct patterns of vegetation dominance across growth stages. *C. canephora* dominated the seedling (IVI = 164%) and sapling (IVI = 111.76%), whereas H. brasiliensis led to the dominant species at the pole (IVI = 149.77%) and tree (IVI = 69.16%) stages. The increasing appearance of economically crucial species, including P. *americana, D. zibethinus, S. aromaticum,* and *G. sepium*, indicates a gradual transition from coffee-dominated regeneration to a more diverse overstory. This observed vegetation pattern aligns with the Jember Regency Regional Strategic Plan (RENSTRA) 2021–2026, which identifies Panti Subdistrict as a production center for robusta coffee, rubber, cocoa, clove, and durian [42]. The finding suggest that farmers intentionally sustain coffee regeneration while integrating high-value tree species, thereby sustaining coffee production and enhancing income diversification through AFS.

These vertical stratifications are consistent with vegetation patterns reported in other Indonesian CAF in Kalibaru, Banyuwangi, where *C. canephora* (IVI=128.87%), *D. zibethinus* (IVI= 63.87%), and *S. mahagony* (IVI= 64.43%), G. sepium (21.95%), and P. speciosa (10.03%) were identified as important components across different vegetation growth stage [43]. The comparable co-dominance of understory coffee and canopy tree species across these systems suggests that multistrata stand development is a common structural characteristic of CAF in Indonesia. Furthermore, the persistent structural association between *C. canephora* and *H. brasiliensis* observed in this study supports previous findings that rubber functions effectively as a shade tree, regulating microclimate and improving coffee physiological performance and climate resilience [42,43].

3.2. Vegetation structure

The regeneration of woody species in the CAF of Panti District exhibited a typical inverted J-shaped pattern, with densities declining from 5,208 seedlings ha^{-1} to 2,267 saplings ha^{-1}, 500 poles ha^{-1}, and 115 trees ha^{-1} (Figure 2a). Other AFS in Jember, East Java, also showed high regeneration, with seedling and understory densities reaching 2,419 individuals ha^{-1} and sapling densities reaching 3,131 individuals ha^{-1} [44]. This pattern, characterized by abundant regeneration and progressively fewer individuals in larger growth stages, reflects the combined effects of natural self-thinning and competition for light beneath the coffee canopy. The >56% decline in density from seedlings to saplings suggests that this transition constitutes the primary demographic bottleneck. At this stage, survival is constrained not only by competition for light and growing space but also by differences in physiological performance, as seedlings are more vulnerable to photoinhibition under shaded conditions [45]. The regeneration pattern observed in this study is consistent with previous findings from CAF, where similar inverted J-shaped stand structures have been reported in Gayo, Central Aceh, Indonesia, and Liquiçá, Timor-Leste [44,45].



a) b)

Figure 2. (a) The density of individual per hectare across growth stage (b) diameter breast height (DBH) class distribution of woody species across six DBH classes.

Consistent with the regeneration structure (Figure 2a), the DBH class distribution followed an inverted J-shaped curve (Figure 2b). Individuals were strongly concentrated in the 10–20 cm DBH class (n = 60), followed by a progressive decline across the 21–30 cm (n = 34), 31–40 cm (n = 10), 41–50 cm (n = 4), and 51–60 cm (n = 1) classes. The slight increase in the >60 cm class (n = 5) suggests the persistence of a small cohort of large legacy trees (Figure 2). This distributional pattern is characteristic of uneven-aged stands with continuous recruitment. It is commonly observed in structurally complex shade-grown CAF systems, suggesting sustained regeneration and long-term stand stability [25].

The tree species composition across all DBH classes demonstrates a layered stand structure formed by cultivation management practices and tree retention. The low DBH classes (I–II) are dominated by economically important species, namely *H. brasiliensis, S. mahagoni, and C. canephora*. Medium DBH classes (II–III) are dominated by fruit-bearing trees such as *D. zibethinus, P. americana, and P. speciosa* [46,47]. High DBH classes (IV–VI) consist of 46 individuals, dominated by *Ficus* sp. and *P. pinnata*. These high DBH classes function as canopy stratification, microclimate regulation, and habitat provision in AFS landscapes. Their presence reflects retained trees or remnants resulting from past farmer selection, where individuals with ecological, functional, or cultural value are retained in AFS management [48].

