



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(8): 714-722
Received: 16-06-2026
Accepted: 20-07-2026

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Tree diversity and carbon stocks in evergreen coffee-based agroforestry and adjoining natural forests of Kodagu, India

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i8i.6322>

Abstract

Biodiversity conservation and carbon sequestration are important ecosystem functions of tropical forests, while agroforestry systems can provide complementary ecological benefits within agricultural landscapes. The present study evaluated tree diversity, stand structure, biomass, carbon stock and species composition in evergreen coffee-based agroforestry (CAF) and adjoining natural forests (NF) of Kodagu district, Karnataka, in the Central Western Ghats. A stratified random sampling, with thirty 20×20 m plots established in each land-use type. Trees with girth at breast height (GBH) ≥30 cm were inventoried. Tree diversity was assessed using species richness, Menhinick's richness index, Shannon diversity index, Simpson's dominance index, species evenness and beta diversity, while stand structure was characterized by tree density, basal area and girth-class distribution. Importance Value Index (IVI) was used to identify dominant species. Aboveground biomass, belowground biomass, total biomass, carbon stock and CO₂ equivalent were estimated using standard methods. Natural forests supported higher tree species richness (50 species) than CAF (42 species), whereas CAF recorded slightly higher Shannon diversity (3.19) and species evenness (0.61) than NF (3.09 and 0.46, respectively). Tree density and basal area were higher in NF (373 stems ha⁻¹ and 38.65m²ha⁻¹) than CAF (288 stems ha⁻¹ and 29.53m²ha⁻¹). Similarly, aboveground biomass, total biomass and carbon stock were greater in NF (269.25, 341.95 and 160.72 Mg ha⁻¹, respectively) than CAF (208.83, 265.22 and 124.65 Mg ha⁻¹, respectively), with corresponding CO₂ equivalents of 589.35 and 457.10 Mg CO₂ha⁻¹. The dominant species in CAF were *Grevillea robusta*, *Mangifera indica* and *Syzygium cumini*, while *Hopea parviflora*, *Syzygium cumini* and *Aporosa lindleyana* dominated NF. Both land use types exhibited a unimodal girth distribution, with maximum representation in the 90-120 cm class. Natural forests demonstrated greater structural development and carbon storage, whereas traditional coffeebased agroforestry retained considerable tree diversity and mature shade trees, highlighting its complementary role in biodiversity conservation and carbon sequestration.

Keywords: Biodiversity, tree density, stand structure, carbon sequestration, western ghats

1. Introduction

Biodiversity forms the foundation of ecosystem functioning and plays a fundamental role in maintaining ecological stability, productivity and resilience. Forest ecosystems support more than 80 per cent of the world's terrestrial biodiversity and provide essential ecosystem services, including carbon sequestration, nutrient cycling, soil conservation, water regulation and climate regulation (MEA, 2005; FAO, 2020) ^[1,2]. However, rapid deforestation, habitat fragmentation and land-use change have resulted in unprecedented biodiversity loss, threatening ecosystem integrity and reducing the capacity of forests to provide these critical services (IPBES, 2019) ^[3]. Conserving biodiversity has therefore become a global priority for achieving sustainable development and mitigating climate change.

Tropical forests are particularly important because they harbour nearly two-thirds of the world's terrestrial species while storing approximately 45 per cent of global terrestrial carbon in vegetation and soils (Pan *et al.*, 2011; Poorter *et al.*, 2015) ^[4,5]. The structural complexity and high species diversity of tropical forests enhance ecosystem productivity through complementary resource use, niche partitioning and functional diversity, thereby improving biomass accumulation and

long-term carbon storage (Tilman *et al.*, 2014) [6]. Consequently, the conservation of tropical tree diversity is increasingly recognized as a nature-based solution for climate change mitigation and ecosystem restoration.

In recent decades, agroforestry systems have emerged as effective land-use strategies capable of reconciling agricultural production with biodiversity conservation. Unlike intensive monoculture agriculture, agroforestry integrates trees with crops or livestock, thereby creating structurally diverse landscapes that provide habitat for numerous plant and animal species while sustaining ecosystem functions (Nair, 1993; Jose, 2009) [7, 8]. The presence of diverse tree species in agroforestry systems enhances nutrient cycling, improves soil fertility, regulates microclimatic conditions and increases resilience against climatic extremes (Schroth *et al.*, 2004) [9]. Furthermore, agroforestry landscapes function as ecological corridors that improve habitat connectivity between fragmented forest patches and facilitate the movement and persistence of native biodiversity (Bhagwat *et al.*, 2008) [10].

