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Linking Biodiversity and Carbon Stocks in Homegarden Agroforestry Systems Across an Elevation Gradient in Nagaland, Northeast India

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Abstract

Homegardens are multifunctional agroforestry systems that support livelihood security, biodiversity conservation, and climate change mitigation in the tropics. However, quantitative assessments of their ecological attributes across elevation gradients remain limited in Northeast India. This study evaluated species diversity, structural characteristics, vegetation biomass, and carbon stocks of homegardens across three elevation zones (E1: <250 m, E2: 250–500 m, and E3: >500 m amsl) in subtropical Nagaland. A multistrata vegetation structure comprising 130 plant species was observed, with trees accounting for 47.59% of the total species composition. Mean homegarden area declined significantly from 988.17 ± 181.63 m² at lower elevations (E1) to 291.46 ± 35.70 m² at higher elevations (E3) ($p < 0.05$). The Shannon diversity index showed no significant variation across elevations, whereas species richness and evenness increased significantly with elevation. Aboveground biomass, total biomass, and total biomass carbon exhibited non-significant increasing trends along the elevation gradient, ranging from 65.38 to 69.74 Mg ha⁻¹, 78.71 to 83.99 Mg ha⁻¹, and 36.99 to 39.48 Mg C ha⁻¹, respectively. In contrast, soil organic carbon (SOC) stock increased significantly from 58.93 ± 1.33 Mg C ha⁻¹ at E1 to 93.64 ± 3.61 Mg C ha⁻¹ at E3 (0–60 cm depth). The findings indicate that biodiversity and vegetation carbon storage were influenced more by management practices and species composition than by elevation alone, while soil carbon dynamics were strongly associated with elevational variation. Overall, homegardens of Nagaland function as important reservoirs of biodiversity and carbon while supporting household livelihoods.

Introduction

The present era is characterised by accelerating climate change, environmental pollution, land degradation, and rapid biodiversity loss. North East India, despite being one of the regions with the highest forest cover (65.45% of its total geographical area and accounting for around 24% of the country's forest cover) and being home to two global biodiversity hotspots, is experiencing increasing pressure on its natural resources (Department of Land Resources 2019; ISFR 2023; Singh and Chaudhary 2023). Over the past few decades, widespread habitat alteration driven by unregulated extraction of forest resources, illegal mining, shifting cultivation, and expanding developmental activities has resulted in some of the highest rates of natural resource depletion in the country (Saikia and Khan 2014; Gogoi et al. 2020; Das et al. 2025; Rajak et al. 2025).

The North East region possesses diverse indigenous agroforestry system ((Das et al. 2012; Bhutia et al. 2024; Giri et al. 2024; Pangging et al. 2025). However, they remain poorly documented, especially at regional scales (Das et al. 2023; Mylliemngap 2023). Documentation on their structural, functional, and ecological attributes is crucial for a thorough understanding of their ecological role, as well as their contribution to food, nutritional and economic security in households. These tree based systems is particularly important in mountainous regions, where market access is often restricted, and farming systems are vulnerable to climatic uncertainties (Gonçalves et al. 2021; Sharma et al. 2024b). Among the varied indigenous land use practices, homegardens are widely recognised as one of the most common and culturally embedded agroforestry systems in North East India (Devi and Das 2010; Sahoo et al. 2019; Sharma et al. 2024a). Structurally, homegardens resemble natural forest ecosystems in terms of their

multi-storeyed vertical arrangement often integrated with animal components within household compounds. In North East India, livestock and poultry play a very integral part of homegardens, with studies reporting livestock in approximately 60–64% and poultry or avian components present in up to 85% of homegardens (Subba et al. 2020; Sharma et al. 2024a)

Each stratum of homegardens performs important ecological functions such as microclimate regulation, carbon sequestration, soil moisture conservation, erosion control, nutrient recycling and habitat provision, while also providing food, fuel, fodder, timber, medicinal products, and other goods for household consumption and income generation (Fernandes and Nair 1986; Montagnini and Nair 2004; Verchot et al. 2007; Yashmita-Ulman 2021; Korpelainen 2023; Sharma et al. 2024b). They play a critical role in local food systems by providing a year-round diverse range of plants and animal products, contributing significantly to dietary diversity, nutritional security, and livelihood resilience of small farm households (Sharma et al. 2022).

Home gardens also play a major role in conserving biodiversity, as they harbour a wide range of edible, medicinal, and economically valuable species. They often help conserve species that have declined in natural habitats, such as agarwood (Saikia and Khan 2014; Barbhuiya et al. 2016; Ulman et al. 2021; Chowdhury et al. 2024).

The structural diversity and rich species composition make home gardens highly adaptable to changing climates. These systems buffer temperature extremes and remain productive under climatic stress. This resilience is due to complementary interactions among different plant components (Tynsong and Tiwari 2010; Mallick et al. 2024; Gebremariam et al. 2025). The high proportion of woody perennials further boosts vegetation biomass and carbon storage. Regular litter deposition and minimal soil disturbance enhance soil organic carbon pools (Bargali and Bargali 2020; Jegora et al. 2025). Homegardens also improve soil fertility and conserve moisture. They act as protective buffers around homesteads, reducing surface runoff and limiting contaminants in streams and rivers (Linger 2014; Fahad et al. 2022). Given these benefits, agroforestry systems, including homegardens, have been recognised by the IPCC as important nature based strategies for climate mitigation and adaptation (IPCC 2019; IPCC 2022).

Therefore, there is a need to quantify ecological and functional attributes of homegardens in a systematic manner. Estimating carbon stocks in these systems is particularly important for climate mitigation planning, exploring carbon credit opportunities, and designing climate-resilient land use strategies. At the same time, detailed information on species composition, Importance Value Index (IVI), and diversity patterns can aid in selecting suitable species for the development of region-specific agroforestry models, while also improving the understanding of farmer preferences and livelihood needs under changing climatic conditions. Furthermore, such information has important ecological implications for biodiversity conservation, ecosystem stability, carbon sequestration, and the sustainable management of homegarden agroforestry systems across diverse landscapes (Kumar 2023).

Despite the recognised ecological and socioeconomic importance of homegardens, research on this system in Nagaland remains limited, particularly with respect to variations in structure, species diversity, and carbon storage potential along elevation gradients. Nagaland is characterised by highly diverse

topography and a rich mix of indigenous communities, where homegardens have traditionally supported household food and nutritional security, traditional healthcare practices, and supplementary income through the sale of surplus produce. In this context, the present study represents one of the first comprehensive assessments of homegarden agroforestry systems in Nagaland. It examines species diversity, structural characteristics, IVI, vegetation biomass and carbon stocks, as well as soil organic carbon across different elevation zones in Chümoukedima district. The study further evaluates how elevation, garden size, and species composition influence the structural and functional attributes of homegardens. Overall, the findings are expected to contribute to the development of climate-resilient and ecologically sustainable agroforestry models, strengthen the scientific understanding of biodiversity-carbon relationships in indigenous land-use systems, and provide baseline information for assessing carbon sequestration potential and future carbon credit opportunities in homegarden agroforestry systems of the region.