3.3. Diversity and Evenness Index

Variation in species diversity at each growth stage is shown by the Shannon diversity index value (H′) and the uniformity value (E) in Table 5. H′ ranges from 0.60 - 1.77 at the seedling to tree stage, which indicates a low diversity category (H′ < 2.0) [49]. However, H′ increased consistently across growth stages. This trend indicates that species diversity increases with growth rate, resulting in higher diversity in the tree strata than in the seedling strata. Management practices such as weeding and weed removal reduce seedling diversity. This pattern is characteristic of managed multistrata AFS, where intensive management reduces understory regeneration while retaining or leaving shade trees ultimately increases canopy-level diversity.

Table 5. Shannon diversity index (H′) and Pielou’s evenness (E) of vegetation communities at different growth stages in coffee agroforestry systems.

Growth stage	H′	E
Seedling	0.60	0.50
Sapling	1.33	0.58
Pole	1.35	0.65
Tree	1.77	0.81

The diversity values observed in the present CAF in Panti District were generally consistent with those reported from other CAFs in East Java. Previous studies in Sumberejo, Patokpicis, and Bambang villages of East Java reported H′ values ranging from 0.53–1.95 at the seedling level, 0.66–0.96 at the sapling level, and 1.69–1.86 at the tree level, and E values ranging from 0.48–0.95 at all growth stages [48]. Another study in Kalibaru District, Banyuwangi Regency, East Java, also reported higher diversity values, namely H′ of 2.03–2.16 at the sapling level and 2.00–2.21 at the tree level, with evenness values of 0.70–0.72 and 0.70–0.73, respectively [43]. A similar pattern was also observed in the Abedongoro District, Ethiopia, where shaded coffee forests and natural mixed forests had H′ values of 0.83 ± 0.48 and E values of 0.96 ± 0.03 [50]. These findings indicate that vegetation communities with more complex structures tend to have a more even distribution of species, thus supporting higher ecological stability.

3.4. Estimation of Biomass and Carbon Stocks

CAF in Panti District stores a total ecosystem carbon stock of 161.3 Mg C ha^{-1}, equivalent to 591.7 Mg CO_2e ha^{-1} (Table 6). The AGC from shade trees is the largest contributor to the total carbon stock of 93.9 ± 90.9 Mg C ha^{-1} (58.2%), followed by SOC at 36.2 ± 35.6 Mg C ha^{-1} (22.4%) and BGC from shade trees at 18.8 ± 18.2 Mg C ha^{-1} (11.7%). In contrast, the AGC of coffee plants only contributes 8.2 ± 7.4 Mg C ha^{-1} (5.1%). Combined, shade tree carbon stocks (AGC + BGC) accounted for 69.9% of the total ecosystem carbon stock, significantly higher than the contribution of coffee plants (AGC + BGC), which accounted for only 6.1%. A similar pattern was also reported in the CAF system in Western Ethiopia, where shade tree biomass carbon stocks (AGC and BGC) were much higher than those of coffee plants. In contrast, coffee biomass only contributed about 37.5 Mg C ha^{-1} (12.8%) of the total AFS carbon stock [51]. These findings highlight the dominant role of shade trees in long-term carbon sequestration.

Table 6. Carbon stock and CO_2 equivalent of different ecosystem components in a coffee-based agroforestry system.