Among tropical agroforestry systems, shade-grown coffee plantations have attracted considerable attention because they closely resemble natural forest ecosystems in terms of vegetation structure and species composition. Traditional coffee cultivation under diverse native shade trees supports higher levels of biodiversity than sun-grown coffee systems by maintaining complex canopy architecture and providing suitable habitats for birds, mammals, insects and epiphytic flora (Perfecto *et al.*, 1996; Moguel and Toledo, 1999) [11, 12]. Native shade trees also contribute significantly to ecosystem services, including timber production, nutrient recycling, soil conservation and carbon sequestration, making coffee agroforestry an ecologically sustainable production system (Beer *et al.*, 1998; Jose, 2009) [13, 8].

The Western Ghats of India, recognized as one of the world's 36 biodiversity hotspots, contain exceptionally rich flora and fauna with high levels of endemism (Myers *et al.*, 2000) [14]. Within this region, Kodagu district represents a unique landscape where extensive evergreen forests occur in close association with traditional shade-grown coffee plantations. Unlike many commercial coffee-growing regions, coffee plantations in Kodagu retain a large number of native tree species that contribute to landscape-level biodiversity conservation while providing essential shade for coffee cultivation. These agroforestry practices therefore serve as important supplementary habitats outside protected forests and contribute to maintaining ecological connectivity across the landscape.

Assessment of tree diversity and stand structure provides valuable information for understanding ecosystem functioning and evaluating the conservation potential of agroforestry systems. Structural attributes such as tree density, basal area and species dominance strongly influence biomass production, carbon accumulation and ecosystem productivity. Diversity indices, including species richness, Shannon diversity and species evenness, are widely used to assess the ecological quality and stability of forest communities and to compare biodiversity across contrasting land-use types (Magurran, 2004) [15]. Similarly, the Importance Value Index (IVI) identifies ecologically dominant species and provides insight into community composition and forest dynamics.

Although several studies have investigated biodiversity and carbon storage in tropical forests and agroforestry systems, comparative assessments between evergreen coffee-based agroforestry and adjoining natural evergreen forests in the Central Western Ghats remain limited. Such comparisons are essential for understanding the extent to which traditional coffee-based agroforestry contributes to biodiversity conservation while maintaining ecosystem functions similar to those of natural forests.

Therefore, the present study aimed to compare tree diversity, stand structure, biomass accumulation and carbon stocks between evergreen coffee-based agroforestry and adjoining natural forests of Kodagu district, Karnataka. The findings provide insights into the conservation value of traditional shade coffee systems and their role in sustaining biodiversity and enhancing carbon sequestration within one of the world's most ecologically significant tropical landscapes.

2. Materials and Methods

2.1 Study area

The study was conducted in the coffee-growing landscapes of Kodagu district, Karnataka, situated in the Central Western Ghats of southern India between 11° 56' - 12° 52' N latitude and 75° 22'-76° 11' E longitude. The district occupies approximately 4,102 km² and is characterized by undulating to mountainous terrain with elevations ranging from about 300 to 1,750 m above mean sea level. Kodagu forms an integral part of one of the world's globally recognized biodiversity hotspots owing to its exceptional floristic richness, endemic species and extensive forest cover.

The climate of the region is humid tropical and strongly influenced by the southwest monsoon. Annual rainfall varies between 1,690 and 4,441 mm (Fig. 2.1), with nearly ninety percent of the precipitation received during June to September. Mean annual temperature ranges from approximately 15 °C to 36 °C (Fig. 2.2). Deep lateritic to red loamy soils, abundant rainfall and moderate temperatures create highly favourable conditions for the growth of evergreen forests as well as shade-grown coffee plantations. Evergreen forests constitute nearly half (49.45%) of the district's forest cover and therefore represent the dominant natural vegetation of Kodagu.

2.2 Experimental design and sampling

The investigation was conducted using a stratified random sampling method. Only evergreen vegetation was considered in the present study. Within this vegetation type, coffee-based agroforestry (CAF) (Plate 3.1) located adjacent to natural evergreen forests (NF) (Plate 3.2) were selected to minimize differences arising from climatic, topographic and edaphic conditions.

Thirty sample plots of size 20 m × 20 m (400 m²) were established in coffee-based agroforestry and another thirty plots of identical size were laid in adjoining natural forests, resulting in a total of sixty sample plots for evergreen vegetation (Fig. 2.3). The sample plots were randomly distributed while avoiding recently disturbed locations, forest edges and areas subjected to intensive anthropogenic interference to ensure representative sampling of mature stands.