Materials and method

Study sites

The present investigation was carried out during 2024 to assess the structure, floristic composition, biomass, and carbon stock of homegardens in Chümoukedima district of Nagaland located in the foothills of the Naga Hills (Fig. 1).

The study area is bounded by 25°48' N to 26°00' N latitude and 93°30' E to 93°54' E longitude with the inhabited areas primarily distributed between 150 and 900 m asl. The climate of the study area is a sub-tropical, with warm and humid summers, mild winters, and a well-defined monsoon season. Most of the annual rainfall is received during July to September. Analysis of meteorological data collected from Agro Met Field Unit, ICAR Nagaland Centre for the period 2010–2024 shows that the mean annual maximum temperature ranged from 28.49 to 30.50°C, while the mean annual minimum temperature varied between 17.98 and 18.74°C. The mean annual temperature remained fairly stable, fluctuating between 23.23 and 24.50°C). Annual rainfall exhibited noticeable year-to-year variation, ranging from 985.20 mm to 2137.90 mm. Similarly, mean annual relative humidity varied from 57.96% to 78.58% (Fig. 2.). The district exhibits a plains-hills continuum, where low-lying areas are mainly under wetland paddy cultivation, while upland and sloping terrains support forest patches and plantation-based systems. Major plantation crops include pineapple (*Ananas comosus*), rubber (*Hevea brasiliensis*), arecanut (*Areca catechu*), and teak (*Tectona grandis*), often integrated within traditional agroforestry systems.

Sampling Design

To study the structural and functional attributes of homegarden, the whole district was stratified into three elevation zones: E1 (< 250 m amsl), E2 (250–500 m amsl), and E3 (> 500 m amsl). In each elevation zone, three villages were selected. From each village, six homegardens were randomly chosen, resulting in a total of 54 homegardens (3 elevation zones × 3 villages × 6 homegardens). Only well-established and actively

managed homegardens were included in the study. Prior consent was obtained from the household owners before data collection.

Homegarden Characterization and Vegetation Inventory

The size of the homegardens (m^2) were measured using a handheld Garmin GPS. To analyze their vegetation composition, total plant species (excluding weed species) present in each homegarden were inventoried. Vegetation attributes such as total number of species per homegarden were assessed. Plant species were identified using standard regional floras and taxonomic keys.

Vegetation Indices

Species diversity was assessed using standard ecological indices such as Shannon–Wiener diversity index (H'), species richness (S) and Pielou's evenness index (J') following Shannon and Weaver (1963) and Pielou (1975). These indices are widely used to evaluate biodiversity patterns in agroforestry including homegardens (Magurran 2004).

Biomass Estimation

In each homegarden, complete enumeration of woody perennials (trees and shrubs) was done. Height of the trees and diameter at breast height were measured using clinometer and tree caliper, respectively. In shrubs, basal girth was measured. Aboveground biomass (AGB) for woody perennial was estimated using non-destructive allometric equations developed for forest trees, fruit trees, palms, bamboos, shrubs, and coffee (Frangi and Lugo 1985; Andrade et al. 2017; Naik et al. 2018, 2019; Rawat et al. 2018; Nath et al. 2019a; Laskar et al. 2020; Das et al. 2021; Bhutia et al. 2025). Belowground biomass (BGB) of woody perennials was calculated using a default value of 0.20 recommended for tropical forest ecosystem (IPCC 2006).

Vegetation Carbon Stock Estimation

Aboveground and belowground carbon content in plants were calculated by multiplying estimated biomass of trees and shrubs with a conversion factor of 0.47 (IPCC 2006). Total carbon stock in vegetation was determined by adding aboveground and belowground carbon.

Soil carbon stock

A total of 648 soil samples from four depth intervals: D1 (0–15 cm), D2 (15–30 cm), D3 (30–45 cm), and D4 (45–60 cm) were collected from homegardens of study area. Bulk density was measured by soil core method (Blake and Hartge 1986) and soil organic carbon (SOC) content was determined using the Walkley and Black wet oxidation method (Walkley and Black 1934). The carbon stock in soil (Mg C ha^{-1}) for each

depth interval (0–15 cm depth) was computed using the formula given (Brown 2004) as follows: Carbon stock ((Mg C ha^{-1}) = Soil bulk density (g cm^{-3}) x soil depth (15 cm) x C x 100

Where, C is the carbon concentration in soil expressed as a decimal fraction.

The cumulative soil carbon stock for the 0–60 cm soil profile was obtained by combining the carbon stock values across all four depth intervals.

The data so obtained were analyzed by using **SPSS statistical software**.

Result

Homegarden Structure and Diversity

Homegarden size differed significantly across the elevation gradient ($p < 0.05$), with a consistent decline as elevation increased (Fig. 3). The largest homegardens were observed in the lower elevation zone (E1), with mean value of 988.17 m² (range: 356–3192 m²). In the mid-elevation zone (E2), the mean size of homegarden dropped to 486.83 m² (range: 90–1364 m²), and it further reduced in the higher elevation zone (E3), where the smallest homegardens were recorded, with a mean value of 291.46 m² (range: 100–638 m²). Considerable variation in garden size was evident in the lower elevation zone, where holdings ranged from small household plots to larger microzones systems.

Diversity analysis of woody and non-woody perennials showed that the mean Shannon–Wiener index was highest in E3 (2.03 ± 0.09), followed by E1 (1.77 ± 0.09) and E2 (1.72 ± 0.12), with no significant differences among the elevation zones. Species richness value was significantly different with maximum mean value (1.65 ± 0.13) in E3 and minimum (1.25 ± 0.09) in E1 and value in E2 (1.35 ± 0.13) was at par with E1 and E3. However, species evenness were also found to be significantly different with maximum mean value of 0.83 ± 0.02 in E3 and minimum in E1 (0.68 ± 0.03) which value was at par with E2 (0.69 ± 0.04) (Table 1)

Table 1
Diversity indices (Mean ± SE) of woody/nonwoody perennials of Homegardens across altitudinal gradients in Subtropical Nagaland.

Diversity Parameters	**Elevation**		
	E1 (< 250 m)	**E2 (250–500 m)**	**E3 (500–750 m)**
Shannon–Wiener Index	1.77^{a} ± 0.09	1.72^{a} ± 0.12	2.03^{a} ± 0.09
Species Richness Index	1.25^{b} ± 0.09	1.35^{ab} ± 0.13	1.65^{a} ± 0.13
Species Evenness Index	0.68^{b} ± 0.03	0.69^{ab} ± 0.04	0.83^{a} ± 0.02

Different letters superscripted along row mean value indicate significant different ($p < 0.05$), SE- standard error.

