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Carbon stock and tree diversity across land-use systems in the heterogeneous landscapes of the GKVK biodiversity heritage site

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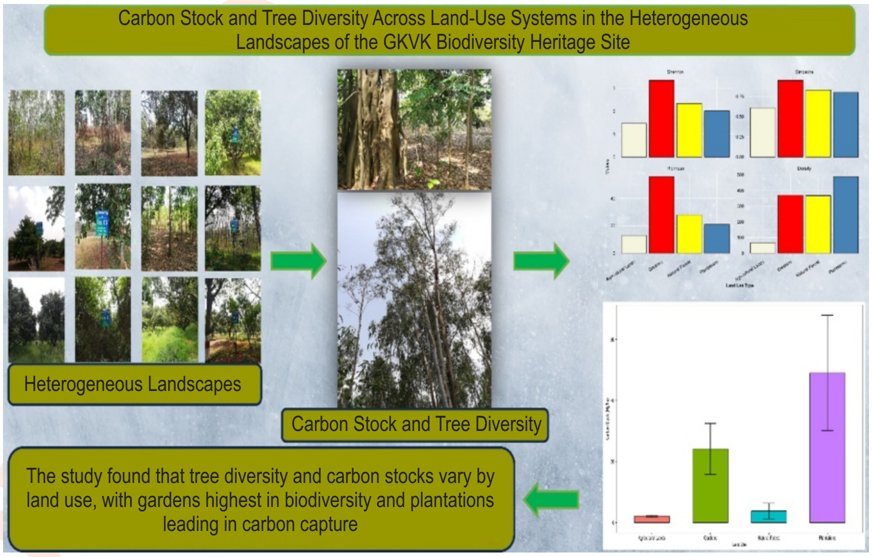
Abstract

Aim: This study aims to evaluate tree diversity and carbon stocks across diverse land-use systems within the heterogeneous landscape of the GKVK Biodiversity Heritage Site, Bengaluru.

Methodology: A random quadrat sampling method (135 quadrats of 20 m^2) was used to measure tree diversity (Shannon (H'), Simpson (1-D), species richness) and population structure (basal area, stem density, girth class). Carbon stocks were estimated using non-destructive allometric equations based on tree diameter and wood density.

Results: During the course of study, 1,611 individuals from 75 species were reported. Gardens exhibited the highest biodiversity (H' = 3.35; 1-D = 0.95; species richness = 56) and stem density (370 individuals ha^{-1}) whereas agricultural lands showed the lowest diversity (H' = 1.46;1-D: 0.61; species richness =13) and stem density (67.19 individuals ha^{-1}). Plantations with the highest stem density (488.89 individuals ha^{-1}) contributed significantly to carbon sequestration, boasting the maximum average basal area (12.38 m^2 ha^{-1}) and carbon stock (49.39 Mg ha^{-1}). A strong correlation (r=0.985, p<0.0001) between basal area and carbon stock underscores the role of forest structure in carbon storage. Medium- and large-diameter trees were identified as key contributors to carbon stock.



Carbon Stock and Tree Diversity Across Land-Use Systems in the Heterogeneous Landscapes of the GKVK Biodiversity Heritage Site

The study found that tree diversity and carbon stocks vary by land use, with gardens highest in biodiversity and plantations leading in carbon capture

Interpretation: This study revealed that tree diversity and carbon stocks vary significantly across land-use systems, with gardens exhibiting the highest biodiversity and plantations contributing the most to carbon sequestration. Medium- and large-diameter trees are crucial for carbon storage, highlighting the importance of conserving mature trees and improving biodiversity. These findings offer insights for promoting sustainable land management and enhancing carbon capture.

Key words: Carbon stock, Diversity, Heterogenous landscapes, land use systems

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Introduction

Tropical ecosystems store approximately one-quarter of the world's terrestrial carbon, remove vast amounts of atmospheric CO_2, and harbor half of all known plant species and two-thirds of global biodiversity on just 12% of Earth's land (Adame *et al.,* 2013; Mitchard, 2018). In particular, forest and woodland ecosystems play vital roles in carbon sequestration, making their conservation a crucial component of sustainable efforts to combat global warming (Löf *et al.,* 2019). Most of the carbon stored on land exists within tree trunks, branches, foliage, and roots, and is referred to as biomass. Trees function as long-term carbon reservoirs, capturing atmospheric CO_2 through photosynthesis and storing it for decades to centuries, thereby regulating the global carbon cycle and reducing greenhouse gas concentrations in the atmosphere. However, these vital carbon reservoirs are facing increasing anthropogenic pressures.

Despite their critical importance, many landscapes worldwide have been altered by urbanization, agriculture, tourism, infrastructure expansion, mining and other anthropogenic pressures, posing significant threats to their natural dynamics and sustained functionality (WWF, 2020). These anthropogenic pressure lead to extinctions of localized tree species and loss of extensive carbon stock, creating an urgent need for landscape-scale carbon assessments (Jew *et al.,* 2016; Gatti *et al.,* 2021). Evaluating carbon storage across different landscape types is essential for developing effective management frameworks that enhance carbon sequestration in human-modified environments. Integration with frameworks such as Reducing Emissions from Deforestation and Degradation (REDD+) can simultaneously advance both carbon management and biodiversity conservation objectives (Hinsley *et al.,* 2014).

