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Original Research Article

Tree Diversity and Carbon Stock Dynamics in the Coffee Agroforestry Systems of Kodagu, Western Ghats

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Abstract: In coffee-based agroforestry systems under diverse shade tree patterns in Kodagu, Central Western Ghats, India, tree diversity and carbon stock were investigated in both *Coffea arabica* and *Coffea canephora* plantations spanning 4106 km^2 during 2023-24 and 2024-25. Six distinct shade patterns—native, mixed and exotic species—were assessed under varying management regimes (low, medium and high). Field enumeration recorded tree density, basal area, species richness and structural attributes using nested sampling approaches. Biodiversity indices such as the Shannon-Wiener Index (SWI) and Simpson's Index (SI) evaluated species diversity and dominance, revealing maximum biodiversity in native and mixed shade systems than in exotic species-dominated systems. The carbon stock distribution was studied across Above-Ground Biomass (AGB), Below-Ground Biomass (BGB) and Soil Organic Carbon (SOC). *Arabica* plantations recorded higher total biomass (362.43 Mg ha^{-1}) than *Robusta* (215.50 Mg ha^{-1}), with native and mixed shade systems outperforming exotic systems. SOC contributed over 50 per cent to the total carbon stock, with significant variations across shade patterns and management regimes. *Arabica* systems showed higher carbon stock (353.06 Mg ha^{-1}) and CO_2 sequestration potential (1294.57 Mg C ha^{-1}) than *Robusta* systems (272.97 Mg ha^{-1} and 1000.88 Mg C ha^{-1}, respectively). Native and mixed shade systems exhibited superior SOC accumulation and carbon sequestration potential (1212.02 Mg C ha^{-1} and 1194.81 Mg C ha^{-1}) compared to exotic systems (1036.34 Mg C ha^{-1}). These findings highlight the ecological importance of native and mixed shade systems in enhancing biodiversity, carbon storage and soil health. The study advocates integrating native tree species for long-term sustainability and resilience in coffee agroforestry systems.

Keywords: Coffee Agroforestry, Tree Diversity, Carbon Stock, Soil Organic Carbon, Biodiversity Indices, Carbon Sequestration, Kodagu.

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INTRODUCTION

India is the seventh-largest coffee producer globally, contributing 3.4 per cent to global production and 4.8 per cent to exports (*Anon.,* 2024). Coffee cultivation plays an important role in supporting India's socioeconomic fabric, particularly in locations like the Central Western Ghats, which house traditional agroforestry landscapes. These landscapes are important not just for coffee production, but also for biodiversity conservation and ecosystem services.

Kodagu district, located in the Western Ghats, produces about 35 percent of India's coffee (*Anon.,* 2024). Referred to as the "land of the river Cauvery," it is crucial for water resources supporting millions in Karnataka and Tamil Nadu. Predominantly, coffee here is shade-grown within agroforestry systems that blend native, mixed and exotic tree species. The traditional practice of shade-grown coffee in Kodagu creates multi-storied agroforestry structures through intercropping coffee with black pepper, orange, avocado and cardamom. These plantations, covering approximately 33 per cent of Kodagu's total area, are most diversified coffee production systems in the world (Toledo and Moguel, 2012). However, recent intensification practices, like native shade trees replacement with fast-growing exotics such as silver oak (*Grevillea robusta*),

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have raised sustainability concerns. While *Grevillea robusta* offers advantages such as fast growth and compatibility with pepper cultivation, it has led to reductions in tree diversity and canopy cover, impacting biodiversity, water availability and carbon sequestration potential in the long term (Peeters *et al.,* 2003; Schaller *et al.,* 2003).

Agroforestry systems in tropical regions, such as Kodagu's, are globally recognized for their potential in carbon storage and biodiversity conservation. Research indicates that integrating shade trees in coffee plantations improves soil structure, enhances carbon sequestration and supports diverse flora and fauna (Jose and Bardhan, 2012; Perfecto *et al.,* 1996). Shade trees contribute significantly to carbon cycling through aboveground and belowground biomass, litter production and nutrient recycling, thereby maintaining soil fertility and ecosystem stability (Oelbermann *et al.,* 2005; Nair, 1989). Despite these recognized benefits, data on carbon stocks, tree diversity and nutrient dynamics specific to Kodagu's coffee agroforestry systems remain limited. This study aims to address these gaps in knowledge by evaluating tree diversity, structural characteristics and carbon stocks across different coffee agroforestry systems in Kodagu. By focusing on varying shade management practices, including native, mixed and exotic tree species, the research seeks to quantify the ecological and carbon sequestration benefits of these systems. The findings provide actionable insights for promoting sustainable agroforestry practices, enhancing carbon storage and conserving biodiversity in coffee-growing landscapes. This research also aims to contribute to global discussions on sustainable land management and mitigating climate change by highlighting agroforestry system role in carbon sinks and biodiversity reservoirs.

MATERIAL AND METHODS

The research was carried out during 2023-24 and 2024-25 in the coffee agroforest systems at Kodagu district, Western Ghats, India. The region is known for its unique shade-grown coffee plantations that integrate native, mixed and exotic tree species. Six distinct shade patterns in coffee agroforest systems were identified for this study, *viz*., (1) *Coffea arabica* plantation with native tree species as shade, (2) *Coffea arabica* plantation with mixed tree species (native and exotic) as shade, (3) *Coffea arabica* plantation with exotic tree species (*Grevilia robusta*) as shade, (4) *Coffea canephora* plantation with native tree species as shade (5) *Coffea canephora* plantation with mixed tree species (native and exotic) as shade and (6) *Coffea canephora* plantation with exotic tree species (*Grevilia robusta*) as shade.