2.3 Tree inventory and vegetation assessment

Trees having a girth at breast height (GBH) of at least 30 cm were enumerated within each sample plot. Tree species were identified, as far as possible, in the field based on their vegetative and reproductive characteristics, including leaf morphology, bark texture, branching pattern, flowers and fruits. Species identification was carried out using standard taxonomic references (Pascal and Ramesh, 1987 and Saldanha, 1996). Plant specimens of species that could not be identified in the field were collected following standard herbarium techniques and brought to the College of Forestry, Ponnampet, where their identity was confirmed with the assistance of taxonomists and available herbarium collections.

Girth at breast height was measured at 1.37 m above ground level using a measuring tape, whereas total tree height was determined using a Blume-Leiss hypsometer. Geographic coordinates and elevation of each plot were recorded using a handheld Global Positioning System (GPS).

Tree diversity was quantified using species richness, Menhinick's richness index, Shannon diversity index, Simpson's dominance index, species evenness and beta diversity. Importance Value Index (IVI) was computed from relative density, relative frequency and relative dominance to identify ecologically dominant species within each land-use type. Tree density, basal area and girth class distribution were also estimated to characterize stand structure.

2.4 Biomass and carbon estimation

Aboveground tree biomass was estimated using a non-destructive approach by multiplying tree volume with species-specific wood density values and a biomass expansion factor. Belowground biomass was estimated as 27 per cent of aboveground biomass following established guidelines, and total biomass was obtained by summing aboveground and belowground biomass.

Carbon stock was estimated by considering 47 per cent of total biomass as carbon, while carbon dioxide equivalent (CO₂e) was calculated by multiplying carbon stock by a conversion factor of 3.66. Biomass, carbon stock and CO₂e were expressed on a hectare basis.

2.5 Statistical analysis

Differences in tree density, basal area, biomass, carbon stock and CO₂ equivalent between coffee-based agroforestry and adjoining natural forests were evaluated using independent sample *t*-tests. Mean values are presented as mean $\pm$ standard error, and statistical significance was assessed at $p < 0.05$.

3. Results and Discussion

3.1 Tree diversity

Evergreen coffee-based agroforestry (CAF) supported 42 tree species, whereas adjoining natural forests (NF) contained 50 species, indicating greater floristic richness in the natural forest ecosystem (Table 3.1). Of these, 25 species were common to both land-use systems, while 17 species were exclusive to CAF and 25 species were exclusive to NF, indicating both shared floristic composition and distinct species assemblages (Fig. 3.1). Despite the relatively lower species richness, coffee-based agroforestry exhibited a slightly higher Shannon diversity index (3.19) than natural forests (3.09), suggesting a more equitable distribution of individuals among species. Similarly, species

evenness was higher in CAF (0.61) than in NF (0.46), while Simpson's dominance index remained low (0.06-0.07) in both land-use systems, indicating the absence of strong dominance by a few species. The beta diversity value (0.46) further suggested moderate species turnover between the two ecosystems.

The greater species richness observed in natural forests reflects the relatively undisturbed conditions that favour natural regeneration and the persistence of shade-tolerant climax species (Whitmore, 1998) [16]. Similar observations have been reported by Pascal (1988) [17], who described the evergreen forests of the Western Ghats as highly species-rich ecosystems due to favourable climatic conditions and long-term ecological stability. However, the relatively high Shannon diversity and evenness recorded in coffee-based agroforestry indicate that traditional shade coffee systems maintain diverse tree communities despite agricultural management.

The maintenance of native shade trees in Kodagu coffee plantations is largely driven by traditional management practices, where farmers intentionally retain indigenous tree species for shade regulation, timber, fuelwood and other ecosystem services. Such practices increase structural heterogeneity and create favourable habitats for numerous plant and animal species. Bhagwat *et al.* (2008) [10] reported that tropical agroforestry systems, particularly shade-grown coffee plantations, function as important refuges for biodiversity by maintaining vegetation complexity comparable to natural forests. Similarly, Perfecto *et al.* (1996) [11] and Moguel and Toledo (1999) [12] demonstrated that traditional coffee agroforestry conserves substantial proportions of native tree diversity and provides habitat connectivity between fragmented forest patches.

The moderate beta diversity observed between coffee plantations and adjoining natural forests indicates that although both systems share several species, each also supports unique floristic components. This finding emphasizes the complementary role of coffee agroforestry in landscape-level biodiversity conservation, particularly in biodiversity hotspots such as the Western Ghats.