Importance Value Index

The Importance Value Index (IVI) of the woody/non woody perennials revealed that several dominant species were common across all homegardens along the elevational gradient (Table 2). In E1, the dominant species with the highest IVI was *Areca catechu* (IVI: 39.80). Other species with relatively high IVI values in this zone included *Bambusa tulda* (IVI: 32.10), *Cocos nucifera* (IVI: 18.82), *Parkia roxburghii* (IVI: 18.46) and *Mangifera indica* (IVI: 17.55) and *Musa paradisiaca* (IVI: 15.93). Within the E2, showed a broadly similar composition to E1, with *Bambusa tulda* (38.85), *Areca catechu* (*33.93*), again representing the most dominant species. Species like *Musa paradisiaca* (IVI: 17.83*), Mangifera indica* (IVI: 16.54), *Cocos nucifera* (IVI: 15.63), *Parkia roxburghii* (IVI: 15.10) also exhibited high dominance. Likewise, the dominant species in the E3 were *Areca catechu* (IVI: 33.06), *Musa paradisiaca* (IVI: 31.19) and *Parkia roxburghii* (IVI: 26.02). Other prominent species in this zone include *Mangifera indica* (IVI: 20.68), *Artocarpus heterophyllus* (IVI: 14.14), *Schima wallichi* (IVI: 12.41).

Table 2
Importance Value Index (IVI) of woody/nonwoody perennials of Homegardens across altitudinal gradients in Subtropical Nagaland.

Tree Species	Elevation		
	E1 (< 250 m)	E2 (250–500 m)	E3 (500–750 m)
Acacia auriculiformis	0.00	0.73	0.00
Acrocarpus fraxilifolius	7.96	0.99	0.00
Albizia procera	0.00	1.21	1.21
Annacardium occidentale	1.11	1.02	1.95
Annona reticulata	2.11	2.27	0.66
Aquilaria malaccensis	5.23	1.88	0.00
Areca catechu	39.80	33.93	33.06
Artocarpus heterophyllus	4.74	12.64	14.14
Averrhoa carambola	3.20	9.28	4.21
Azadirachta indica	1.35	0.00	0.00
Baccaurea ramiflora	0.00	0.66	0.00
Bambusa tulda	32.10	38.85	10.69
Bauhinia spp.	0.50	0.60	0.00
Broussonetia papyrifera	4.11	0.00	3.00
Cajanus cajan	0.76	3.10	2.46
Carica papaya	6.61	5.42	9.37
Cassia fistula	0.00	0.65	0.00
Celtis tetrandra	0.00	0.56	0.00
Choerospondias axillaris	3.15	2.50	0.06
Chukrasia tabularis	0.00	2.59	0.00
Citrus limon	5.73	2.91	1.58
Citrus maxima	5.46	9.85	6.25
Citrus reticulata	2.07	2.68	0.57
Clerodendrum spp.	3.36	6.32	8.45
Cocos nucifera	18.82	15.63	2.34
Coffee robusta	0.00	0.76	9.56

Tree Species	Elevation		
	E1 (< 250 m)	E2 (250–500 m)	E3 (500–750 m)
Dabergia sissoo	0.00	0.69	0.00
Daubanga grandiflora	0.50	0.48	0.77
Emblica officinalis	4.16	3.59	2.41
Eriobotrya japonica	0.00	0.76	0.00
Ficus hispida	4.68	3.40	3.08
Ficus roxburghii	2.27	0.00	1.90
Ficus spp.	1.04	0.00	0.00
Gmelina arborea	1.36	4.25	2.38
Hibiscus sabdariffa	2.53	2.54	3.47
Leucaena leucocephala	0.71	0.00	0.00
Litchi chinensis	4.93	8.07	4.69
Livistonia jenkinsinia	0.00	0.00	0.00
Macaranga denticulata	0.00	4.49	0.00
Mangifera indica	17.55	16.54	20.68
Manilkara zapota	1.94	1.30	0.00
Melia azederach	5.02	3.71	13.49
Moringa oleifera	3.40	2.49	0.00
Morus alba	1.58	0.00	0.76
Muntingia calabura	0.61	1.24	0.00
Murraya koenigii	0.45	1.88	0.69
Musa paradisiaca	15.93	17.83	31.19
Ocimum tenuiflorum	0.30	0.00	0.00
Oroxylum indicum	2.19	6.13	0.00
Parkia roxburghii	18.46	15.10	26.02
Phoenix dactylifera	4.24	0.00	0.00
Phyllanthus acidus	5.59	0.00	0.00
Pongamia pinnata	1.55	0.00	0.54
Prunus cerasoides	0.00	0.00	0.00

Tree Species	Elevation		
	E1 (< 250 m)	E2 (250–500 m)	E3 (500–750 m)
Prunus persica	0.61	0.60	0.70
Psidium guajava	6.04	7.61	11.92
Pterocarpus santalinus	1.29	0.00	0.77
Punica granatum	0.52	0.61	1.48
Pyrus communis	0.00	0.00	1.60
Rhus semialata	0.00	0.00	0.68
Ricinus communis	12.30	6.93	9.54
Santalum album	2.01	0.00	0.93
Schima wallichi	0.00	2.60	12.41
Senna siamea	4.20	0.00	0.70
Spondias pinnata	1.16	6.87	11.43
Syzygium cumini	2.73	1.31	4.95
Tamarindus indica	5.61	9.76	5.88
Tectona grandis	8.42	6.62	5.71
Terminalia arjuna	1.11	0.00	0.00
Thysanolaena maxima	3.56	3.52	6.95
Zanthoxylum rhetsa	0.00	0.63	2.73
Ziziphus mauritiana	1.27	1.45	0.00

Vegetation Biomass and Carbon Stocks

Table 3 Biomass and biomass carbon stock (Mean ± SE) of woody/non-woody perennials of homegardens across altitudinal gradients in Subtropical Nagaland.

Parameters	Elevation		
	E1 (< 250 m)	**E2 (250–500 m)**	**E3 (500–750 m)**
Biomass (Mg ha⁻¹)			
Aboveground biomass	65.38[a] ±8.78	68.15[a] ±7.97	69.74[a] ± 9.55
Belowground biomass	13.33[a] ±1.80	13.92[a]±1.63	14.26[a] ± 1.96
Total biomass	78.71[a]±10.57	82.07[a]±9.61	83.99[a]± 11.51
Biomass carbon stock (Mg C ha⁻¹)			
Aboveground biomass carbon	30.73[a] ±4.13	32.03[a]±3.75	32.78[a] ± 4.49
Belowground biomass carbon	6.26[a] ± 0.84	6.54[a] ± 0.77	6.70[a] ± 0.92
Total biomass carbon	36.99[a] ± 4.97	38.57[a] ± 4.52	39.48[a] ± 5.41

Different letters superscripted along row mean value indicate significant different ($p < 0.05$), SE- standard error.