Coffee farms were stratified by shade pattern to ensure geographic interspersion and capture three management regimes: low, medium and high. Low regimes included small farms (<2.5 ha) with minimal inputs, traditional practices and little mechanization. Medium regimes involved medium-sized farms (2.5–10 ha) with moderate inputs, partial mechanization and systematic practices. High regimes covered large farms (>10 ha) with intensive inputs, mechanization and advanced agronomic practices. This stratification aligned with agroforestry methodologies linking management intensity to farm size and inputs. Six land-use systems with three management levels were selected, with four samples per shade-management combination, totaling 72 plots. Stabilized coffee plantations aged 15–20 years (*C. arabica*) and 35–40 years (*C. canephora*) were chosen, with similar management practices where feasible (Fig.1). Using a nested design, 36 quadrats (25 × 50 m) for each coffee species were laid out randomly (four per regime-shade type) for tree enumeration and two 5 × 5 m subplots within each quadrat were used to assess coffee biomass (Fig. 2). This ensured robust data collection on ecological and agronomic outcomes in Kodagu coffee systems.

a. Data Collection

In each 25 × 50 m (0.125 ha) plot, woody plants having girth at breast height (GBH) ≥30 cm were identified to species level using field keys and taxonomist support. The tree height and GBH were measured with a Hypsometer (Blume Leiss) and measuring tape. By this two, the tree density per hectare was determined. Composite soil samples were taken from five depths (0–20, 20–40, 40–60, 60–80 and 80–100 cm), pooled and mixed for fertility analysis.

b. Assessment of Diversity of trees and Structures in Coffee Agroforest Systems

Tree stand structures were evaluated based on density of tree, basal area, and the girth class distribution. To evaluate species distribution, diversity indices such as the Shannon–Wiener diversity (H'), Simpson's index (D) and species richness were employed. Species richness was accessed by recording tree species numbers in each of the quadrat. Shannon–Wiener Index (H') was used to quantify species diversity and evenness, with higher values indicating greater diversity and more uniform species distribution. Simpson's Index (D) assessed dominance, representing the likelihood that two randomly selected individuals would belong to the same species, with lower values indicating higher diversity. Tree girths were categorized into size classes and their frequencies were represented using bar graphs to visualize the distribution patterns. Stem density, reflecting structural complexity, was assessed by counting the number of trees with girths greater than 30 cm per unit area. Basal area, indicating structural heterogeneity, was determined by adding the total basal area of trees, with higher values signifying greater forest complexity. Shannon and Simpson indices were calculated using standard formulas, offering a detailed analysis of tree diversity, dominance and structural attributes within the coffee agroforests.

c. Carbon Stock in Coffee Agroforest Ecosystem

Above-ground biomass (AGB): The AGB was calculated using non-destructive methods based on density of the wood and stem volume (Chave *et al*., 2004; Vashum and Jayakumar, 2012). Volume estimation was based on tree metrics, including GBH (≥30 cm) and height. When species-specific equations were unavailable, regional volume equations were utilized. Biomass for coffee plants was calculated using allometric equations (Segura *et al*., 2006) based on diameter and height measurements. The total AGB per hectare was calculated by combining the biomass of trees and coffee plants in each plot (25 m × 50 m). AGB was multiplied by 0.27 to determine Below-Ground Biomass (BGB). The total biomass (TB) was the sum of AGB and BGB.

The carbon stock was calculated as 47 per cent of the total biomass weight (*Anon.,* 2007), with the formula: Carbon stock (Mg C ha^{-1}) = 0.47 × TB weight (Mg ha^{-1}). The amount of carbon sequestrated as CO_2 was calculated by converting carbon stock to CO_2 equivalents using the factor 3.67 (Ajaykumar, 2003). The Soil Organic Carbon (SOC) was estimated at various depths of the soil (0–100 cm) by collecting composite soil samples. Walkley and Black method (1934) used for SOC analysis. Soil organic carbon was then calculated using the formula: Carbon (Mg ha–1) = SOC (%) × bulk density of the soil (Mg m^{-3}) × Sampling depths (cm). The total carbon stock in the coffee agro-forest ecosystem was calculated by adding the carbon stocks of the trees, coffee plants and soil.

d. Data Analysis:

The research data were analyzed statistically using ANOVA, with Duncan's multiple-range test (DMRT) used to compare treatment means and origin Pro 2023b and SPSS 28 were used for data analysis.