Tree species diversity plays a crucial role in ecosystem carbon dynamics, as diverse forest communities enhance carbon storage capacity and provide essential resources that support ecosystem function (Bai *et al.,* 2024). Diversity indices serve as key quantitative metrics for characterizing forest structural complexity and carbon sequestration potential (Ehbrecht *et al.,* 2021). Comprehensive floristic assessments are essential for understanding diversity-carbon relationships and developing effective conservation strategies that preserve both biodiversity and carbon stocks in human-modified landscapes (Haq *et al.,* 2023). Understanding the spatial biomass distribution is essential for identifying carbon sources and sinks from land degradation and forest regeneration. Carbon stocks can be assessed using field measurements or remote sensing approaches, with field-based estimates providing critical ground-truth data for carbon and climate models, especially in data-deficient regions (Behera *et al.,* 2017; Pechanec *et al.,* 2018). Given the difficulties in accurately estimating emissions from land-use changes, recent research has increasingly focused on comprehensive carbon stock assessments to reduce uncertainties in understanding the global carbon cycle (Salunkhe *et al.,* 2018). Despite extensive documentation of tree carbon sequestration roles (Chaturvedi *et al.,* 2011; Gandhi and Sundarapandian, 2017; Joshi and Dhyani, 2019; Mohanta *et al.,* 2022; Salunkhe *et al.,* 2023), urban forest ecosystems, particularly institutional campuses, remain significantly understudied. Effective landscape management for carbon storage requires comprehensive data on existing stocks, temporal dynamics, and land-use impacts (Oulehle *et al.,* 2011; King *et al.,* 2023). However, such assessments are lacking in urban forest systems. The GKVK campus in Bengaluru, a biodiversity heritage site encompassing forests, farmlands, plantations, and gardens, exemplifies understudied urban ecosystems that receive less conservation attention than protected forests. This study addresses this gap by assessing carbon stocks and tree diversity to establish baseline data for the evidence-based conservation of this valuable urban ecosystem.

Materials and Methods

Study area: The research was carried out at Gandhi Krishi Vigyana Kendra (GKVK), University of Agricultural Sciences Bangalore, within the designated biodiversity heritage site. The site spans 167 ha of the campus and includes 14 distinct patches (Fig. 1). The study area is characterized by heterogeneous landscapes, including agricultural lands, natural forests, gardens, and plantations.

Climate: The GKVK campus is situated at 13.081449° N, 77.576935° E of 924 m amsl. The campus receives annual rainfall ranging from 528 mm to 1,374.4 mm, with an average of 915.5 mm. During the study period (November 2020 to March 2021), the site recorded an average temperature of 23.32°C and an average rainfall of 973 mm (Fig. 2). Weather data were sourced from the Department of Agrometeorology in UAS, Bangalore.

Sampling design and Vegetation data collection: A random quadrat sampling method was used to assess tree vegetation, including girth and height measurements of various species. Quadrats, measuring 20 m^2, were systematically established across the study site (Birhane *et al.,* 2007). Within each quadrat, all individuals with girth at breast height (GBH) ≥ 30 cm were identified, and their GBH and height were recorded. Individuals with GBH <30 cm and height >1 m were classified as saplings and counted within a 5 m^2 subplot located in one corner of the primary quadrat (Tamilselvan *et al.,* 2021). A total of 135 quadrats were sampled across the study site to collect biomass data.

Tree population structure: Shannon index (*H'*), Simpson index (D) and species richness were calculated to assess diversity. The basal area (BA), stem density (Elzinga *et al.,* 2001), and girth class distribution were used to understand the tree population structure. The tree population was divided into six girth classes to study the regeneration status: a:10-50, b:51-100, c:101-150, d:151-200, e:201-250, f:251-300 cm. Additionally, to understand the influence of tree diameter on carbon storage, the diameter at breast height (DBH) was calculated and categorized into three classes: a:small (≤ 15 cm), b:medium (>15 cm to ≤ 40 cm), and c:large (>40 cm) (McNicol *et al.,* 2018).