A similar pattern was observed for biomass carbon stocks (Table 3). Mean aboveground biomass carbon (AGBC) was 30.73 ± 4.13 Mg ha⁻¹ (range: 26.60–34.86 Mg ha⁻¹) at E1, 32.03 ± 3.75 Mg ha⁻¹ (range: 27.44–36.06 Mg ha⁻¹) at E2, and 32.78 ± 4.49 Mg ha⁻¹ (range: 28.29–37.27 Mg ha⁻¹) at E3. Mean belowground biomass carbon (BGBC) increased from 6.26 ± 0.84 Mg ha⁻¹ (range: 5.42–7.10 Mg ha⁻¹) at E1 to 6.54 ± 0.77 Mg ha⁻¹ (range: 5.60–7.36 Mg ha⁻¹) at E2 and 6.70 ± 0.92 Mg ha⁻¹ (range: 5.78–7.62 Mg ha⁻¹) at E3. Mean total biomass carbon (TBC) followed the same trend, increasing from 36.99 ± 4.97 Mg ha⁻¹ (range: 32.02–41.96 Mg ha⁻¹) at E1 to 38.57 ± 4.52 Mg ha⁻¹ (range: 33.04–43.42 Mg ha⁻¹) at E2 and 39.48 ± 5.41 Mg ha⁻¹ (range: 34.07–44.89 Mg ha⁻¹) at E3.

The soil organic carbon (SOC) stock of homegardens showed a distinct increasing trend with elevation (E1: <250; E2:250–500; E3: >500m) and a consistent decline with soil depth (D1:0–15 cm; D2: 15–30 cm; D3:30–45 cm and D4: 45–60 cm) across the study sites (Fig. 4). At the lower elevation (E1), mean SOC ranged from 13.96 ± 0.35 to 17.23 ± 0.47 Mg C ha⁻¹, with higher values in the upper soil layers (0–15 cm depth) that decreased progressively with depth (Fig. 8). The mid-elevational zone (E2) recorded SOC, varying between 13.79 ± 1.00 and 25.65 ± 1.12 Mg C ha⁻¹, while the upper elevation (E3) exhibited the highest SOC stocks, ranging from 17.69 ± 0.68 to 29.36 ± 1.32 Mg C ha⁻¹. Both E2 and E3 followed the same depth-wise pattern observed in E1, with SOC concentration declining from the surface to deeper layers. The cumulative soil carbon stock (0–60 cm) also differed significantly across elevations (Fig. 5), with mean values of 58.93 ± 1.33 Mg C ha⁻¹ in E1, increasing to 74.35 ± 3.83 Mg C ha⁻¹ in E2, and reaching the highest level of 93.64 ± 3.61 Mg C ha⁻¹ in E3.

Correlations Analysis

Correlation analysis showed a significant relationships among homegarden characteristics, biodiversity indices, and carbon variables (Table 4). Homegarden area was negatively correlated with species evenness ($r = -0.325$, $p < 0.05$), species richness ($r = -0.336$, $p < 0.05$), and AGB ($r = -0.348$, $p < 0.05$). A significant negative correlation was also observed between homegarden area and soil organic carbon (SOC) stock ($r = -0.301$, $p < 0.05$). All diversity indices were positively related to SOC and SOC stock. Species richness showed the strongest positive correlation with SOC ($r = 0.497$, $p < 0.01$) and SOC stock ($r = 0.508$, $p < 0.01$), while Shannon index and species evenness were also positively correlated with both ($p < 0.05$). Species richness was positively correlated with AGB ($r = 0.350$, $p < 0.05$. Since AGBC is derived from AGB, a similar positive relationship can be inferred between species richness and biomass carbon.

Table 4
Pearson's correlation coefficients (r) among homegarden area, biodiversity indices, AGB, SOC, and SOC stock.

Correlations								
		Area	**Shannon Weiner Index**	**Species Evenness Index**	**Species Richness Index**	**AGB**	**SOC**	**SOC stock**
Area	Pearson Correlation	1	− .111	− .325*	− .336*	− .348*	− .287	− .301*
	Sig. (2-tailed)		.464	.027	.022	.018	.053	.042
	N	46	46	46	46	46	46	46
Shannon	Pearson Correlation	− .111	1	.856**	.821**	.261	.364*	.385**
	Sig. (2-tailed)	.464		.000	.000	.079	.013	.008
	N	46	46	46	46	46	46	46
Evenness	Pearson Correlation	− .325*	.856**	1	.706**	.203	.364*	.382**
	Sig. (2-tailed)	.027	.000		.000	.175	.013	.009
	N	46	46	46	46	46	46	46
Richness	Pearson Correlation	− .336*	.821**	.706**	1	.350*	.497**	.508**
	Sig. (2-tailed)	.022	.000	.000		.017	.000	.000
	N	46	46	46	46	46	46	46
*. Correlation is significant at the 0.05 level (2-tailed).								
**. Correlation is significant at the 0.01 level (2-tailed).								

Discussion

Floristic composition and structure

The homegardens studied here showed high species diversity, with 130 plant species recorded across 54 homegardens. This confirms the well-known role of homegardens as repositories of agrobiodiversity and traditional ecological knowledge (Gadekar et al. 2020; Kassa et al. 2022; Kassa et al. 2023; Sharma et al. 2024b; Yaregal 2024). Similar levels of richness have been reported from other parts of North East India and the Western Ghats (Devi and Das 2010; Patel et al. 2022; Thangjam et al. 2022), although some studies have reported higher (Saikia and Khan 2014; Sahoo and Rocky 2015) or lower richness (Vibhuti et al. 2019). Such differences may be linked to variation in sampling intensity, garden size, environmental conditions and management, as well as local preferences and market orientation (Peyre et al. 2006; Abebe et al. 2010; Patel et al. 2022; Sharma et al. 2024a).

Trees formed the major component of the system, followed by herbs and shrubs. This pattern is widely reported and reflects the central role of trees in providing food, timber, fuel, shade and ecological stability to the system (Das and Das, 2005; Abebe et al. 2010; Devi and Das, 2010; Patel et al. 2022). The presence of multiple vertical layers gives these homegardens a forest-like structure. Such layering helps in better use of light and space and allows different species to coexist (Nair 1993; Peyre et al. 2006). The presence of microzones within larger homegardens observed in this study reflects structural variation associated with garden size. Similar size dependent structural patterns have been reported in other tropical homegarden systems (Das and Das, 2005; Abebe et al. 2010; Devi and Das, 2010; Patel et al. 2022). The bamboo groves planted along the borders further highlights its multifunctional role in boundary demarcation, wind protection, and meeting various household utility needs.

Influence of elevation on homegarden size

Homegarden size decreased with increasing elevation. Larger homegardens at lower elevations are likely supported by gentler slopes, better market access, and relatively larger landholdings, which allow more diversified and extensive systems. Smaller sizes in the mid- and higher elevation zones (E2 and E3) may be due to steeper slopes, fragmented land, and other physical constraints common in upland areas. Similar trends have been reported from other tropical mountain regions where topography and population pressure influence land-use patterns (Abebe et al. 2010). The considerable variation in garden size within each elevation zone, especially at lower elevations, further indicates the role of household factors such as labour availability, economic condition, and management priorities in determining garden size and structure (Kumar 2023).