3.2 Stand structure

Evergreen natural forests exhibited significantly greater structural development than coffee-based agroforestry (Table 3.2). Tree density varied from 288 stems ha⁻¹ in coffee plantations to 373 stems ha⁻¹ in natural forests, while basal area varied from 29.53 to 38.65 m² ha⁻¹. These differences indicate the presence of larger and more mature tree populations in natural forests resulting from continuous natural regeneration and minimal anthropogenic disturbance.

Higher tree density and basal area are typical characteristics of mature evergreen forests, where long periods of undisturbed growth allow the establishment and persistence of large canopy trees (Chazdon, 2014) [18]. Basal area is widely recognized as one of the best indicators of stand productivity and biomass accumulation because it integrates both tree size and stand density (Brown, 1997) [19]. Therefore, the significantly higher basal area observed in natural forests reflects their superior structural complexity and biomass carrying capacity.

Although tree density was comparatively lower in coffee-based agroforestry, mature shade trees substantially contributed to stand basal area. Traditional coffee plantations in Kodagu retain numerous native canopy trees to regulate microclimatic

conditions necessary for coffee cultivation. Beer *et al.* (1998)^[13] reported that shade management practices promote the retention of large trees, thereby maintaining vertical stratification and structural complexity similar to natural forests. Jose (2009)^[8] further emphasized that agroforestry systems containing diverse mature trees provide multiple ecological services while maintaining productive agricultural landscapes.

The structural differences observed between the two land-use systems therefore reflect differences in management intensity rather than complete alteration of forest characteristics. The persistence of large shade trees demonstrates that traditional coffee agroforestry continues to retain many structural attributes associated with natural evergreen forests.

3.3 Biomass and carbon stock

Significant differences were observed in biomass accumulation and carbon storage between coffee-based agroforestry and adjoining natural forests (Table 3.2). Aboveground biomass varied from 208.83 Mgha⁻¹ in coffee plantations to 269.25 Mg ha⁻¹ in natural forests, while total biomass varied from 265.22 to 341.95 Mgha⁻¹. Consequently, carbon stock varied from 124.65 MgCha⁻¹ in coffee plantations to 160.72 MgCha⁻¹ in natural forests, corresponding to CO₂ equivalents of 457.10 and 589.35 Mg CO₂e ha⁻¹, respectively. All biomass and carbon parameters differed significantly ($p < 0.01$).

The greater biomass accumulation in natural forests can be attributed primarily to their higher tree density, larger basal area and greater abundance of mature canopy trees. Numerous studies have demonstrated that large-diameter trees contribute disproportionately to total forest biomass despite representing only a small proportion of total stem density (Brown, 1997; Slik *et al.*, 2013)^[19,20]. Similarly, Chave *et al.* (2014)^[21] emphasized that biomass accumulation is strongly influenced by tree diameter, height and wood density, making mature forests the largest terrestrial carbon reservoirs.

The substantial carbon stocks observed in coffee-based agroforestry highlight the important ecological role of traditional shade coffee systems in climate change mitigation. By retaining native shade trees, coffee plantations continue to accumulate considerable woody biomass while supporting agricultural production. Beer *et al.* (1998)^[13] reported that shaded coffee plantations store substantially greater biomass and carbon than unshaded monoculture coffee systems because of the contribution of perennial shade trees. Jose (2009)^[8] similarly recognized agroforestry as an efficient land-use system capable of simultaneously enhancing carbon sequestration and agricultural sustainability.

The comparatively lower carbon stock recorded in coffee plantations is expected because management interventions such as pruning, selective thinning and periodic harvesting limit biomass accumulation relative to undisturbed natural forests. Nevertheless, the relatively high carbon stocks observed in the present study indicate that evergreen coffee agroforestry represents an important carbon sink capable of complementing

the climate mitigation function of adjoining natural forests.

3.4 Dominant tree species

Importance Value Index (IVI) analysis revealed clear differences in species dominance between the two land-use types (Fig. 3.2). Coffee-based agroforestry was dominated by *Grevillea robusta*, *Mangifera indica* and *Syzygium cumini*, whereas adjoining natural forests were dominated by *Hopea parviflora*, *Syzygium cumini* and *Aporosa lindleyana*. These differences reflect variations in ecological processes and management practices operating within the two ecosystems.

The dominance of *Grevillea robusta* and *Mangifera indica* in coffee plantations reflects deliberate farmer preferences for shade regulation, timber production and additional economic benefits. *Grevillea robusta* has become one of the most widely retained shade tree species in Indian coffee plantations because of its rapid growth, desirable canopy architecture and commercial timber value (Beer *et al.*, 1998)^[13]. In contrast, *Hopea parviflora* and *Aporosa lindleyana* are characteristic evergreen forest species that dominate mature forest communities under natural successional processes (Pascal, 1988)^[17].