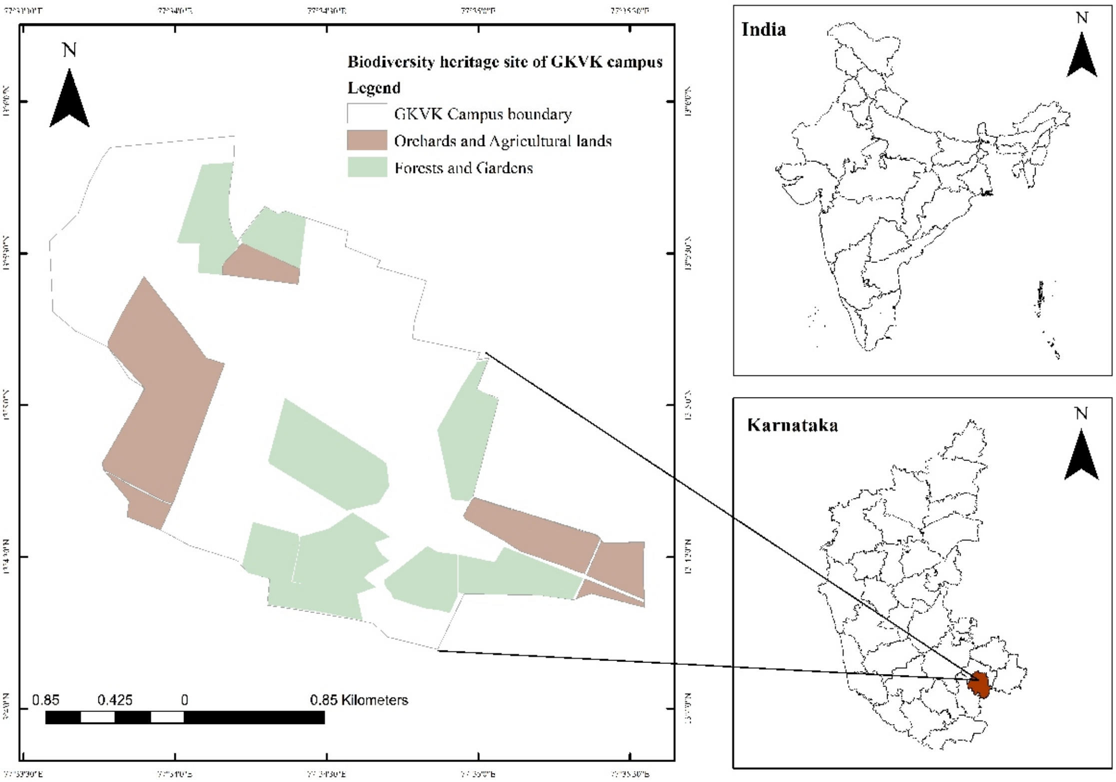

Fig. 1: Map of the study area [Designed by the authors based on the demarcation map from the Karnataka Biodiversity Board (2009) notification (Karnataka Biodiversity Board, 2009)].

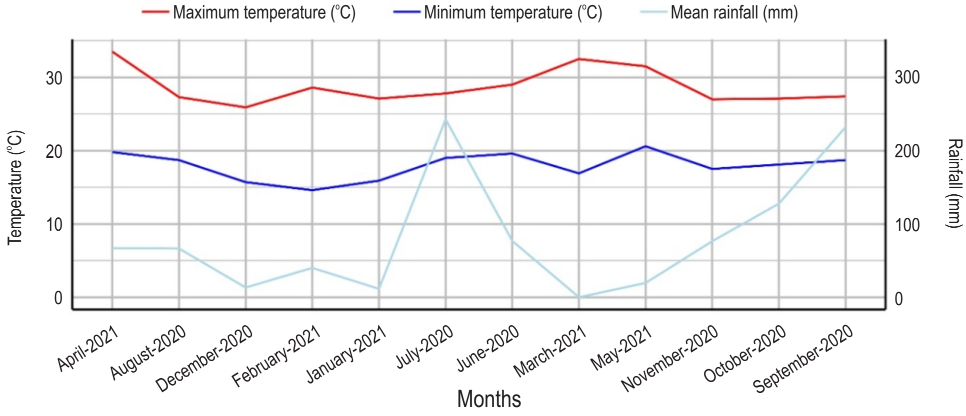

Fig. 2: Mean temperature and rainfall of the study area during the study period.

Allometric biomass estimation: Allometric method was used to estimate tree biomass. Allometric equations have many advantages over other carbon stock estimation methods, including their simple framework, low cost, and non-destructive nature (Chave *et al.,* 2015). However, allometric equations have some limitations, such as low accuracy in forests with atypical tree growth patterns or high diversity of tree species (Liang *et al.,* 2018). Different databases and literature were reviewed to obtain information on wood density. Total tree biomass was estimated using the sum of the aboveground biomass (AGB) and belowground biomass (BGB). AGB was calculated using the allometric equation (Chave *et al.,* 2015), which incorporates tree diameter, height, and wood density as parameters. BGB was estimated using the standard root-to-shoot ratio of 0.26 for tropical forests, as recommended by the Intergovernmental Panel on Climate Change (IPCC 2006).

Data analysis: Raw data were compiled, organized, and pre-processed using Microsoft Excel 2021 to ensure accuracy, consistency, and readiness for analysis. RStudio version 2024. 9.0.375 (Cranberry Hibiscus) (Posit Team, 2024) was used to analyse and visualize the data. Pearson correlation (r) was calculated to assess the relationship between biodiversity indices, species richness, and stem density across land-use systems.

Results and Discussion

In the study area, 1611 individuals from 75 tree species were identified, each contributing uniquely to its ecological diversity and carbon sequestration potential. The recorded tree species richness in the present study is comparable to other tropical forests in India (26 to 85 species, Shruthi *et al*., 2018). This species richness could potentially be due to rapid establishment of locally adaptable early successional species, as well as continuous planting activities on the campus. The average height and diameter of tree species were 10.71 m and 16.13 cm, respectively, suggesting moderate height and girth in the population. Tree biomass estimation of an area depends on tree density, height, and basal area (Trogisch *et al.,* 2021) and studies have reported that trees display differences in architectural characteristics, both within individual sites and across different locations (Ette *et al.,* 2023). Tree density in the present study was lower than that in other tropical forests (Sahu *et al.,* 2010), and other tropical dry deciduous forests of India (Chaturvedi *et al.,* 2011). This could be attributed to ongoing anthropogenic disturbances on the campus and to the fragmentation of forests and their patchy conditions, as a consequences of past disturbances. Three tree species, *Eucalyptus tereticornis, Acacia auriculiformis* and *Mangifera indica,* accounted 46.89% of the individuals and 58.37% of the basal area; therefore, they formed the foundation of the ecosystem.