Component	Carbon Stock (Mg C ha⁻¹)	CO_2 Equivalent (Mg CO_2e ha⁻¹)	Contribution (%)
Shade tree AGC	93.9± 90.9	344.4 ± 333.6	58.2
Coffee AGC	8.2 ± 7.4	30.1 ± 27.2	5.1
Shade tree BGC	18.8 ± 18.2	68.9 ± 66.7	11.7
Coffee BGC	1.6 ± 1.5	5.9 ± 5.5	1.0
LC	2.3 ± 1.0	8.4 ± 3.7	1.4
SOC	36.2 ± 35.6	132.9 ± 130.6	22.4
HC	0.3 ± 0.2	1.1 ± 0.7	0.2
Total Carbon	161.30	591.7	100

Note: AGC = aboveground carbon; BGC = belowground carbon; LC = litter carbon; SOC = soil organic carbon; HC = herbaceous carbon.

Compared with other CAF across tropical and subtropical regions, the AGC stock of the Panti CAF (102.1 ± 92.4 Mg C ha^{-1}) showed an intermediate position among reported CAF (Table 7). AGC stocks in mixed shade-tree AGF systems in Nepal (43.5 ± 48.3 Mg C ha^{-1}) and Inga-based systems in Peru (43.2–55.8 Mg C ha^{-1}) were considerably lower, whereas higher values were reported in structurally mature systems dominated by large shade trees, including *A. schimperiana and A. gummifera*-based CAF in Ethiopia (180–181 Mg C ha^{-1}) (Table 7). Similarly, the total carbon stock of the Panti CAF (161.3 Mg C ha^{-1}) was higher than several lower-biomass systems. The mixed shade-tree systems in Nepal (138.8 Mg C ha^{-1}) and *Inga* sp.-based CAF in Peru (118.2 Mg C ha^{-1}), but remained lower than high-biomass systems in Ethiopia, particularly *A. schimperiana*-based CAF (321.8 Mg C ha^{-1}) and natural mixed forest systems (284.7 Mg C ha^{-1}). These differences highlight that carbon storage capacity among AFS is strongly regulated by stand development, shade-tree composition, and potential biomass accumulation.

The relatively high AGC contribution in the Panti CAF was primarily associated with the structural characteristics of the shade-tree community, particularly the presence of large-diameter individuals (Table 4; Figure 2). Although individual density declined across growth stages (Figure 2a), large-diameter trees contributed disproportionately to stand-level Biomass because biomass accumulation increases nonlinearly with increasing stem diameter, resulting in greater carbon storage capacity [51,52]. This pattern was further supported by the substantial BA contributions of *H. brasiliensis* at the pole stage (5.57 m^2 ha^{-1}) and Ficus sp. at the tree stage (5.62 m^2 ha^{-1}) (Table 4). Nevertheless, the dominance of smaller-diameter classes (I-III) and the limited representation of medium- and large-sized trees (Figure 2) suggest that the stand structure has not yet reached its maximum biomass accumulation potential compared with more structurally mature systems. Consequently, the relatively high variability in AGC stock (SD = 92.4 Mg C ha^{-1}) likely reflects the uneven distribution of large biomass pools among plots, with carbon storage concentrated in areas where retained mature shade trees are present.

Table 7. Comparison of carbon stock components (Mg C ha^{-1}) in coffee agroforestry systems across tropical and sub-tropical regions.

Location	Shade tree / system	AGC (Mg C ha⁻¹)	BGC (Mg C ha⁻¹)	HC (Mg C ha⁻¹)	LC (Mg C ha⁻¹)	SOC (Mg C ha⁻¹)	Total C (Mg C ha⁻¹)	Refe-rence
Panti, Jember, Indonesia	Mixed shade trees	102.1 ± 92.4	20.4 ± 18.5	0.3 ± 0.2	2.3 ± 1.0	36.2 ± 35.6	161.3	This study
Gorkha; Lamjung; Nuwakot; Tanahu, Nepal	Mixed shade trees	43.5 ± 48.3	18.6 ± 20.3	-	-	75.7 ± 11.2	138.8	[53]
Nono Sale, Ethiopia	Natural mixed forest	143.7 ± 67.4	31.6 ± 6.7	3.9 ± 0.2	2.4 ± 0.3	103.2 ± 7.7	284.7	[54]
Nono Sale, Ethiopia	*Albizia schimperiana*	181 ± 62.5	39.3 ± 6.3	1.8 ± 0.6	1.6 ± 0.2	98.1 ± 1.3	321.8	[54]
Nono Sale, Ethiopia	*Syzygium guineense*	145.3 ± 52.3	30.3 ± 5.2	3.8 ± 0.9	2.5 ± 0.5	73.2 ± 2.8	254.9	[54]
Nono Sale, Ethiopia	Natural mixed forest	143	31.4	3.9	2.4	10.3	190.92	[55]