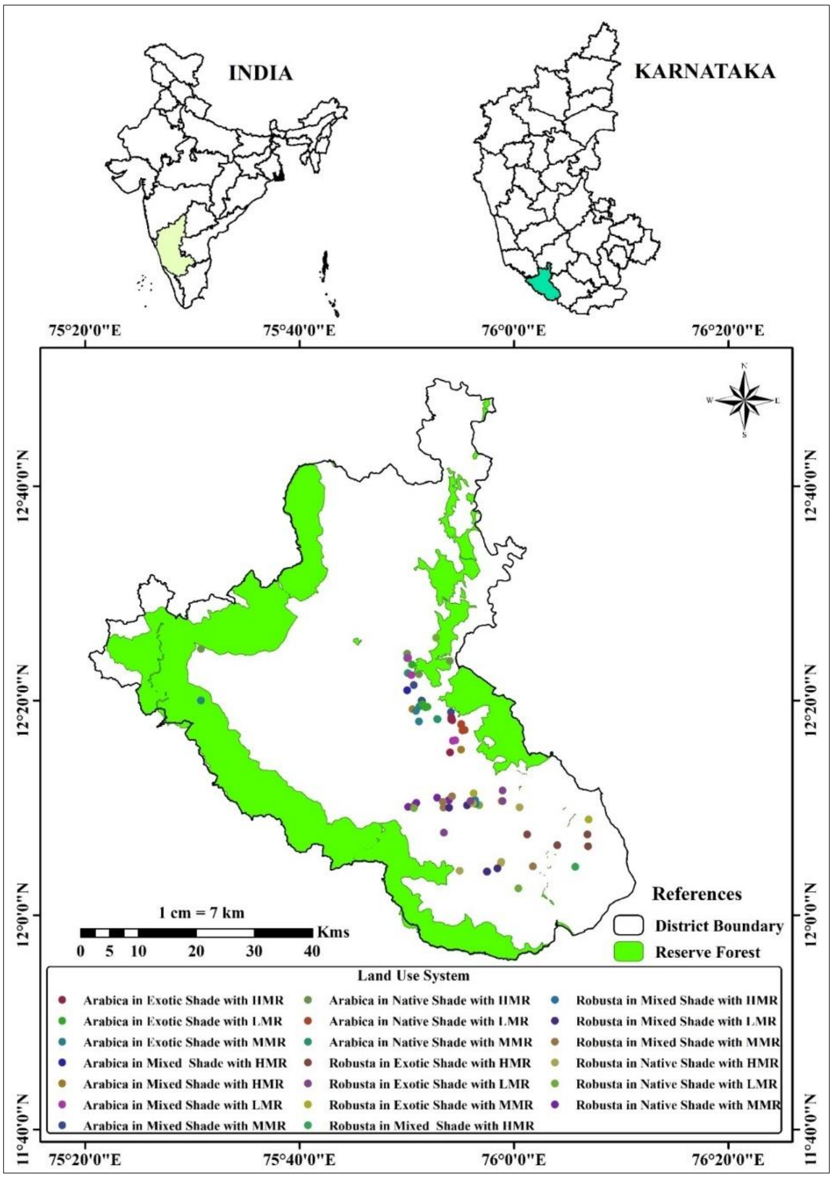

Fig. 1: Location of sample coffee plantations

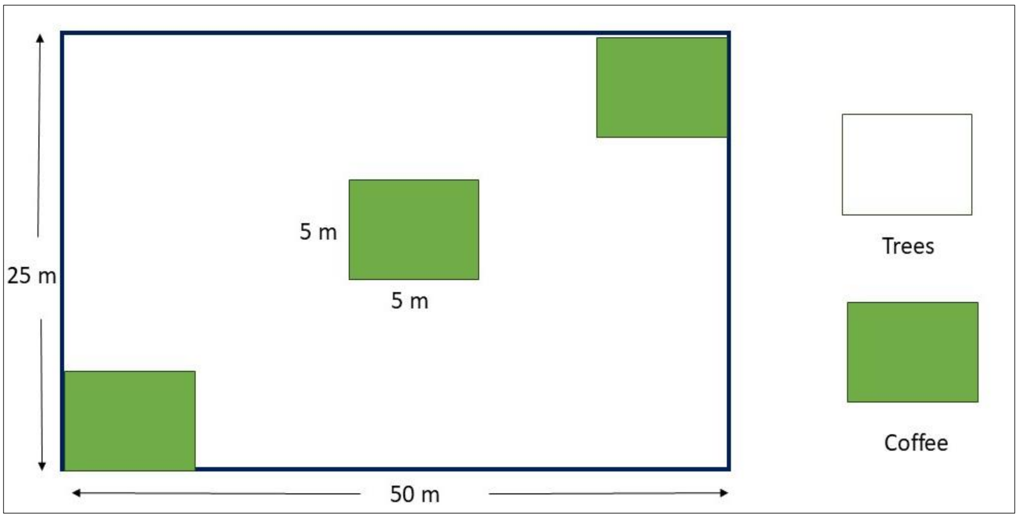

Fig. 2: Nested phase sampling technique at each sample plot

Table 1: Impact of shade patterns and management practices on shade tree diversity and richness in coffee agroforestry systems (AFS)

Treatments	Species richness (S)	Shannon- Weiner Index (H')	Simpson's Index (D)
Coffee species			
Coffea arabica (Arabica) grown in AFS	49	2.38	0.18
Coffea canephora (Robusta) grown in AFS	61	2.61	0.21
Different shade pattern			
Coffea grown under native tree species	49	3.01	0.08
Coffea grown under mixed canopy tree species	63	2.70	0.16
Coffea grown under exotic tree species	24	1.17	0.59
Shade management regimes			
Coffea grown under AFS with high management regimes	46	2.45	0.19
Coffea grown under AFS with medium management regimes	48	2.60	0.17
Coffea grown under AFS with low management regimes	52	2.50	0.21
Coffee sp. with different shade pattern			
Arabica Coffea grown under native tree species as shade in AFS	30	2.53	0.13
Arabica Coffea grown under mixed canopy of tree species as shade in AFS	37	2.30	0.18
Arabica Coffea grown under exotic tree species as shade in AFS	14	1.19	0.53
Robusta Coffea grown under native tree species as shade in AFS	40	3.10	0.06
Robusta Coffea grown under mixed canopy of tree species as shade in AFS	48	2.75	0.16
Robusta Coffea grown under exotic tree species as shade in AFS	22	1.00	0.65

Table 2: Tree density (stems ha^{-1}) and tree basal area (m^2 ha^{-1}) as influenced by different shade types and management regimes in arabica and robusta coffee grown under agroforestry system at Central Western Ghat of India

Treatments		Tree density (stems ha^{-1})				Tree basal area (m^2 ha^{-1})			
		Native shade	Mixed shade	Exotic shade	Mean	Native shade	Mixed shade	Exotic shade	Mean
Arabica	HMR	284.00	246.00	206.00	**245.33**	28.56	27.67	18.57	**24.93**
	MMR	242.00	266.00	262.00	**256.67**	27.77	30.32	22.33	**26.81**
	LMR	140.00	276.00	240.00	**218.67**	27.03	26.77	18.84	**24.21**
	Mean	**222.00**	**262.67**	**236.00**	**240.22**	**27.79**	**28.25**	**19.91**	**25.32**
Robusta	HMR	174.00	254.00	266.00	**231.33**	18.62	21.93	18.88	**19.81**
	MMR	146.00	190.00	224.00	**186.67**	16.58	17.44	15.88	**16.63**
	LMR	156.00	272.00	192.00	**206.67**	20.72	18.21	14.40	**17.78**
	Mean	**158.67**	**238.67**	**227.33**	**208.22**	**18.64**	**19.19**	**16.39**	**18.07**
	HMR	229.00	250.00	236.00	**238.33**	23.59	24.80	18.72	**22.37**
	MMR	194.00	228.00	243.00	**221.67**	22.18	23.88	19.11	**21.72**

	LMR	148.00	274.00	216.00	**212.67**	23.88	22.49	16.62	**20.99**
	Mean	**190.33**	**250.67**	**231.67**	**224.22**	**23.21**	**23.72**	**18.15**	**21.70**
Factors		**SEm±**		**CD (0.05)**		**SEm±**		**CD (0.05)**	
Coffee Spp. (Fact. A)		10.87		30.83		0.74		2.10	
Shade types (Fact. B)		13.31		37.76		0.91		2.57	
Interaction A × B		18.83		NS		1.28		NS	
Management regimes (Fact. C)		13.31		NS		0.91		NS	
Interaction A × C		18.83		NS		1.28		NS	
Interaction B × C		23.06		NS		1.57		NS	
Interaction A × B × C		32.61		NS		2.22		NS	
HMR: High management regimes, MMR: Medium management regimes & LMR: Low management regimes									