Distribution of individuals in this study varied widely, with few species represented by a single individual, highlighting a diverse and uneven population structure. Forests with uneven population structures enhance ecosystem stability, as rare species can become functionally important under environmental changing conditions (Isbell *et al.,* 2015). This diversity in species abundance also boosts carbon sequestration, with mixed-species stands outperforming monocultures through complementarity effects (Liang *et al.,* 2016; Huang *et al.,* 2018). Dominant species, such as *Eucalyptus tereticornis* and *Acacia auriculiformis,* stand out with the highest basal areas, reflecting their significant impact on forestpopulation. *Eucalyptus tereticornis,* with 426 individuals, contributes a substantial basal area of 2.42 m^2 ha^{-1} and an exceptional carbon stock of 92.82 Mg ha^{-1}. On the other hand, species such as *Ficus virens* and *Diospyros montana,* despite their lower population numbers, exhibited high carbon stocks, underscoring the importance of large, mature trees in carbon sequestration (Table 1). Species dominance typically increases in response to stress or past disturbances (Liu *et al.,* 2018).The dominance of *Eucalyptus tereticornis* on the GKVK campus is likely due to extensive planting and maintenance carried out in the past. In the present study *Eucalyptus tereticornis* accumulated the maximum carbon stock (13.92 %) with a high basal area (30.56 %) and a higher number of individuals (26.46 %). Similarly, Sahu *et al.* (2016) observed significant single-species dominance in density, basal area, and carbon stock in the forests of the Eastern Ghats. This suggests that *Eucalyptus tereticornis* contributes significantly to carbon storage in the biodiversity heritage sites of GKVK campus.

Tree species diversity is a vital component of any forest ecosystem, and understanding species diversity is essential in plant ecology and forestry to compare species composition. Biodiversity indices are used to standardize species diversity and abundance across different habitats for comparison, with higher values reflecting greater species richness (Naidu and Kumar, 2016). Gardens exhibited the highest biodiversity, with a *H'* of 3.35 and species richness of 56 (Table 2). Their high variety and low dominance (Simpson's index: 0.95) suggest that active management and intentional species introduction help sustain diverse plant life. Botanical gardens have demonstrated higher biodiversity values, primarily because they are intentionally designed to maximize taxonomic diversity for conservation, education, and display purposes (Chen and Su, 2018). Additionally, their intensive management practices, including controlled irrigation, pest management, and soil enrichment, optimize the growing conditions for a wide range of species that do not typically coexist in natural environments (Entwisle *et al.,* 2017).

The *H'* in this study varied across land use systems (1.46 to 3.35), indicating moderate tree species diversity, falls within the range reported for Indian forests, and the concentration of dominance, measured by Simpson's index, also fell within the range (0.610–0.949) reported for tropical forests in other studies (Kumar *et al.,* 2022). Tree species diversity in tropical forests varies significantly across locations, primarily because of differences in biogeography, habitat and disturbance (Storch *et al.,* 2018). The stem density in gardens (370 individuals ha^{-1}) also indicates robust vegetation cover, supporting substantial tree populations. In comparison, natural forests displayed slightly lower biodiversity with *H'* of 2.34 and species richness of 28. A moderate Simpson's Index (0.83) indicates reduced species dominance, reflecting a stable natural ecosystem where species coexist more equally, and the high stem density (366.67 individuals ha^{-1}) further supports their role as key habitats for diverse species. Agricultural lands, on the other hand, exhibited the lowest biodiversity, with a *H'* of 1.46 and species richness of 13, likely due to reduced tree diversity and structural simplification. A low Simpson's Index (0.61) suggests that a few species dominate these areas, which is a common outcome of converting natural ecosystems into monocultures or simplified agricultural systems. Additionally, the low stem density (67.19 individuals ha^{-1}) highlights reduced tree vegetation. Plantations, while not as diverse as natural forests or gardens, showed moderate biodiversity with a *H'* of 2.01 and species richness of 21. Plantations also featured the highest stem density (488.89 individuals ha^{-1}), likely because of dense planting strategies for

Table 1: Species-wise average height, average diameter and carbon stock in the study area (N: Total number of trees; BA: Basal Area (m^{2}ha^{-1}); CS: Carbon stock (Mg ha^{-1})