Nono Sale, Ethiopia	*Albizia gummifera*	180.2	39.0	1.8	1.6	9.8	232.4	[55]
Nono Sale, Ethiopia	*Syzygium* sp.	144.9	30.1	3.8	2.5	7.3	188.6	[55]
Tabalosos, Peru	*Inga* sp.	55.8 ± 17.4	9.9 ± 2.7	3.7 ± 0.8	3.2 ± 0.9	45.7 ± 28.1	118.2	[56]
San Luis de Shuaro & Perené, Peru	*Inga edulis*	43.2	9.3	0.1	2.7	105.4	162.9	[57]
Villa Rica & San Luis de Shuaro, Peru	*Retrophyllum rospigliosii*	46.6	9.9	0.2	1.3	129.6	190.4	[57]
San Luis de Shuaro & Perené, Peru	*Pinus tecunumanii*	42.5	9.3	0.2	1.5	106.1	163.7	[57]
Villa Rica, Peru	*Eucalyptus grandis*	72.1	14.2	0.1	3.9	98.6	178.5	[57]
Perené, Peru	*Inga* sp. & *Pinus tecunumanii*	70.1	15.1	0.2	2.4	77.0	163.1	[57]

Comparison of carbon stock distributions among CAFs (Figure 3) shows clear differences in carbon allocation patterns between carbon compartments. The Panti district CAF is characterized by a dominant AGC (63.3%) and a low SOC (22.4%). This pattern contrasts with several other CAFs in Figure 3, where SOC represents the dominant carbon stock, particularly in CAFs *I. edulis* (AGC 26.5% vs SOC 64.7%), *P. tecunumanii* (AGC 26.0% vs SOC 64.8%), *R. rospigliosii* (AGC 24.5% vs SOC 68.1%), and *E. grandis* (AGC 40.4% vs SOC 55.2%) [57]. These contrasting patterns of carbon allocation highlight the variability in carbon sequestration mechanisms among AFS, suggesting that carbon storage in the Panti CAF is predominantly driven by woody biomass accumulation rather than by persistent soil organic carbon.

The SOC stock in the Panti CAF (36.2 Mg ha^{-1}) represented a relatively modest contribution compared with other CAF (Table 7). This value is higher than those reported for low-SOC systems such as *Syzygium* sp. (7.3 Mg ha^{-1}), *A. gummifera* (9.8 Mg ha^{-1}), and natural mixed forest systems (10.3 Mg ha^{-1}). However, it remains lower than several AFS including *Inga* sp. (45.7 Mg ha^{-1}) and mixed shade tree systems (75.7 Mg ha^{-1}), as well as moderate- to high-SOC systems such as *S. guineense* (73.2 Mg ha^{-1}), *Inga* sp. + *P. tecunumanii* (77.0 Mg ha^{-1}), *E. grandis* (98.6 Mg ha^{-1}), *A. schimperiana* (98.1 Mg ha^{-1}), natural mixed forest systems (103.2 Mg ha^{-1}), *I. edulis* (105.4 Mg ha^{-1}), *P. tecunumanii* (106.1 Mg ha^{-1}), and *R. rospigliosii* (129.6 Mg ha^{-1}) [54]. The relatively lower SOC storage in Panti is associated with limited litter input, lower root biomass contribution, and reduced long-term stabilization of organic matter compared with systems containing larger trees, denser canopy structures, and greater BGB inputs. Field observations during the surveys indicated that farmers routinely removed litter from the AFS plots, reducing the return of organic matter to the soil. Consequently, Panti's carbon storage capacity is currently more dependent on aboveground vegetation than on soil carbon accumulation.