The occurrence of *Syzygium cumini* as a dominant species in both ecosystems indicates its broad ecological adaptability and importance within the evergreen forests of the Western Ghats. Species possessing wide ecological amplitude often contribute substantially to stand structure and biomass accumulation across different land-use systems (Chazdon, 2014)^[18].

The IVI results demonstrate that although coffee plantations are managed ecosystems, they continue to retain numerous native evergreen tree species that contribute significantly to biodiversity conservation and ecosystem functioning. Similar conclusions were reached by Bhagwat *et al.* (2008)^[10], who reported that traditional coffee agroforestry acts as an important supplementary habitat for native forest species and enhances landscape connectivity in tropical biodiversity hotspots.

3.5 Girth class distribution

Figure 3.3 shows the girth class distribution of trees in evergreen coffee-based agroforestry (CAF) and adjoining natural forest (NF). Both land-use types exhibited a unimodal distribution, with the highest proportion of trees occurring in the 90-120 cm girth class (37% in CAF and 32% in NF), followed by a gradual decline in higher girth classes. NF had a greater proportion of trees in the lower girth classes (30-90 cm), whereas CAF showed relatively higher representation in the 120-150 cm and 150-180 cm classes. Trees above 180 cm constituted only a small proportion of both populations. The greater representation of medium-to-large trees in CAF may reflect the deliberate retention of mature shade trees for coffee cultivation, while the higher proportion of smaller trees in NF suggests ongoing natural regeneration. Similar structural patterns in traditional shade coffee systems have been reported by Bhagwat *et al.* (2008)^[10] and Perfecto *et al.* (2014)^[22].

Table 3.1: Tree diversity in coffee-based agroforestry and adjoining natural forest in evergreen vegetation type

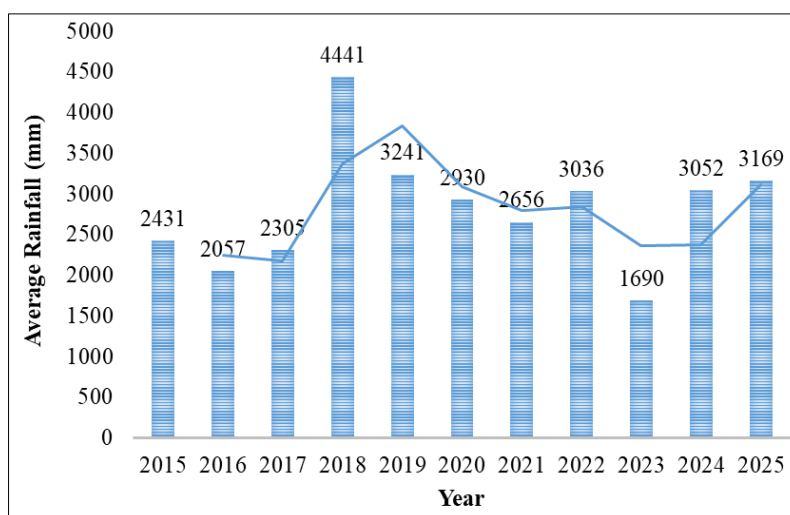
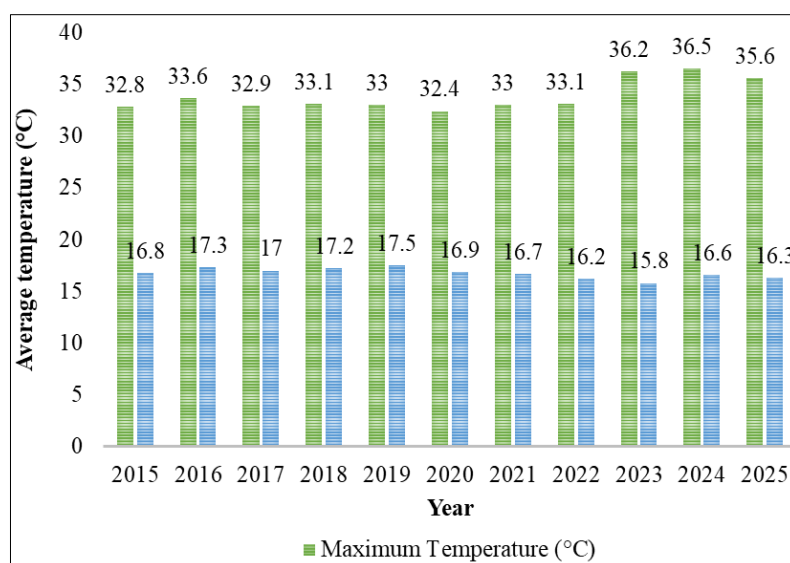
Vegetation type	Evergreen	
Land use type Diversity Parameters	CAF	NF
Species Richness	42	50
Menhinick	2.26	2.37
Shannon Diversity Index (H')	3.19	3.09
Simpson index of Dominance (D)	0.06	0.07
Species Evenness	0.61	0.46
Beta diversity (β)	0.46	