Name of the species	Average height (m)	Average diameter (cm)	N	BA	CS
Acacia auriculiformis	13.47	20.61	249	1.70	51.14
Ailanthus excelsa	22.50	10.17	1	<0.01	0.79
Ailanthus malabarica	12.95	16.98	10	0.05	14.10
Albizia amara	5.02	5.80	32	0.03	2.28
Albizia lebbeck	14.00	21.13	1	0.01	2.77
Albizia odoratissima	13.04	21.88	14	0.11	10.71
Amoora lawii	11.08	14.98	31	0.11	11.14
Anacardium occidentale	4.71	18.07	17	0.08	1.96
Andira inermis	13.00	13.98	1	<0.01	1.19
Annona muricata	3.93	6.46	3	<0.01	0.08
Arenga obtusifolia	2.75	7.31	2	<0.01	0.25
Artocarpus heterophyllus	10.17	25.09	12	0.12	6.44
Azadirachta indica	9.98	23.20	3	0.03	10.12
Bauhinia purpurea	6.83	14.27	6	0.02	1.72
Bauhinia variegata	4.00	5.60	8	<0.01	0.28
Broussonetia papyrifera	5.00	1.91	1	<0.01	0.01
Butea monosperma	11.00	17.16	3	0.01	1.67
Cassia fistula	4.50	11.81	2	<0.01	0.88
Cassia siamea	14.76	16.84	10	0.04	15.24
Delonix regia	11.13	18.47	4	0.03	4.78
Dillenia indica	6.00	9.11	1	<0.01	0.30
Diospyros melanoxylon	3.75	6.57	32	0.02	0.60
Diospyros montana	13.50	51.16	1	0.04	23.79
Diospyros sp.	9.50	16.36	2	0.01	3.98
Dracaena reflexa	1.50	3.92	1	<0.01	0.01
Enterolobium contortisiliquum	10.17	15.57	3	0.01	2.59
Eucalyptus citriodora	6.26	6.48	13	0.01	0.81
Eucalyptus tereticornis	14.85	18.97	426	2.42	92.82
Ficus benghalensis	3.00	3.18	1	<0.01	0.02
Ficus benjamina	8.00	15.89	1	<0.01	1.08
Ficus krishnae	12.50	44.49	1	0.03	7.80
Ficus mollis	6.50	18.43	2	0.01	1.71
Ficus tsjahela	5.50	9.85	1	<0.01	0.30
Ficus virens	12.00	88.97	1	0.11	27.52
Gliricidia sepium	7.25	8.74	8	0.01	1.32
Gmelina arborea	14.29	23.81	12	0.11	21.28
Grevillea robusta	12.38	13.99	35	0.11	7.18
Jacaranda mimosifolia	6.96	9.57	124	0.28	7.36
Lagerstroemia lanceolata	13.53	18.09	16	0.08	18.26
Leucaena leucocephala	13.15	27.04	6	0.07	7.16
Mangifera indica	5.23	19.82	80	0.51	8.80
Manihot glaziovii	19.37	34.95	1	0.02	18.22
Manilkara zapota	4.88	15.29	20	0.07	2.20
Melia dubia	5.40	14.05	5	0.03	6.07
Michelia × longifolia	4.00	9.53	1	<0.01	0.15
Michelia champaca	14.50	32.57	1	0.02	6.50
Mimusops elengi	4.00	3.71	1	<0.01	0.05
Monoon fragrans	5.50	8.90	1	<0.01	0.21
Peltophorum pterocarpum	13.44	30.43	8	0.13	11.80
Persea americana	8.00	9.53	1	<0.01	0.37
Phyllanthus emblica	5.00	9.85	1	<0.01	0.34
Phyllanthus polyphyllus	4.00	18.75	1	0.01	0.70
Polyalthia longifolia	5.50	5.72	1	<0.01	0.09
Pongamia pinnata	6.89	13.43	33	0.12	3.75
Pritchardia pacifica	1.00	3.81	1	<0.01	0.01
Psidium cattleyanum	12.00	19.70	1	0.01	4.17
Psidium guajava	4.27	8.17	11	0.02	0.55

Table continued

Pterocarpus marsupium	10.76	17.08	16	0.08	40.61
Pterygota alata	4.88	6.04	4	<0.01	0.39
Santalum album	4.08	5.03	145	0.06	1.00
Sapindus laurifolius	8.50	19.29	6	0.04	12.55
Schleichera oleosa	12.50	27.33	2	0.02	16.30
Securinega leucopyrus	5.00	10.88	1	<0.01	0.39
Simarouba glauca	9.73	13.74	34	0.11	4.99
Sterculia urens	9.00	21.77	2	0.01	3.79
Swietenia mahagoni	8.82	15.18	14	0.06	3.96
Syzygium cumini	14.05	29.15	7	0.09	12.80
Syzygium jambos	8.13	16.68	4	0.02	5.23
Syzygium operculatum	13.00	49.57	1	0.04	18.80
Tamarindus indica	11.18	22.32	49	0.50	32.10
Tectona grandis	16.26	15.81	52	0.21	28.02
Terminalia arjuna	10	31.14	1	0.01	7.18
Terminalia bellirica	12.00	47.03	1	0.03	15.59
Terminalia tomentosa	16.33	26.48	3	0.04	35.27
Xanthophyllum ovatifolium	5.33	10.49	3	<0.01	0.57
Mean±SD	10.71±5.16	16.13±9.15			

Table 2: Tree diversity and population in the study site

Land use type	Shannon index	Simpsons index	Species richness	Stem density (Ind ha^{-1})
Agricultural lands	1.46	0.61	13	67.19
Gardens	3.35	0.95	56	370.00
Natural forest	2.34	0.83	28	366.67
Plantations	2.01	0.80	21	488.89

commercial or conservation purposes. In this study, gardens were most diverse compared with other land-use systems, which can be attributed to the introduction of a wide variety of species and continuous planting of different species in the garden. However, plantations had the highest stem density, which may be due to dense plantation of tree species with less spacing compared with other land-use systems.

Plantations characterized by a high-level of species dominance, common in managed environments focused on a few commercially valuable species, are effective for biomass production and carbon storage. However, they often lack the ecological complexity of the natural ecosystems. These insights suggest that biodiversity, as measured by the Shannon and Simpson indices, is generally associated with higher stem density and it indicates that the study site contains productive ecosystems, and enhancing species richness and managing stem density can significantly improve biodiversity.

The pair plot matrix (Fig. 3) provides an assessment of the relationships between key diversity indices, species richness and stem density. A strong positive correlation between the *H'* and species richness (0.989*) suggested that sites with higher species richness also had higher diversity. Similarly, the moderate positive correlation observed between *H'* and stem density (0.512) and Simpson's index also showed a strong positive correlation with species richness (0.893) and a moderate positive correlation with stem density (0.475), indicating that sites with higher species richness had lower species dominance, thereby supporting greater ecological balance. A higher species richness reduces the dominance of any single species through negative density-dependent processes (LaManna *et al.,* 2017), and greater niche partitioning in species-rich communities enables the coexistence of multiple species through specialized resource use (Levine *et al.,* 2017; Godoy *et al.,* 2017). Increased species richness and higher stem density corresponded to greater diversity, as indicated by the *H'* and Simpson's index.