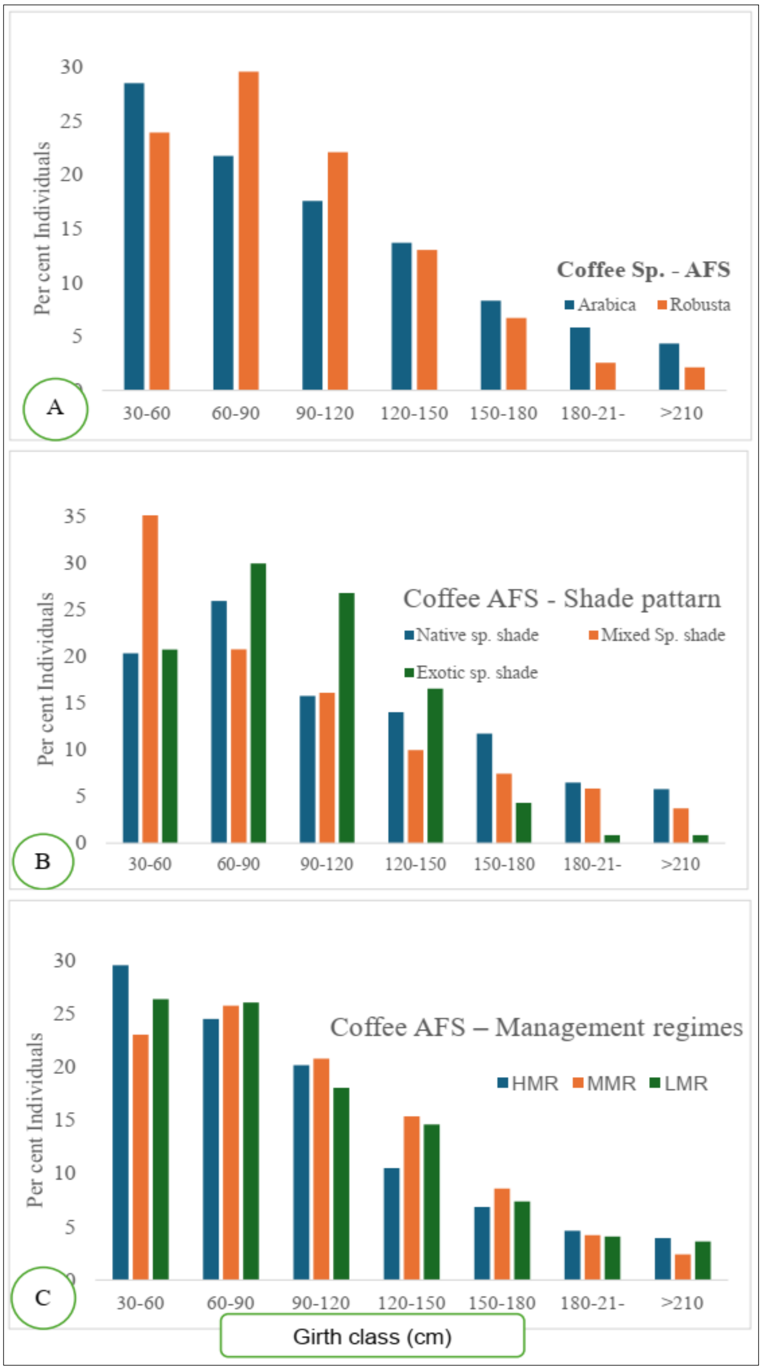

Fig. 3: Girth class distribution of trees in various production practices / land use systems of Kodagu

Table 3: Total above and below ground biomass of shade trees and coffee plants (Mg ha^{-1}) as influenced by different shade types and management regimes in arabica and robusta coffee grown under agroforestry system in Central Western Ghat of India

Treatments		Total (Tree + coffee) AGB (Mg ha^{-1})				Total (Tree + coffee) BGB (Mg ha^{-1})			
		Native shade	Mixed shade	Exotic shade	Mean	Native shade	Mixed shade	Exotic shade	Mean
Arabica	**HMR**	317.90	331.71	251.21	**300.27**	85.83	89.56	67.83	**81.07**
	MMR	353.40	328.12	203.61	**295.04**	95.42	88.59	54.97	**79.66**
	LMR	275.83	304.93	201.69	**260.82**	74.47	82.33	54.46	**70.42**
	Mean	**315.71**	**321.59**	**218.84**	**285.38**	**85.24**	**86.83**	**59.09**	**77.05**
Robusta	**HMR**	177.70	190.99	170.45	**179.71**	47.98	51.57	46.02	**48.52**
	MMR	189.75	149.73	155.57	**165.01**	51.23	40.43	42.00	**44.55**
	LMR	198.49	154.73	139.73	**164.32**	53.59	41.78	37.73	**44.37**
	Mean	**188.65**	**165.15**	**155.25**	**169.68**	**50.93**	**44.59**	**41.92**	**45.81**
	HMR	247.80	261.35	210.83	**239.99**	66.91	70.56	56.92	**64.80**
	MMR	271.57	238.93	179.59	**230.03**	73.32	64.51	48.49	**62.11**
	LMR	237.16	229.83	170.71	**212.57**	64.03	62.05	46.09	**57.39**
	Mean	**252.18**	**243.37**	**187.04**	**227.53**	**68.09**	**65.71**	**50.50**	**61.43**
Factors		**SEm±**		**CD (0.05)**		**SEm±**		**CD (0.05)**	
Coffee Spp. (Fact. A)		10.61		30.10		2.87		8.13	
Shade types (Fact. B)		13.00		36.87		3.51		9.95	
Interaction A × B		18.38		52.14		4.96		14.08	
Management regimes (Fact. C)		13.00		NS		3.51		NS	
Interaction A × C		18.38		NS		4.96		NS	
Interaction B × C		22.52		NS		6.08		NS	
Interaction A × B × C		31.84		NS		8.60		NS	
HMR: High management regimes, MMR: Medium management regimes & LMR: Low management regimes									