CAF = Coffee-based Agroforestry; NF = Adjacent Natural Forest

Table 3.2: Tree density, basal area, biomass and carbon stock in coffee-based agroforestry and adjoining natural forests

Vegetation	Land use type	Tree density (stems ha ⁻¹)	Basal area (m ² ha ⁻¹)	AGTB (Mg ha ⁻¹)	BGTB (Mg ha ⁻¹)	TTB (Mg ha ⁻¹)	Carbon stock (Mg ha ⁻¹)	CO ₂ e (Mg C ha ⁻¹)
Evergreen	CAF (Mean ± SE)	288 ±15.29	29.53 ±1.74	208.83 ±13.41	56.39 ±3.62	265.22 ±17.03	124.65 ±8.00	457.10 ±29.35
	NF (Mean ± SE)	373 ±10.88	38.65 ±1.41	269.25 ±10.28	72.70 ±2.78	341.95 ±13.06	160.72 ±6.14	589.35 ±22.51
	t -value	-4.53	-4.08	-3.58	-3.58	-3.58	-3.58	-3.58
	p -value	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**

CAF = Coffee-based Agroforestry; NF = Natural Forest; AGTB = Aboveground tree biomass; BGTB = Belowground tree biomass; TTB = Total tree biomass; * = p (<0.05); ** = p (<0.01)

**Fig 2.1:** Average Annual Rainfall (mm) of the study area during 2015-25

(Source: Karnataka State Natural Disaster Monitoring Centre, Bengaluru)

Fig 2.2: Average Annual Temperature (°C) of the study area during 2015-25

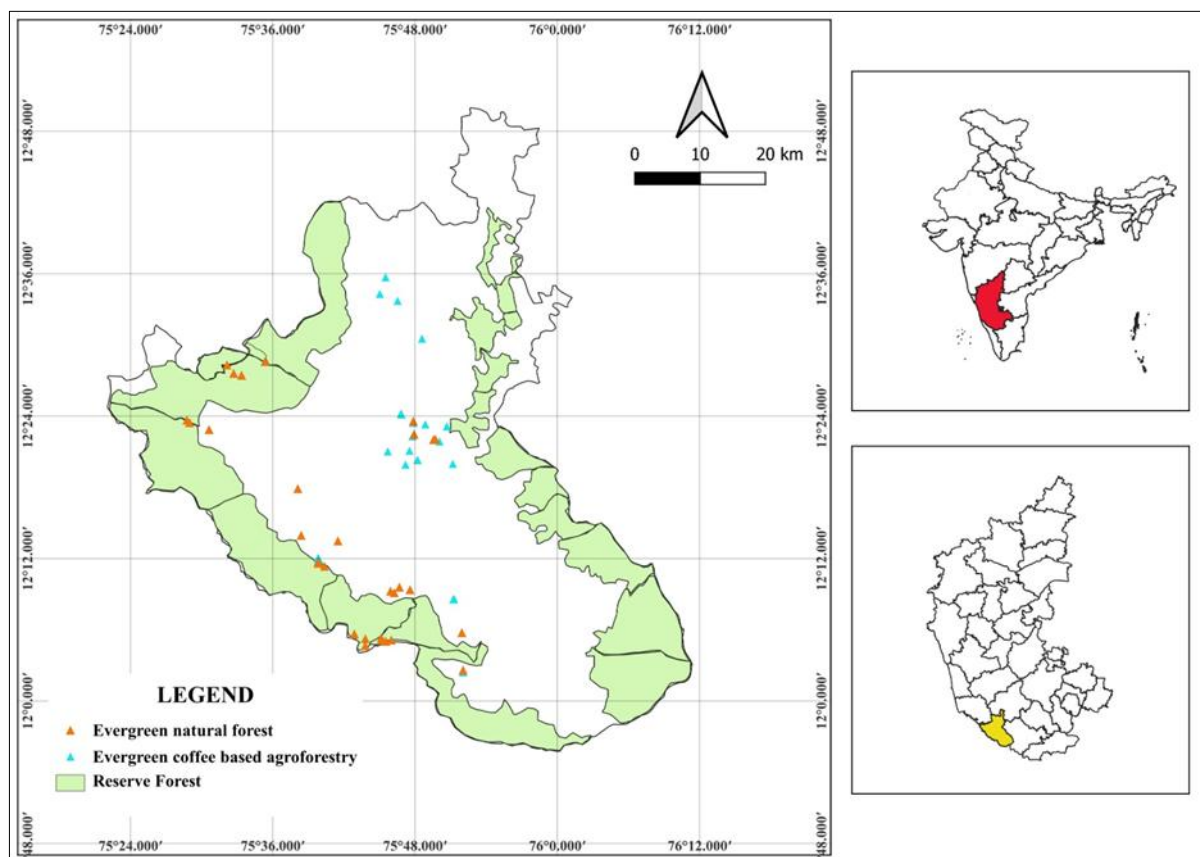
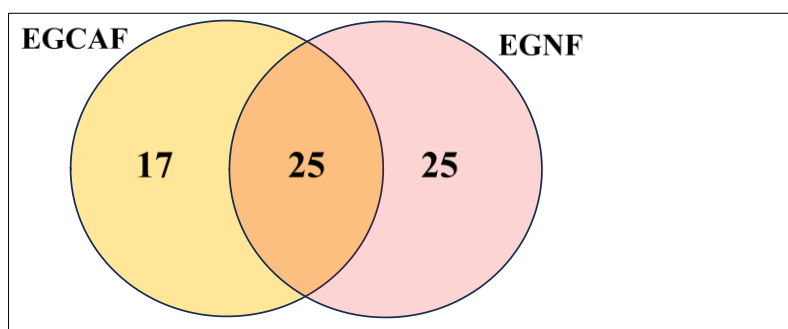