The diameter distribution of trees is frequently used to depict the population structure of forests, and tree distribution across various girth classes illustrates the efficiency of growing forests in utilizing functional and structural resources. The study area showed good regeneration status, with the highest number of individuals in the lower girth classes (10–50 cm), which indicates a high recruitment of younger seedlings (Fig. 4). DBH class analysis showed that the medium diameter class with a high number of individuals (869) and species richness (45), significantly contributed to carbon stock (199.91 Mg ha^{-1}). In contrast, the large-diameter class, despite having fewer individuals (25) and lower species richness (15), also contributed

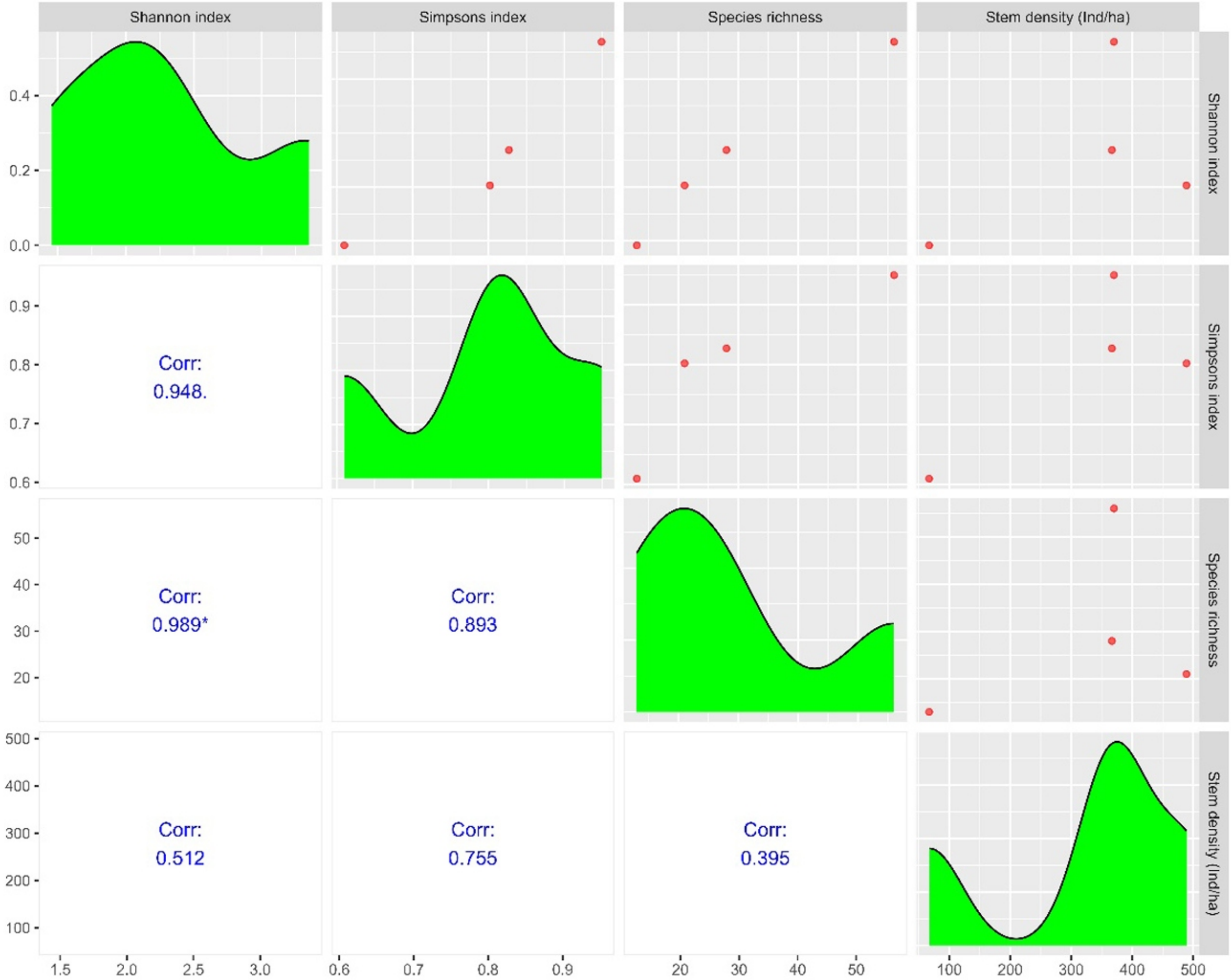

Fig. 3: Relationships between biodiversity indices and vegetation metrics in different land use systems.

notably to carbon storage (47.82 Mg ha^{-1}) due to three size. The small diameter class, although diverse (56 species) and numerous (716 individuals), had a lower average height and, consequently, less carbon stock (20.87 Mg ha^{-1}). This indicates that, while small-diameter trees are important for biodiversity, medium- and large-diameter trees are more effective for carbon storage (Table 4). The inverse J-shaped curve observed in the study site showed a decrease in the number of individuals from lower to higher, size classes, which reflects a dynamic population with ongoing regeneration and growth. This result aligns with the population structure of trees observed in other forests of the Gandhamaran in the Eastern Ghats (Sahu *et al.,* 2010).