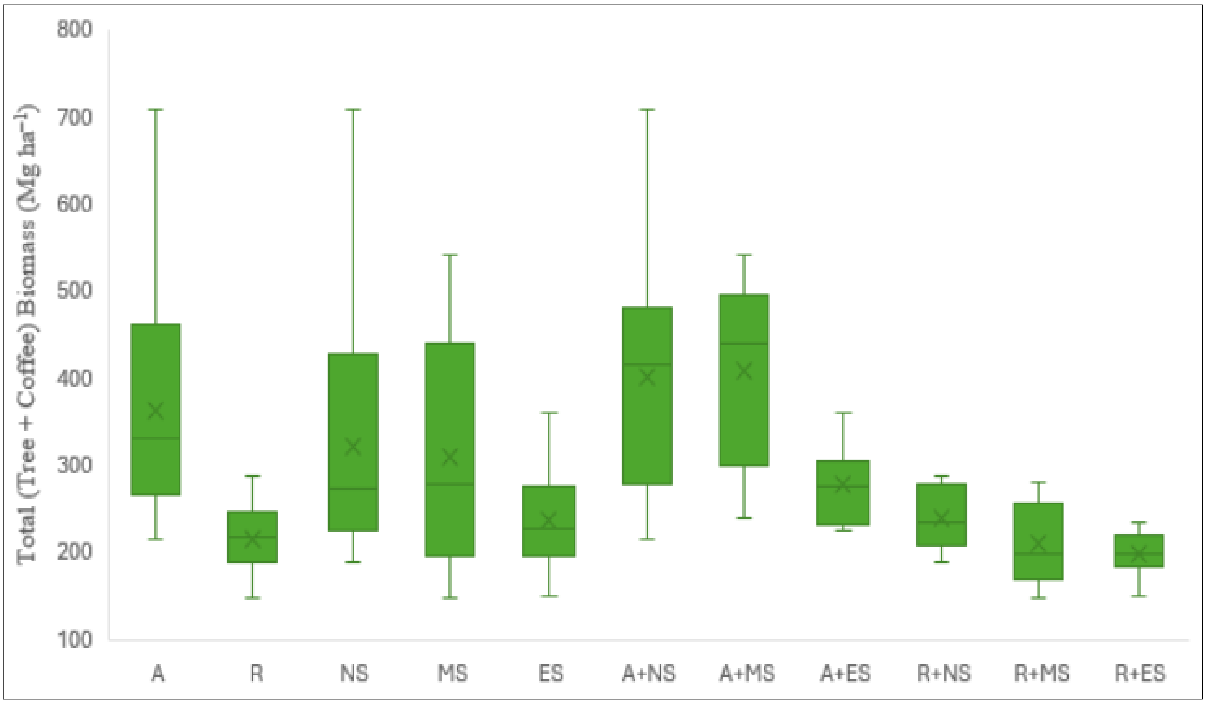

Fig. 4: Total biomass (AGB & BGB) of shade trees and coffee plants (Mg ha^{-1}) as influenced by different shade types (NS-native, MS-mixed & ES-exotic) in Arabica (A) and Robusta (R) coffee grown under agroforestry system

Table 4: Carbon stock and CO_2eq sequestration of standing shade trees and coffee plants (Mg ha^{-1}) as influenced by different shade types and management regimes in Arabica and Robusta coffee grown under agroforestry system at Central Western Ghat of India

Treatments		Carbon (Tree + Coffee) stock (Mg ha^{-1})				Total (Tree + Coffee) Co_2eq (Mg C ha^{-1})			
		Native shade	Mixed shade	Exotic shade	Mean	Native shade	Mixed shade	Exotic shade	Mean
Arabica	**HMR**	189.75	198.00	149.95	**179.23**	695.77	726.00	549.80	**657.19**
	MMR	194.07	195.86	121.54	**170.49**	773.45	718.13	445.63	**645.74**
	LMR	164.65	182.01	120.39	**155.68**	603.69	667.38	441.43	**570.83**
	Mean	**182.82**	**191.96**	**130.62**	**168.47**	**690.97**	**703.84**	**478.95**	**624.59**
Robusta	**HMR**	106.07	114.00	101.74	**107.27**	388.92	417.99	373.05	**393.32**
	MMR	113.26	89.37	92.86	**98.50**	415.28	327.70	340.48	**361.15**
	LMR	118.48	92.36	83.41	**98.08**	434.43	338.65	305.82	**359.63**
	Mean	**112.60**	**98.58**	**92.67**	**101.28**	**412.88**	**361.45**	**339.78**	**371.37**
	HMR	147.91	156.00	125.84	**143.25**	542.34	572.00	461.42	**525.25**
	MMR	153.67	142.61	107.20	**134.49**	594.37	522.92	393.05	**503.45**
	LMR	141.56	137.19	101.90	**126.88**	519.06	503.01	373.63	**465.23**
	Mean	**147.71**	**145.27**	**111.65**	**134.88**	**551.92**	**532.64**	**409.37**	**497.98**
Factors		**SEm±**		**CD (0.05)**		**SEm±**		**CD (0.05)**	
Coffee Spp. (Fact. A)		6.40		18.14		23.23		65.88	
Shade types (Fact. B)		7.83		22.22		28.45		80.69	
Interaction A × B		11.08		31.89		40.24		114.11	
Management regimes (Fact. C)		7.83		NS		28.45		NS	
Interaction A × C		11.08		NS		40.24		NS	
Interaction B × C		13.57		NS		49.28		NS	
Interaction A × B × C		19.19		NS		69.69		NS	
HMR: High management regimes, MMR: Medium management regimes & LMR: Low management regimes									

Table 5: Soil carbon stock (Mg ha^{-1}) at 0-20 cm and 21-40 cm depth as influenced by different shade types and management regimes in arabica and robusta coffee grown under agroforestry system at Central Western Ghat of India

Treatments		Soil carbon stock (Mg ha^{-1}) at 0-20 cm depth (D1)				Total Soil carbon stock (Mg ha^{-1}) at 0-100 cm depth			
		Native shade	Mixed shade	Exotic shade	Mean	Native shade	Mixed shade	Exotic shade	Mean
Arabica	**HMR**	61.20	62.40	55.20	**59.60**	205.80	188.15	194.30	**196.08**
	MMR	52.80	60.60	52.80	**55.40**	175.90	202.85	181.15	**186.63**
	LMR	46.20	58.80	55.20	**53.40**	155.05	178.75	162.55	**165.45**
	Mean	**53.40**	**60.60**	**54.40**	**56.13**	**178.92**	**189.92**	**179.33**	**182.72**
Robusta	**HMR**	58.20	59.40	53.40	**57.00**	181.80	179.00	145.70	**168.83**
	MMR	51.00	53.40	49.20	**51.20**	185.50	190.30	172.65	**182.82**
	LMR	48.60	42.60	52.80	**48.00**	176.10	144.50	169.60	**163.40**
	Mean	**52.60**	**51.80**	**51.80**	**52.07**	**181.13**	**171.27**	**162.65**	**171.68**
	HMR	59.70	60.90	54.30	**58.30**	193.80	183.58	170.00	**182.46**
	MMR	51.90	57.00	51.00	**53.30**	180.70	196.58	176.90	**184.73**
	LMR	47.40	50.70	54.00	**50.70**	165.58	161.63	166.08	**164.43**
	Mean	**53.00**	**56.20**	**53.10**	**54.10**	**180.03**	**180.59**	**170.99**	**177.20**
Factors		**SEm±**		**CD (0.05)**		**SEm±**		**CD (0.05)**	
Coffee Spp. (Fact. A)		0.83		2.34		3.49		9.90	
Shade types (Fact. B)		1.01		2.87		4.27		NS	
Interaction A × B		1.43		4.05		6.04		NS	
Management regimes (Fact. C)		1.01		2.87		4.27		12.12	
Interaction A × C		1.43		NS		6.04		NS	
Interaction B × C		1.75		4.96		7.40		NS	
Interaction A × B × C		2.48		NS		10.47		NS	
HMR: High management regimes, MMR: Medium management regimes & LMR: Low management regimes									