Diversity patterns across elevation

Plant diversity is a fundamental attribute of stable and resilient agroecosystems, reflecting both species composition and their relative abundance. In the present study, the Shannon–Wiener index did not vary significantly across elevation zones, However, species richness and evenness showed significant variation. Both were higher in the upper elevation zone, suggesting that these homegardens support a greater number of species with a more balanced distribution. This pattern may be linked to the way smaller

homegardens at higher elevations are managed, where farmers tend to include a wider range of species to enhance subsistence security, dietary diversity, and resilience under relatively harsher environmental conditions. In addition, homegardens in these zones appear to retain their traditional, diversified structure, being less influenced by market-driven monocropping practices. Such patterns align with findings from tropical and subtropical homegarden systems, where smaller landholdings often exhibit high species packing and structural complexity to optimize limited space (Kumar and Nair 2004; Mohri et al. 2013; Roy et al. 2022). The higher evenness at upper elevations also indicates lower dominance of a few species and a more uniform representation of plants. Such patterns are often associated with subsistence-oriented systems, where maintaining diversity is important for food and livelihood security rather than market driven specialization. Overall, while elevation did not affect overall diversity (as reflected by the Shannon index), it influenced how species are distributed and how many are present. This suggests that management practices and household priorities play a stronger role than elevation alone in shaping biodiversity within homegardens.

Species dominance and IVI patterns

The IVI results show that a few key species play a major role across all elevations. *Areca catechu* was consistently dominant, indicating its strong ecological presence and economic importance in homegardens of the region. Its greater dominance at the lower elevation (E1) likely reflects more favourable growing conditions for arecanut. In addition, its suitability for multistrata systems and stable market demand make it a preferred species among farmers. Fruit and multipurpose species such as *Cocos nucifera, Mangifera indica*, and *Parkia roxburghii* also recorded high IVI values. These species are important for household nutrition and income. The wide presence of *Musa paradisiaca* across all zones also reflects farmer preference for fast growing and productive crops. Similar trends have been observed in other tropical homegarden systems. Studies from Sri Lanka report the frequent dominance of species such as *Cocos nucifera* and *Areca catechu*, supporting the view of these systems as palm-based agroforestry (Kumar 2011; Lowe et al. 2022). Fruit and multipurpose species like *Mangifera indica*, *Artocarpus heterophyllus*, *Psidium guajava*, and *Moringa oleifera* are also commonly present, reflecting their importance for household consumption and income. Homegardens are known for providing year round plant-based products, contributing to food security and livelihood support (Ferdous et al. 2016; Rahman et al. 2017a, 2017b; Mellisse et al. 2018; Panyadee et al. 2018; Lowe et al. 2022). At higher elevations, the increased presence of species such as *Schima wallichii* suggests some influence of nearby natural vegetation. Overall, the IVI pattern shows that homegardens retain a core set of economically important species across elevations, while also adjusting species composition based on local conditions and management (Jegora et al. 2025). This pattern highlights the dynamic interaction between environmental factors and farmer choice, which helps maintain productivity and system stability (Kumar 2023; Fernandes and Nair 1986)

Biomass and carbon storage

Perennial biomass represents a relatively stable carbon pool in agroforestry systems and reflects system structure, productivity, and climate change mitigation potential (Sharma et al. 2022). In this study, aboveground, belowground, and total biomass did not differ significantly across elevation zones, although

a steady rise with increasing elevation was observed. A similar pattern was also observed for biomass carbon. This limited variation across elevations likely reflects the managed nature of homegardens, where farmers regulate species composition and stand density to maintain productivity. However, the marginal rise in values at higher elevations may be due to denser species arrangement in smaller landholdings, whereas larger homegardens at lower elevations often show partial dominance of a few commercial species particularly palms. It has been stated earlier that biomass in such systems is mainly influenced by tree density, size distribution, and structural arrangement (Yadav et al. 2019; Bhutia et al. 2022). Although elevation is generally considered an important determinant of biomass and carbon sequestration, its effect in the present study appears weak. In natural ecosystems, biomass elevation relationships are often variable, showing negative (Raich et al. 2006; Leuschner et al. 2007; Malhi et al. 2017), positive (Yadav et al. 2019; Birhane et al. 2020), or unimodal patterns (Phillips et al. 2019) due to changes in climatic and edaphic conditions. However, in managed systems like homegardens, biomass accumulation is primarily governed by management practices, species composition, and structural design rather than elevation alone (Kumar and Nair 2004; Nath et al. 2019b). The relatively narrow elevation range considered in this study may have further limited the influence of altitudinal variation. The biomass values recorded in this study (65.38–69.74 Mg ha^{-1} for AGB and 78.71–83.99 Mg ha^{-1} for TB), along with the corresponding ABC (30.73–32.78 Mg C ha^{-1}) and TBC (36.99–39.48 Mg C ha^{-1}), are comparable with earlier studies from India and other regions, highlighting their considerable potential for biomass accumulation and carbon storage (Kumar 2011; Mattsson et al. 2013, 2015; Kumar 2023; Lowe et al. 2024).

Soil organic carbon

Soils are the largest carbon reservoirs in the terrestrial carbon cycle. They play a key role in the global carbon budget and can have large impact on carbon release under a climate change scenario (Lal et al. 1995). The effectiveness of agroforestry systems in storing carbon depends on structure and function of different components (Schroeder 1993; Albrecht and Kandji 2003); environmental parameters (Newaj and Dhyani 2008); socio-economic factors. In humid tropics, agroforestry systems have the potential to sequester over 70 Mg/ha in the top 20 cm of the soil (Mutuo et al. 2005). In the present study, soil organic carbon (SOC) showed a clear increase with elevation and a decline with soil depth. The vertical decrease in SOC might be due to reduced organic inputs and slower carbon turnover in deeper layers, whereas surface soils benefit from regular litter deposition, root activity, and microbial processes. The increase in SOC along the elevation gradient may be linked to cooler temperatures, greater moisture availability, and slower decomposition rates, all of which promote the accumulation of organic matter.

Climatic factors linked to elevation, particularly temperature and precipitation, are known to affect SOC dynamics (Jobbágy and Jackson 2000; Lemenih and Itanna 2004), though the pattern of change is not always consistent across ecosystems, as local environmental conditions and topographic factors may strongly influence carbon storage patterns (Britton et al. 2011). In the present study, however, SOC increased with elevation, a pattern similar to that reported from other hill regions, where cooler conditions tend to slow decomposition and favour the build-up of organic matter (Wang et al. 2004; Garten and Hanson 2006; Kumar 2023; Bhutia et al. 2019).

The cumulative SOC stock (0–60 cm) showed a significant increase along the elevation gradient, rising from 58.93 ± 1.33 Mg C ha^{-1} at lower elevations (E1) to 74.35 ± 3.83 Mg C ha^{-1} at mid elevations (E2), and reaching 93.64 ± 3.61 Mg C ha^{-1} at higher elevations (E3). This shows that homegardens act as effective soil carbon sinks, storing substantial amounts of carbon, with their potential improving with increase in elevations. The considerable variability in SOC within each elevation zone likely reflects the influence of site-specific factors such as species composition, tree density, organic matter inputs, and moisture conditions (Kumar, 2023).