This structural similarity indicates that, despite geographic and compositional differences, both systems maintain healthy regeneration dynamics. This finding suggests that the fundamental ecological principles of forest structures transcend local boundaries and can inform regional conservation approaches. The abundance of individuals in the lower-size classes reflects a regenerating forest with substantial growth potential. The medium and higher size classes contributed more to the carbon stock than the small girth classes which had higher number of individuals. This aligns with the findings suggesting that trees with larger DBH contribute more significantly to the carbon stock (Liu *et al.,* 2018). This highlights the critical role of trees with a larger DBH in the carbon sequestration process, contributing to high carbon stocks. Fig. 5 shows the basal areas across different land use patterns. Agricultural lands exhibited the lowest basal area (0.76-1.97 m^2 ha^{-1}), with a median of 1.26 m^2 ha^{-1}, and an average of 1.35 m^2 ha^{-1}. Gardens displayed moderate to high variability (2.97 -15.92 m^2 ha^{-1}), a median of 6.94 m^2 ha^{-1}, and an average of 8.55 m^2 ha^{-1}. Natural Forests exhibited a wide range of basal area ranging from 1.35 to 24.68 m^2 ha^{-1}, with a median of 8.32 m^2 ha^{-1} and average of 7.48 m^2 ha^{-1}. The plantations also showed significant variability (3.28 - 24.97 m^2 ha^{-1}), a median of

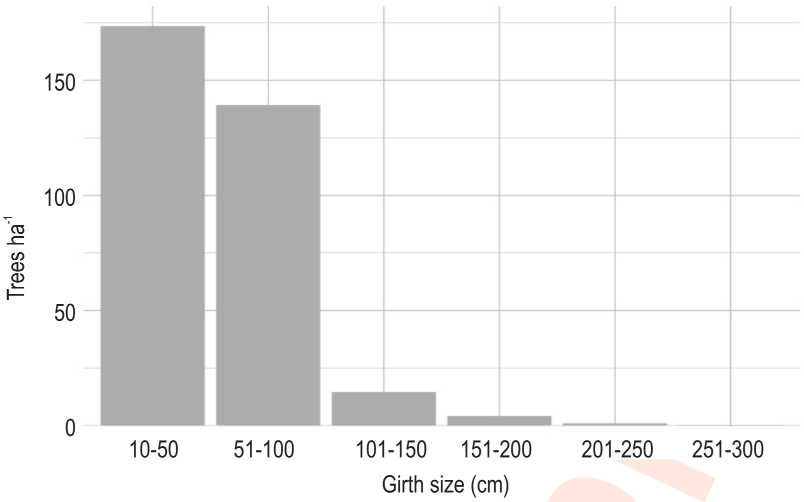

Fig. 4: Girth class wise distribution of trees.

Table 3: Correlation and Regression Analysis of Basal Area (BA) and Carbon Stock (CS)

Site name	BA (m^2 ha^{-1})	CS (Mg ha^{-1})
Area A	6.42	21.46
Area B	8.39	31.69
Area C	9.67	51.84
Area D	9.93	32.26
Area E1	1.52	1.96
Area E2	1.31	1.90
Area E3	3.70	16.52
Area E4	19.55	76.63
Area E5	14.82	57.46
Area E6	5.19	22.28
Area E7	15.02	49.26
Area E8	3.78	6.66
Area E9	1.01	1.49
Area E10	1.40	2.02
Pearson Correlation Coefficient	0.985	
R-squared	0.968	
Adjusted R-squared	0.966	
P-value	<0.0001	

8.95 m^2 ha^{-1}, and an average of 12.38 m^2 ha^{-1}. Among all land-use types, plantations had the highest average basal area of 12.38 m^2 ha^{-1}, highlighting their potential for substantial carbon capture. Reduced basal area reflects multiple anthropogenic disturbances, including maintenance activities, selective tree removal, soil compaction from farm operations, and managed landscape practices that disrupt natural succession processes (Bentsi *et al.,* 2022). Urban forest fragments experience pronounced edge effects that alter microclimatic conditions and reduce large tree recruitment compared to intact forests, ultimately constraining biomass accumulation (Hellenbrand *et al.,* 2025). Basal area in the present study greatly varied between land use systems and these variations in tree BA across land use systems were primarily influenced by species composition, individual growth patterns, and tree age (Joshi and Dhyani, 2019), while disturbances such as agriculture and research activities, further contributed to these variations.

Fig. 6 shows the carbon stocks across various land-use types. The results demonstrated substantial variability in carbon stock among different landscapes. Agricultural lands exhibited the lowest carbon stock (1.07 to 2.85 Mg ha^{-1}), a median of 2.25 Mg ha^{-1}, and an average of 2.13 Mg ha^{-1}. Gardens displayed significant variability (5.91Mg ha^{-1} to 57.82 Mg ha^{-1}), a median of 8.69 Mg ha^{-1}, and an average of 24.80 Mg ha^{-1}. Natural forests showed a wide range of carbon stock ranging from 0.20 to 16.20 Mg ha^{-1}, with a median of 1.56 Mg ha^{-1} and average of 3.80 Mg ha^{-1}. Plantations exhibited the highest carbon stock (10.58 to 116.26 Mg ha^{-1}), with a median of 28.14 Mg ha^{-1} and average of 49.39 Mg ha^{-1}. Plantations sequester carbon more efficiently through three key factors: fast-growing selected species like *Eucalyptus* sp. capture carbon at accelerated rates (Paquette and Messier, 2010); intensive management practices including fertilization and

Table 4: Diameter class wise tree stand characteristics

Diameter class	Species richness	Number of individuals	Average height±SD (m)	Carbon stock (Mg ha^{-1})
Large	15	25	13.29 ± 2.62	47.82
Medium	45	869	13.42 ± 5.31	199.91
Small	56	716	7.33 ± 5.53	20.87