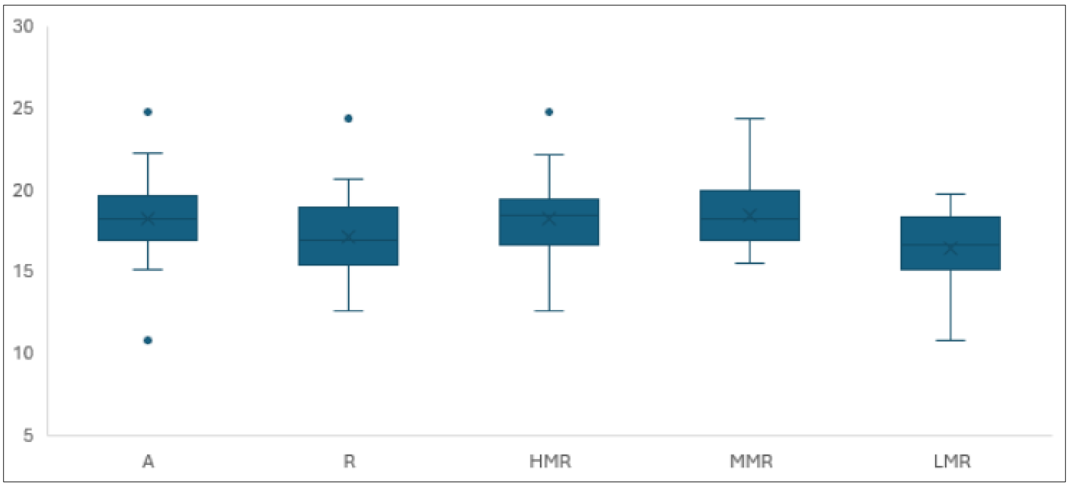

Fig. 5: Soil organic carbon stock (kg m–3) in arabica (A) and robusta (R) coffee grown under agroforestry system with different management regimes

Table 6: Total Carbon stock (Mg ha^{-1}) and CO_2 sequestration both from biomass carbon and soil carbon (Mg C ha^{-1}) as influenced by different shade types and management regimes in arabica and robusta coffee grown under agroforestry system at Central Western Ghat of India

Treatments		**Total Carbon stock (Biomass + Soil)**				**Total CO_2eq (Biomass + Soil)**			
		Native shade	**Mixed shade**	**Exotic shade**	**Mean**	**Native shade**	**Mixed shade**	**Exotic shade**	**Mean**
Arabica	**HMR**	395.55	386.15	344.25	**375.32**	1450.37	1415.88	1262.24	**1376.16**
	MMR	386.84	398.71	302.69	**362.74**	1418.42	1461.92	1109.84	**1330.06**
	LMR	319.70	360.76	282.94	**321.13**	1172.21	1322.80	1037.45	**1177.48**
	Mean	**367.36**	**381.87**	**309.96**	**353.06**	**1347.00**	**1400.20**	**1136.51**	**1294.57**
Robusta	**HMR**	287.87	293.00	247.44	**276.10**	1055.52	1074.33	907.28	**1012.38**
	MMR	298.76	279.67	265.51	**281.31**	1095.45	1025.47	973.53	**1031.48**
	LMR	294.58	236.86	253.01	**261.48**	1080.13	868.48	927.69	**958.77**
	Mean	**293.74**	**269.84**	**255.32**	**272.97**	**1077.03**	**989.43**	**936.17**	**1000.88**
	HMR	341.71	339.58	295.84	**325.71**	1252.94	1245.10	1084.76	**1194.27**
	MMR	342.80	339.19	284.10	**322.03**	1256.93	1243.69	1041.69	**1180.77**
	LMR	307.14	298.81	267.97	**291.31**	1126.17	1095.64	982.57	**1068.13**
	Mean	**330.55**	**325.86**	**282.64**	**313.02**	**1212.02**	**1194.81**	**1036.34**	**1147.72**
Factors		**SEm±**		**CD (0.05)**		**SEm±**		**CD (0.05)**	
Coffee Spp. (Fact. A)		7.27		20.61		26.65		75.57	
Shade types (Fact. B)		8.90		25.24		32.63		92.55	
Interaction A × B		12.58		NS		46.15		NS	
Management regimes (Fact. C)		8.90		25.24		32.63		92.55	
Interaction A × C		12.58		NS		46.15		NS	
Interaction B × C		15.41		NS		56.52		NS	
Interaction A × B × C		21.80		NS		79.94		NS	
HMR: High management regimes, MMR: Medium management regimes & LMR: Low management regimes ; Co2e = carbon dioxide equivalent.									

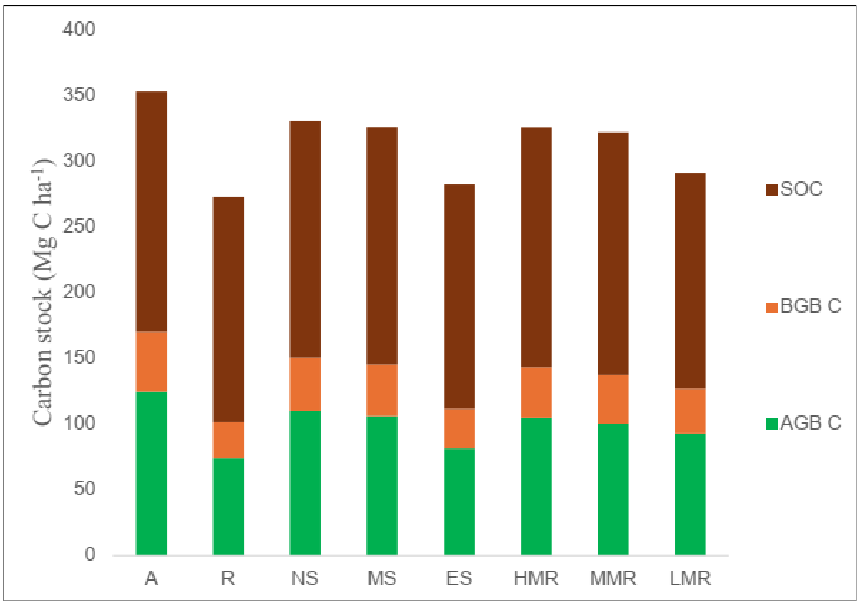

Fig. 6: Total carbon stocks in coffee-based land use system as influenced by different shade types (NS-native, MS-mixed & ES-exotic) and management regimes (high, medium and low) in Arabica (A) and Robusta (R) coffee grown under agroforestry system

RESULTS AND DISCUSSION

Tree Diversity and Structure:

Assessment of tree diversity in coffee agroforestry systems revealed significant variations influenced by shade patterns, management regimes and coffee species. Metrics such as Shannon-Wiener Index (H'), Species Richness (S) and Simpson's Dominance Index (D) highlighted these differences (Table 1). Robusta plantations exhibited greater species richness (61) compared to arabica plantations (49). Among shade patterns, mixed species canopies had the highest richness (63), followed by native species (49) and exotic species (24). Management regimes showed minimal variation, with richness ranging from 46 to 52. Robusta coffee under mixed shade recorded the highest richness (48), followed by native shade (40). Similarly, arabica plantations under mixed shade exhibited higher richness (37) compared to native shade (30), while exotic shade consistently showed the lowest biodiversity. The Shannon-Wiener Index indicated greater ecological stability in robusta plantations (H' = 2.61) than in arabica plantations (H' = 2.38). Native shade recorded the highest diversity (H' = 3.10), followed by mixed species (H' = 2.70) and exotic shade (H' = 1.17). Management regimes showed slight variation, with medium management (H' = 2.45) marginally surpassing low (H' = 2.43) and high (H' = 2.40). The highest diversity was observed in robusta coffee grown under native shade (H' = 3.10), followed by robusta under mixed shade (H' = 2.75). Native and mixed shade patterns promoted biodiversity and ecological stability, while exotic shade significantly reduced diversity. Simpson's Dominance Index further supported these findings, with arabica plantations showing slightly higher diversity (D = 0.18) than robusta plantations (D = 0.21). Native shade had the lowest dominance (D = 0.08), followed by mixed species (D = 0.16) and exotic shade (D = 0.22). Medium management systems recorded slightly better diversity (D = 0.17) compared to low or high systems (D = 0.19). The most diverse combination was robusta coffee under native shade (D = 0.06).

Overall, native and mixed shade systems fostered higher biodiversity and ecological stability, while exotic shade reduced species diversity and simplified ecosystems. These findings align with studies from biodiversity-rich regions like the Western Ghats, where native trees are critical for maintaining ecosystem services (Hareesh and Nagarajaiah, 2019; Sathish *et al.,* 2022). Globally, coffee agroforestry systems demonstrate species richness ranging from 45 in Mexico to 107 in Veracruz, with site conditions, species pools and management practices driving these variations (Bandeira *et al.,* 2005 and Lopez-Gomez *et al.,* 2008). Native and mixed shade trees enhance biodiversity and ecosystem resilience in coffee agroforestry, whereas exotic species pose risks of ecological degradation.

Structural Characteristics (tree density, basal area and girth distribution classes):

Tree density and basal area are crucial indicators of structural dynamics in agroforestry systems (AFS), reflecting their potential for carbon storage, biodiversity conservation and ecological resilience (Table 2). Density of the tree ranged from 140 to 284 stems ha^{-1}, with arabica coffee systems showing significantly higher density (240.22 stems ha^{-1}) than robusta (208.22 stems ha^{-1}). Mixed shade systems recorded the highest density (250.67 stems ha^{-1}), surpassing native shade (190.33 stems ha^{-1}) but statistically comparable to exotic shade (231.67 stems ha^{-1}). Management regimes had no significant effect, though high-management systems showed marginally higher densities. Basal area ranged between 14.40 and 30.32 $m^2 ha^{-1}$, with arabica plantations displaying greater values (25.32 m^2 ha^{-1}) compared to robusta (18.07 m^2 ha^{-1}). Native and mixed shade species significantly outperformed exotic species, recording basal areas of 23.21 and 23.72 m^2 ha^{-1}, respectively, as compared under exotic shade (18.15 m^2 ha^{-1}). Larger basal area under native and mixed shade systems reflects the retention of mature, slow-growing trees that enhance ecosystem services (Vandermeer, 1989; Lin, 2010). The higher density and basal area in arabica coffee plantations are attributed to its ecological preference for shaded environments, which support cooler microclimates (Davis *et al.,* 2021). Mixed shade systems likely facilitate better resource availability and biodiversity, enhancing tree growth and carbon sequestration potential (Soto-Pinto *et al.,* 2000).

With regards to girth class distribution (Fig. 3 A to C), arabica systems were dominated by younger trees (30–60 cm: 28.49%), while robusta had a more even distribution, with a notable concentration in intermediate girth sizes (60–90 cm: 29.56%). Native shade systems retained mature trees, with 41 per cent in the 90–180 cm range and 12 per cent exceeding 180 cm, demonstrating ecological stability and biodiversity conservation (Toledo and Moguel, 2012). Mixed shade systems exhibited balanced age structures, while exotic shade systems favored fast-growing species like *Grevillea robusta*, resulting in dominance within intermediate girth classes but fewer large trees. High-management regimes exhibited a larger proportion of younger trees (30–120 cm: ~75%) due to frequent pruning and replanting, while medium and low-management regimes allowed more trees to reach maturity. These findings are consistent with observations of resource turnover in intensively managed systems (Vinceti *et al.,* 2013).

Present study results highlight the importance of shade type and coffee species in shaping structural parameters and ecological outcomes in AFS. Arabica coffee benefits from dense, shaded environments, promoting higher density of the tree and basal area while supporting the carbon storage and biodiversity. Native and mixed shade systems contribute to ecological sustainability by enhancing soil quality, water retentionand species diversity (Lin, 2010; Soto-Pinto *et al.,* 2000). Conversely, exotic shade systems, lack the ecological benefits necessary for long-term sustainability (Bawa and Kress, 2002). These results align with previous research emphasizing the ecological advantages of native and mixed shade systems in agroforestry (Widiyanto *et al.,* 2024). By promoting mature, biodiverse tree cover, such systems offer a balance between productivity and sustainability, advancing the resilience of coffee agroforestry systems (Devagiri *et al.,* 2019).

Above-Ground, Below Ground and Total Biomass:

Arabica coffee produced significantly higher AGB (285.38 Mg ha^{-1}) and BGB (77.05 Mg ha^{-1}) compared with robusta (169.68 Mg ha^{-1} AGB and 45.81 Mg ha^{-1} BGB). Total biomass followed a similar trend, with arabica (362.43 Mg ha^{-1}) exceeding robusta (215.50 Mg ha^{-1}). Similarly, native and mixed shade systems yielded higher biomass than exotic shade. Native shade achieved the highest TB (320.26 Mg ha^{-1}), followed by mixed shade (309.08 Mg ha^{-1}), whereas exotic shade recorded the lowest (237.54 Mg ha^{-1}). Arabica coffee under native (315.71 Mg ha^{-1} AGB, 85.24 Mg ha^{-1} BGB) and mixed shade (321.58 Mg ha^{-1} AGB, 86.83 Mg ha^{-1} BGB) significantly outperformed exotic shade (218.84 Mg ha^{-1} AGB, 59.09 Mg ha^{-1} BGB). Robusta biomass showed no significant differences across shade types. Biomass under high, medium and low management regimes showed no significant differences. However, high-input systems combined with native or mixed shade enhanced biomass production, indicating the benefits of integrated management (Table 3 and Fig. 4).