The SOC levels recorded in this study are consistent with those reported for other homegarden systems (Manpoong et al. 2021; Subba et al. 2018). Overall, the results highlight the importance of tree-based systems like homegardens as significant soil carbon reservoirs. Their combined contribution through both soil and biomass carbon underscores their role in strengthening ecosystem carbon storage, enhancing climate resilience, and supporting climate change mitigation in hill agroecosystems (Sharma et al. 2022).

Relationships among diversity, structure, and carbon

The correlation analysis in this study revealed a negative relationship between homegarden size and both species richness and evenness. This pattern suggests that smaller plots tend to be more intensively managed, with denser species packing and a more balanced distribution. While natural ecosystems typically follow the species-area relationship, where larger areas accommodate greater diversity, homegardens are shaped by household needs, cultural preferences, and subsistence strategies (Kumar and Nair 2004; Peyre et al. 2006; Abebe et al. 2010). Similar observations have been reported from other tropical homegardens, where smaller landholdings often exhibit greater diversity due to multifunctional requirements (Das et al. 2020a; 2020b; Sahoo and Rocky 2015; Kumar 2023). In contrast, larger homegardens tend to show dominance of a few economically important species, particularly under market-oriented systems. This weak link between size and diversity suggests that species composition is influenced more by management than by area alone in man-made system like homegardens (Kumar 2023). A similar trend was observed between homegarden size and aboveground biomass carbon and soil organic carbon (SOC) stock. Smaller homegardens characterized by higher species density and multistrata arrangement, tended to store more biomass and carbon per unit area. Earlier studies have also reported a decline in carbon stocks with increasing homegarden size (Saha et al. 2009; Kumar 2011). Biodiversity indices were positively related to SOC and SOC stock, indicating that more diverse systems tend to support higher soil carbon. This may be linked to continuous litter inputs, diverse root systems, and increased biological activity, which together favour carbon accumulation. Similar relationships have been observed in agroforestry systems across different regions (Saha et al. 2009; Islam et al. 2015; Melesse 2024; Sharma et al. 2024b; Alamrie and Gobezie, 2025). The positive association between species richness and aboveground biomass further suggests that diversity enhances productivity through efficient resource use and functional complementarity among species (Thompson et al. 2009; Richards and Mendez 2014). However, as these systems are actively managed, practices such as planting density, pruning, and harvesting play a key role in determining biomass accumulation. Overall, the results indicate that biodiversity and carbon storage in homegardens are closely linked and largely shaped by management.

Smaller, diverse, and well-structured systems appear more effective in supporting both biomass production and soil carbon storage, highlighting their role in sustainable land use and climate resilience.

Conclusion

Homegardens of Chumukedima district present a well-developed, multistrata agroforestry system in which structural complexity, species composition, and management practices jointly regulate biomass production and carbon storage. Despite a clear decline in garden size with increasing elevation, species diversity remained stable, while richness and evenness were higher in smaller, intensively managed systems. This indicates that management practices, rather than area or elevation alone, play a decisive role in shaping system composition. Woody biomass and associated carbon stocks showed only marginal variation across elevations, reflecting the regulated nature of these systems. In contrast, soil organic carbon increased markedly with elevation and declined with depth, indicating the strong influence of microclimatic conditions on belowground carbon accumulation. The positive association between species diversity and both biomass and soil carbon further suggests that diversified, multistrata systems enhance overall ecosystem functioning. The negative relationship between homegarden size and carbon storage per unit area emphasizes the efficiency of smaller, well-managed systems.

As one of the first studies examining the combined effects of elevation, structure, biodiversity, and carbon dynamics in homegardens of this region, the findings provide a useful baseline for hill agroecosystems of North East India especially Naga hills. The study demonstrates that well-managed, species-rich, multistrata agroforestry systems can simultaneously support livelihoods, conserve biodiversity and function as effective carbon sinks. These findings have practical implications for the design and development of suitable agroforestry models through selection of complementary and locally adapted farmer-preferred species, maintenance of multilevel canopy structure, and promotion of diversity-oriented management practices. The substantial biomass and soil carbon storage potential observed in these systems also highlights the irrelevance for future climate change mitigation initiatives and possible carbon credit programmes in hill region. Furthermore, the strong link between diversity and soil carbon underscores the importance of conserving species richness for long-term ecological stability and soil health.

The present study was confined to selected homegardens within a relatively narrow elevation range in Chümoukedima district and did not account for seasonal variations in vegetation and soil properties. Therefore, extrapolation of the findings to broader regions of Northeast India should be made cautiously. Further long-term studies across wider agroecological gradients would improve understanding of biodiversity–carbon relationships in homegarden agroforestry systems

Declarations

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field data collection and related research activities.

Ethical approval

This study involved field-based assessment of vegetation and soil characteristics in homegarden agroforestry systems. The research did not involve human participants, animals, or any experimental procedures requiring ethical approval from an institutional ethics committee.

Consent to participate

Prior informed verbal consent was obtained from the homegarden owners before conducting field observations and data collection on their properties.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

Author Contribution

Conceptualization- PLB, BUC, HK, KR; Methodology- PLB, BUC, HK, AK; Validation- PLB; KZ, TLB, AK, Formal analysis- PLB, KZ, AZ, NRS, HV, TLB,AK; Investigation- PLB, KZ; Data curation- PLB, NRS,PKS ; Writing (original draft)- PLB; Writing (review & editing)- PLB, AK, TLB, PKS, HV; Visualization- PLB, BUC; Supervision- HK, BUC, KR.