Overall, Panti CAF's carbon storage is biomass-based, with retained shade trees a key component supporting ecosystem carbon accumulation. The presence of large-diameter trees contributes substantially to AGC storage, while SOC contributes relatively less. These findings emphasize the importance of maintaining and promoting diverse shade tree structures in CAF landscapes to enhance long-term carbon sequestration while maintaining ecosystem function.

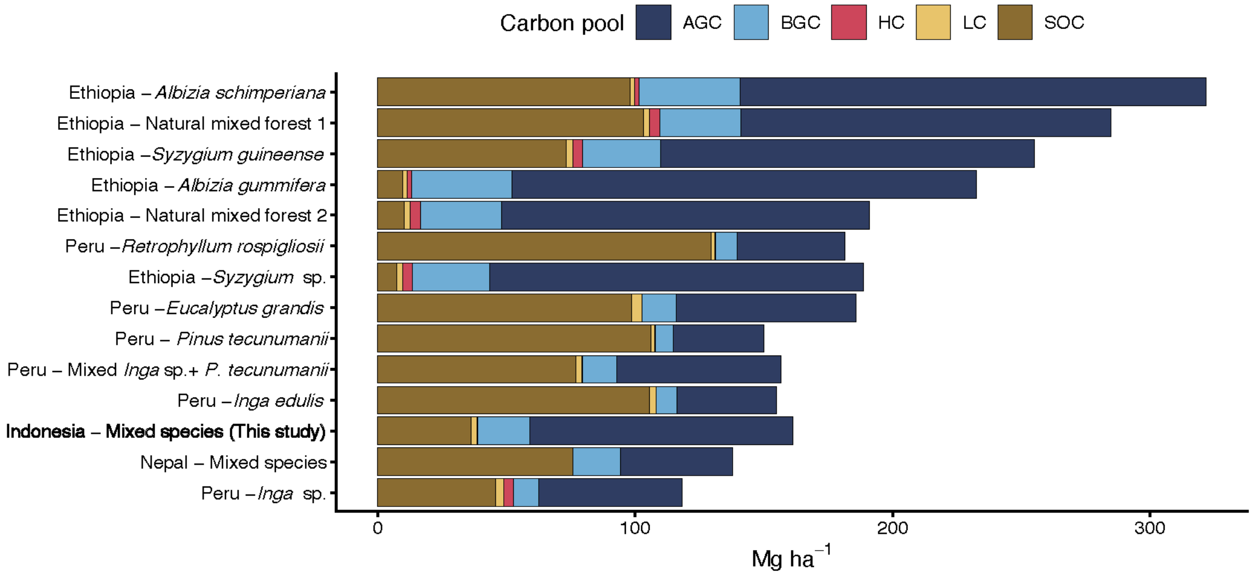


Figure 3. Composition of carbon pools in coffee-based agroforestry systems across tropical and subtropical regions.

4. Conclusion

The CAF in Panti District exhibits a vertically layered vegetation structure, with *C. canephora* dominating at the seedling and sapling stages, and *H. brasiliensis* dominating at the pole and tree stages, along with increasing species diversity across growth stages (H′ = 0.60–1.77). The system stored 161.3 Mg C ha^{-1} (591.7 Mg CO_2e ha^{-1}), dominated by shade tree AGC (58.2%), SOC (22.4%), shade tree BGC (11.7%), and coffee AGC (5.1%), with other components contributing less than 2% to the total carbon stock. This suggests a biomass-driven rather than soil-driven pattern of carbon storage. This confirms that shade tree-based CAFs make a significant contribution to climate change mitigation. Maintenance of large shade trees, canopy diversification, and improved soil carbon management are recommended to enhance the long-term ecological and mitigation value of this system.

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