Fig 2.3: Distribution of sampling sites across evergreen coffee-based agroforestry and natural forests in Kodagu district, Karnataka



EGCAF = Evergreen coffee-based agroforestry; EGNF = Evergreen natural forests

Fig 3.1: Sharing of species among coffee-based agroforestry and adjoining natural forest in two bioclimatic zones

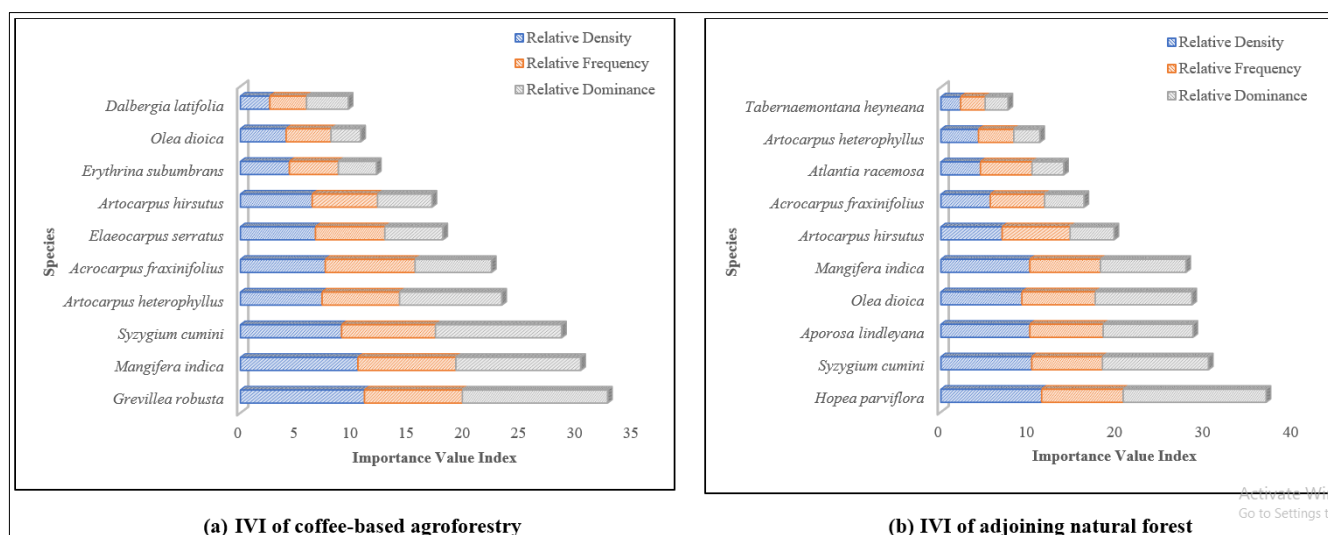


Fig 3.2: Importance Value Index (IVI) of dominant tree species in different land use types in evergreen vegetation (a) IVI of coffee-based agroforestry (b) IVI of adjoining natural forest