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Figures

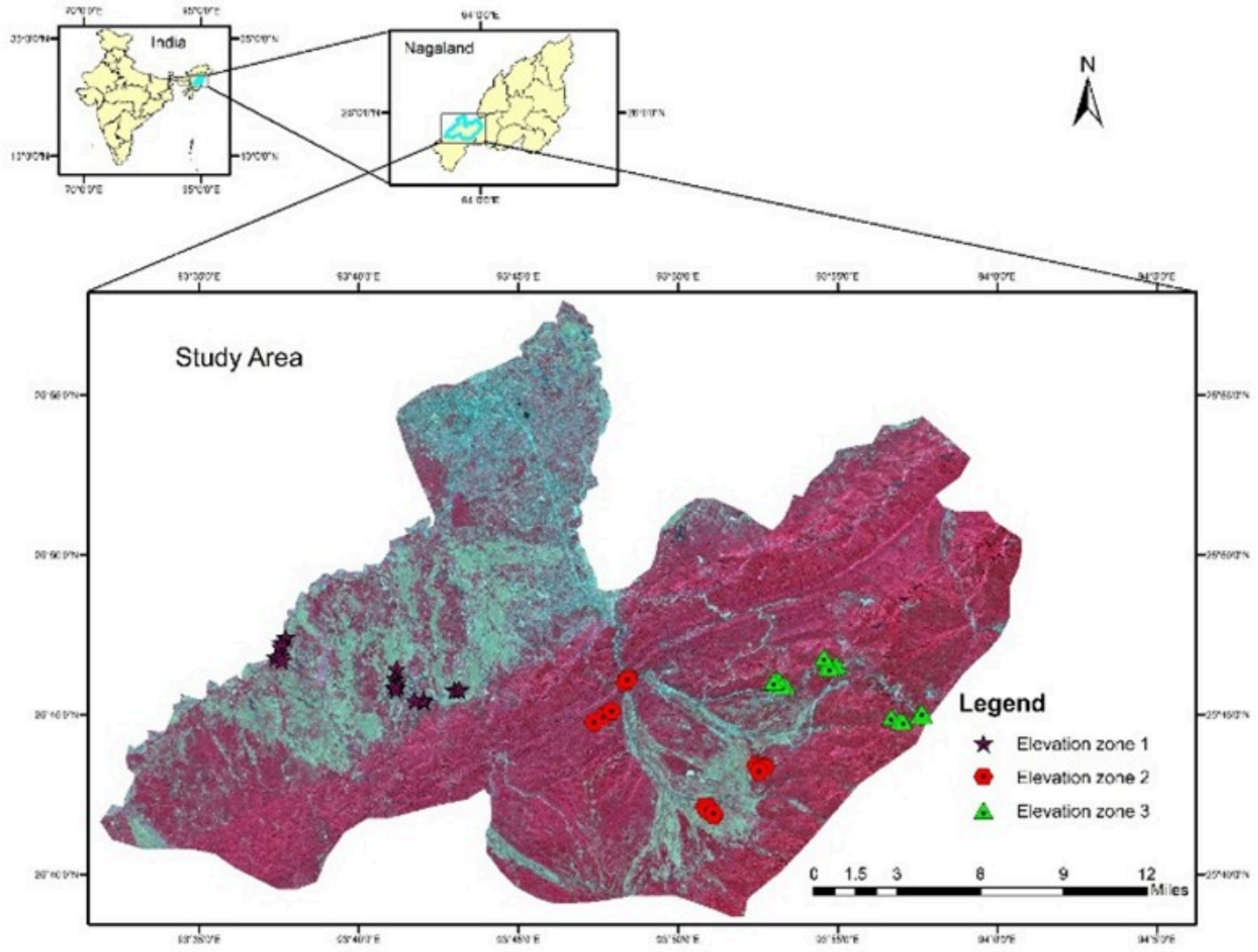


Figure 1

Location map of the study site in Chümoukedima district generated in QGIS 3.22 (red areas indicate vegetation cover); map prepared using the former Dimapur district boundary due to non-availability of updated shapefiles.