Arabica's better performance under native and mixed shade is due to its preference for shaded conditions, supporting efficient photosynthesis and nutrient cycling. Native and mixed shade trees create a stable microclimate and enhance soil organic matter. These findings align with earlier research. Bhagwat *et al.,* (2008) and Beer *et al.,* (1998) noted improved biomass in coffee AFS with diverse shade. Soto-Pinto *et al.,* (2010) and Schroth *et al.,* (2011) reported higher SOC and biomass under native shade. Studies by Lin (2010) and Rigal *et al.,* (2019) highlighted increased carbon sequestration under high-input, mixed-shade systems. Hareesh (2019) and Panwar *et al.,* (2022) documented superior biomass with native shade, supporting these results.

Carbon Stock and CO_2 Sequestration Potential

Under coffee agroforestry systems (AFS), carbon stock and CO_2 sequestration varied significantly by coffee species and shade type (Table 4). From biomass, arabica coffee recorded higher carbon stock (170.34Mg ha^{-1}) and CO_2 sequestration (624.59 Mg ha^{-1}) compared to robusta (101.28 Mg ha^{-1}; 371.37 Mg ha^{-1}). Native (150.52Mg ha^{-1}; 551.92 Mg ha^{-1}) and mixed shade (145.27 Mg ha^{-1}; 532.64 Mg ha^{-1}) systems outperformed exotic shade (111.65 Mg ha^{-1}; 409.37 Mg ha^{-1}). Arabica under native and mixed shade had the highest carbon values (191.96 Mg ha^{-1}; 703.84 Mg ha^{-1}), reflecting its adaptability for shaded microclimates and efficient carbon assimilation at higher altitudes (Soto-Pinto *et al.,* 2010). Native and mixed shade systems promoted greater carbon storage due to enhanced biodiversity and structural complexity (Somarriba *et al.,* 2004; Montagnini and Nair, 2004). Exotic species, characterized by lower wood density, contributed less (Ehrenbergerová *et al.,* 2020).

Additionally, arabica AFS exhibited higher SOC stock (182.72 Mg ha^{-1}) compared to robusta (171.68 Mg ha^{-1}). Mixed-species shade showed the highest SOC stock (56.2 Mg ha^{-1}) at 0–20 cm depth, followed by exotic (53.1 Mg ha^{-1}) and native shade (53.0 Mg ha^{-1}). High management regimes enhanced SOC, particularly in arabica under mixed and native shade (58.3 Mg ha^{-1}). SOC decreased with depth (14.3 - 40.95 Mg ha^{-1}), reflecting reduced organic inputs and microbial activity (Lal, 2004) (Table 5). Arabica systems showed greater SOC stability, with a median SOC stock of 18 kg m^3 compared to 17 kg m^{3}for robusta (Fig. 5), aligning with findings from van Noordwijk *et al.,* (2011). These trends emphasize the role of shade composition, management intensity, and surface organic inputs in shaping SOC dynamics.

The total carbon stock and CO_2 sequestration potential (CO_2e) in coffee-based agroforestry systems (AFS) were significantly influenced by coffee species, shade typeand management regimes (Table 6). Arabica coffee recorded a higher total carbon stock (353.06 Mg ha^{-1}) and CO_2esequestration (1294.57 Mg ha^{-1}) than robusta (272.97 Mg ha^{-1}; 1000.88 Mg ha^{-1}). Native and mixed shade systems outperformed exotic shade in total carbon stock (330.55 and 325.86 Mg ha^{-1} vs. 282.64 Mg ha^{-1}) and CO_2e sequestration (1212.02 and 1194.81 Mg ha^{-1} vs. 1036.34 Mg ha^{-1}). High and medium management regimes enhanced carbon stock (325.71 and 322.03 Mg ha^{-1}) and CO_2e sequestration (1194.27 and 1180.77 Mg ha^{-1}) compared to low-input systems (291.31 Mg ha^{-1}; 1068.13 Mg ha^{-1}).

SOC contributed ~ 70 per cent of total carbon stock in robusta systems and ~ 50 per cent in arabica systems (Fig.6). Native and mixed shade systems had higher SOC stocks due to their biodiversity and structural complexity, while exotic species with fast-growing, low-density trees (e.g., *Grevillea robusta*) contributed less (Bhaduri and Barua, 2019). The study highlights the superior carbon sequestration potential of coffee -based AFS, particularly under native and mixed shade systems combined with high or medium management regimes. These systems optimize both biomass and SOC contributions, aligning with global goals for climate mitigation. The results support the strategic integration of shade tree diversity and intensive management to enhance carbon stocks in tropical agroforestry systems. The findings align with prior studies (Kumar *et al.,* 2014; Gopalakrishna *et al.,* 2019), emphasizing the need for policy frameworks that promote native shade species and sustainable management practices. By maximizing carbon sequestration, coffee AFS can serve as effective tools for climate change mitigation while maintaining biodiversity and agricultural productivity.

CONCLUSION

The study indicated the vital role of coffee agroforestry systems in carbon sequestration, biodiversity conservation and ecological resilience, shaped by coffee species, shade patterns and management regimes. Arabica systems showed superior carbon stock and CO_2sequestration potential, particularly under native and mixed shade, which enhanced biodiversity and structural complexity. High and medium management regimes further boosted biomass and SOC stocks. Native and mixed shade systems proved most effective for maximizing carbon storage, fostering ecological stability and supporting diverse species, outperforming exotic shade, which lacked the ecological benefits of sustainable systems. Soil organic carbon contributed significantly to total carbon stock, especially in robusta systems, while arabica systems demonstrated greater SOC stability under native and mixed shade.

Structural features, such as higher basal area and balanced girth distribution in native and mixed shade systems, created favorable microclimates and supported mature, slow-growing trees, enhancing long-term carbon sequestration and biodiversity. These findings reaffirm the ecological and carbon storage benefits of diverse shade systems and moderate management intensity. Aligned with global climate goals, this research highlights the need for policies promoting native and mixed shade systems in coffee AFS. Such practices enhance carbon storage, sustain biodiversity and support climate-smart agriculture, offering a pathway to carbon-neutral agricultural landscapes while preserving ecosystem services and livelihoods in tropical regions.

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