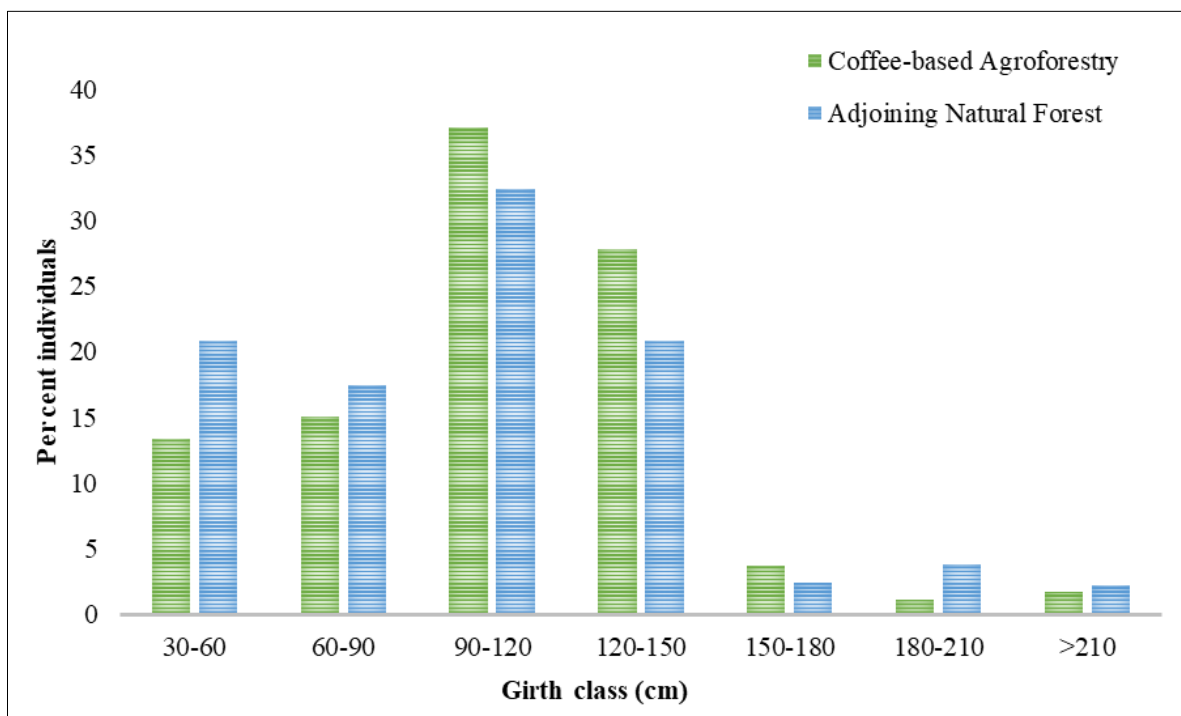


Fig 3.3: Comparison of girth class distribution between coffee agroforests and adjoining natural forest in evergreen vegetation type



Plate 3.1: An overview of coffee-based agroforestry adjacent to the evergreen natural forest



Plate 3.2: An overview of the evergreen natural forest

4. Conclusion

The present study demonstrated clear ecological differences between evergreen coffeebased agroforestry and adjoining natural forests in Kodagu, Central Western Ghats. Natural forests exhibited greater tree species richness, tree density, basal area, biomass accumulation and carbon storage, reflecting their relatively undisturbed structure and greater representation of mature trees. In contrast, coffee-based agroforestry maintained comparatively high tree diversity and evenness, indicating that traditional shade management can conserve a diverse tree assemblage within productive agricultural landscapes. The dominance of native and economically valuable shade trees in CAF further highlights its role in maintaining structural complexity and ecosystem services. The unimodal girth-class distribution in both systems, with the highest proportion of trees in the 90-120 cm class, indicated a predominance of mediumsized trees; the greater representation of smaller trees in NF suggested ongoing natural regeneration, whereas the relatively higher proportion of medium-to-large trees in CAF reflected the retention of mature shade trees.

Acknowledgements

The authors gratefully acknowledge the Karnataka Forest Department (KFD) for granting research permission and extending field support during the study in the evergreen forests of Kodagu district. The financial support provided by the Karnataka Department of Science and Technology (KDST) under its research funding programme is gratefully acknowledged. We also thank the coffee plantation owners for permitting access to their plantations and for their cooperation throughout the study.

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