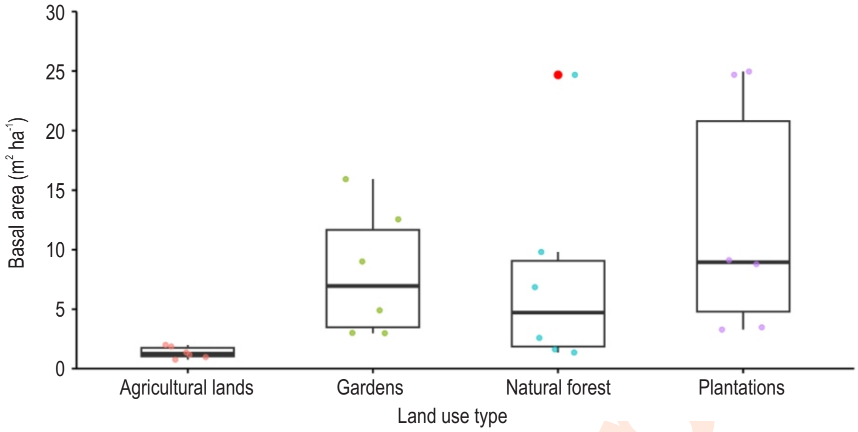

Fig. 5: Variation in basal area across different land use systems.

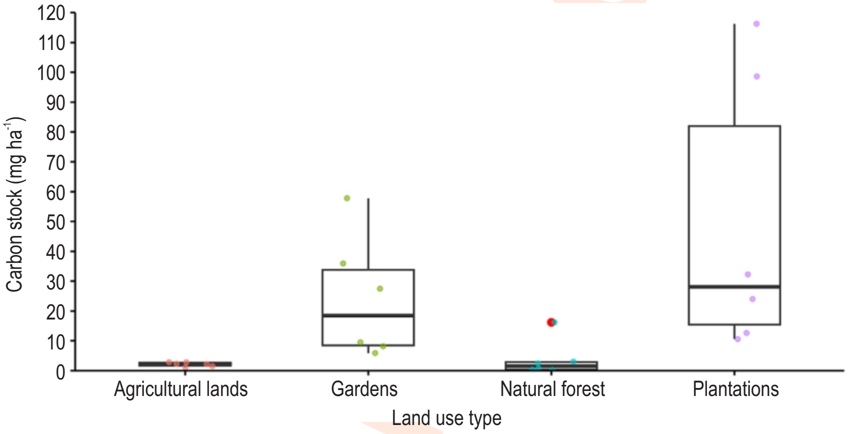

Fig. 6: Variation of carbon stocks across different land use systems.

optimal spacing maximize biomass accumulation (Noormets *et al.,* 2015); and higher tree density increases total biomass per hectare, particularly in younger stands. These findings highlight the crucial role of plantations in carbon sequestration.

The carbon stock in the study area was lower than the average values observed in tropical forests worldwide (Behera *et al.,* 2017), which is also lower than the range reported for dry deciduous forests of the Indian Eastern Ghats (85.02–723.46 Mg ha^{-1}) by Gandhi and Sundarpandian (2017). Increasing forested land, such as through plantation forests, is proposed as an effective strategy for carbon capture to help reduce atmospheric CO_2 levels and combat global warming (Ullah *et al.,* 2024). The carbon stock of an area is influenced by anthropogenic disturbances, both in terms of degree and type (Gupta and Ghose, 2014). In the present study, plantations were the most effective land-use type for carbon storage, while agricultural lands were the least effective in the study area. These results underscore the need for sustainable farming and agroforestry practices to help restore biodiversity in agricultural lands and suggest that targeted management practices aimed at maximizing the biomass potential of agricultural lands could significantly enhance carbon storage.

Table 3 shows the relationship between the BA and carbon stock across various sites reveals a significant positive correlation. Site E4, with an exceptionally high BA of 19.55 m^2 ha^{-1} and a Carbon Stock of 76.63 Mg ha^{-1}, stands out as a critical contributor to carbon storage. In contrast, Sites E9 and E10, with the lowest Basal Areas of 1.01 m^2 ha^{-1} and 1.40 m^2 ha^{-1} and Carbon Stocks of 1.49 Mg ha^{-1} and 2.02 Mg ha^{-1}, respectively, show minimal carbon sequestration potential. Overall, sites with higher Basal Areas, such as E4, E5 (14.82 m^2 ha^{-1}) and E7 (15.02 m^2 ha^{-1}), strongly correlate with increased Carbon Stocks (57.46 Mg ha^{-1} and 49.26 Mg ha^{-1}, respectively). A strong positive relationship between carbon stock and basal area was observed, consistent with previous research (Joshi and Dhyani, 2019; Kothandaraman *et al.,* 2020), and confirmed by a Pearson's correlation coefficient of 0.985 ($p < 0.0001$) between the basal area and carbon stock.

The findings of this study revealed that tree diversity, stem density, and basal area are key determinants of carbon storage across land-use systems. Gardens exhibited the highest biodiversity, whereas plantations, through fast-growing species and high stem density, served as the most effective carbon sinks. Natural forests maintained a balanced species distribution, while agricultural lands showed the lowest biodiversity and carbon stocks. Medium and large trees contributed disproportionately to carbon sequestration, strongly correlating with basal area. These findings underscore the need to prioritize the conservation of mature trees and high-biodiversity patches in land-use planning to maximize both carbon sequestration and ecosystem resilience.

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