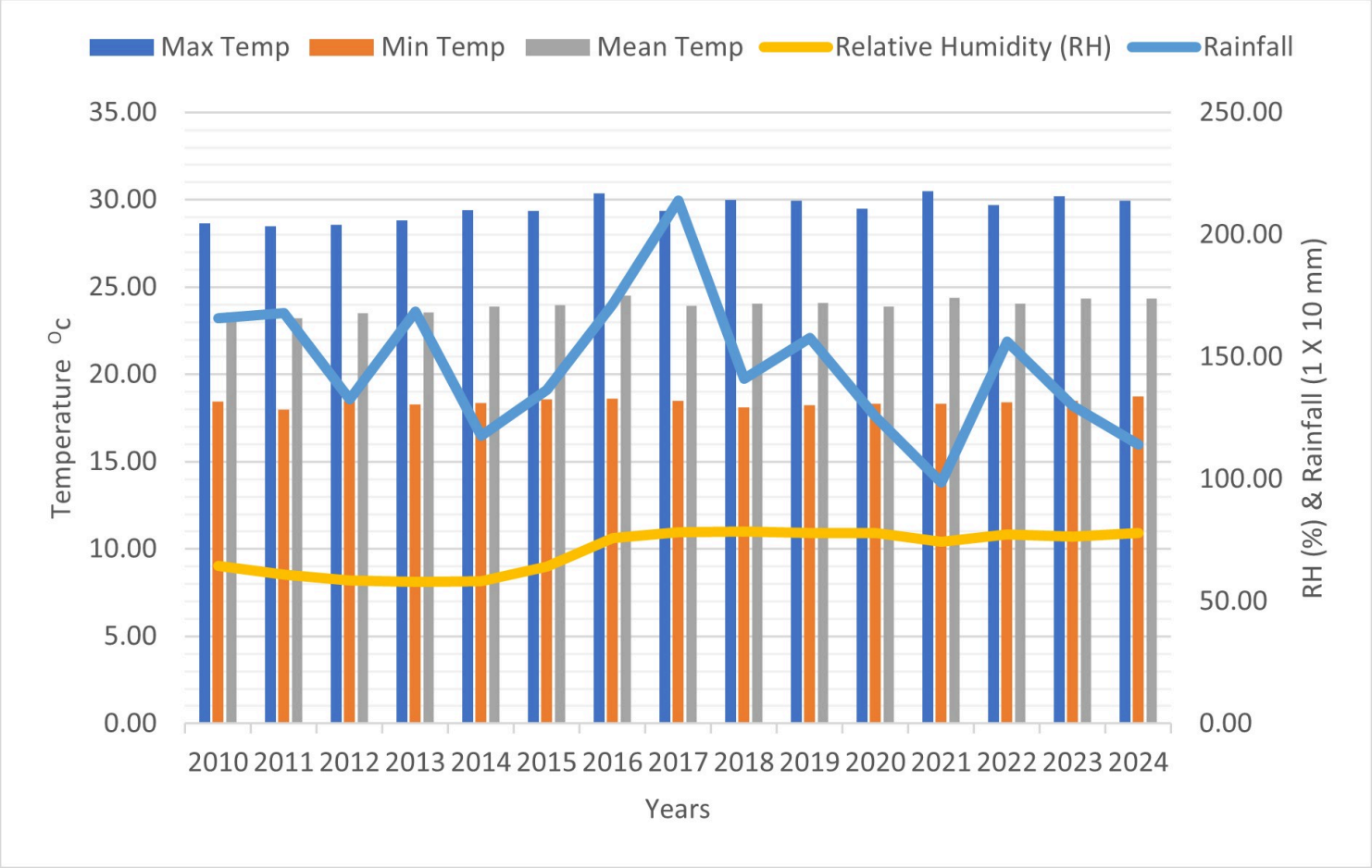


Figure 2

Meterological record of Chumukedima district in Nagaland, India

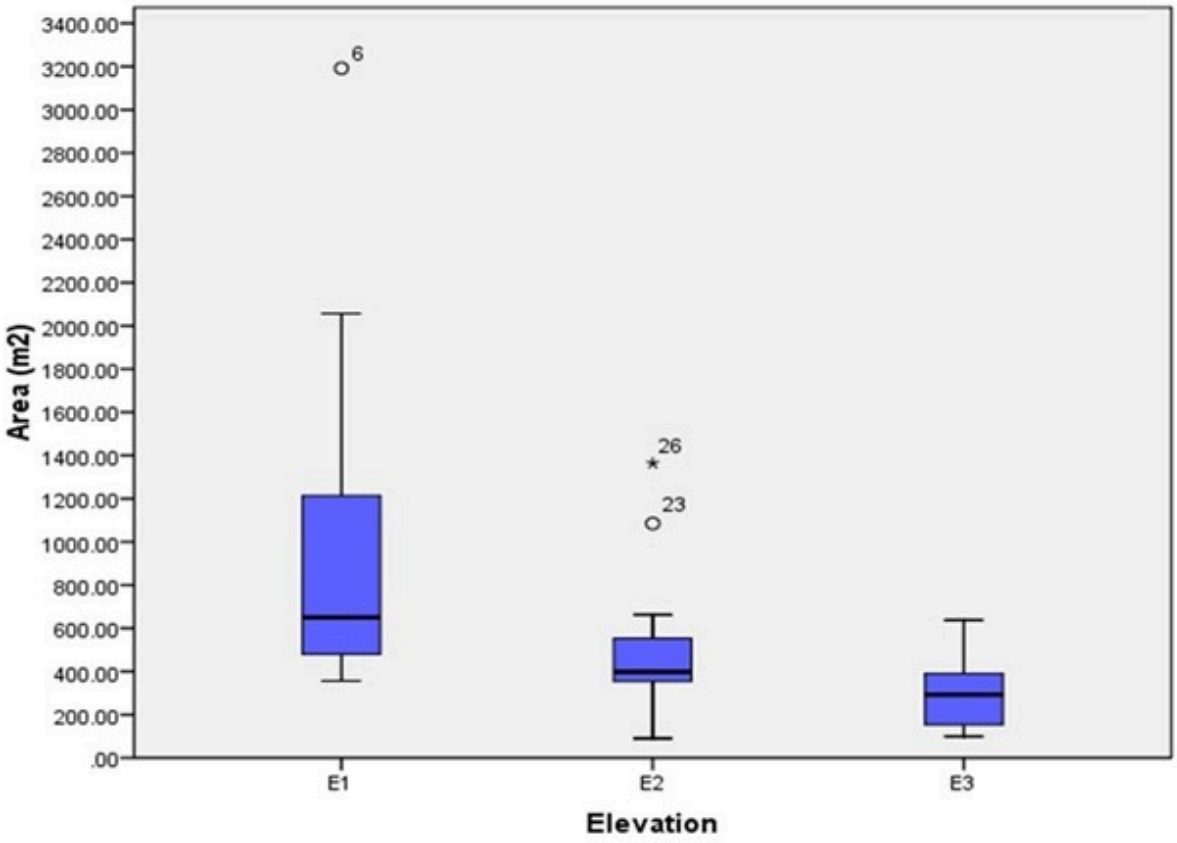


Figure 3

Change in size (m^2) of homegardens along elevation, Nagaland

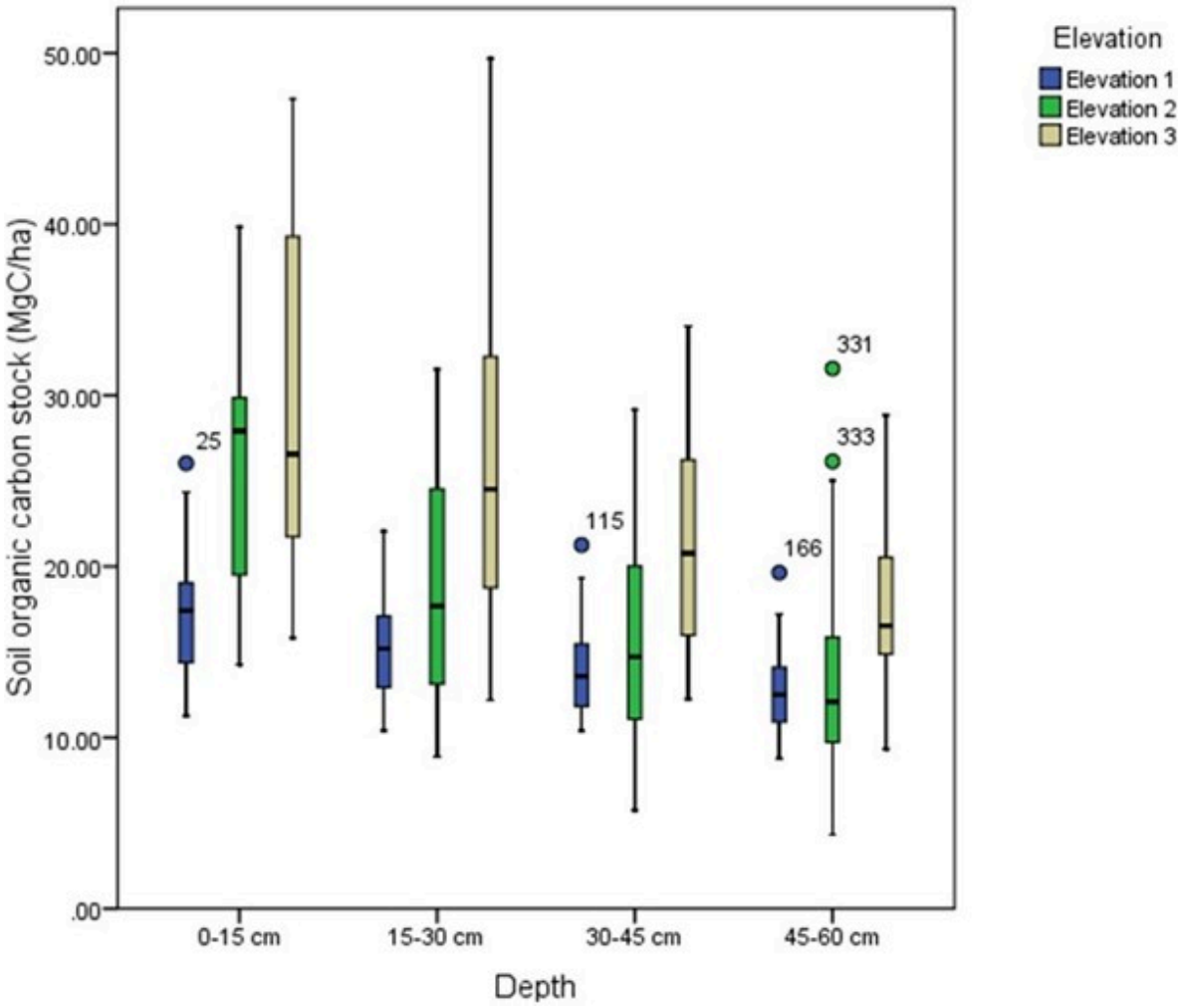


Figure 4

Soil Organic Stock (SOC) MgC ha^{-1} of Homegardens across altitudinal gradients in Subtropical Nagaland.

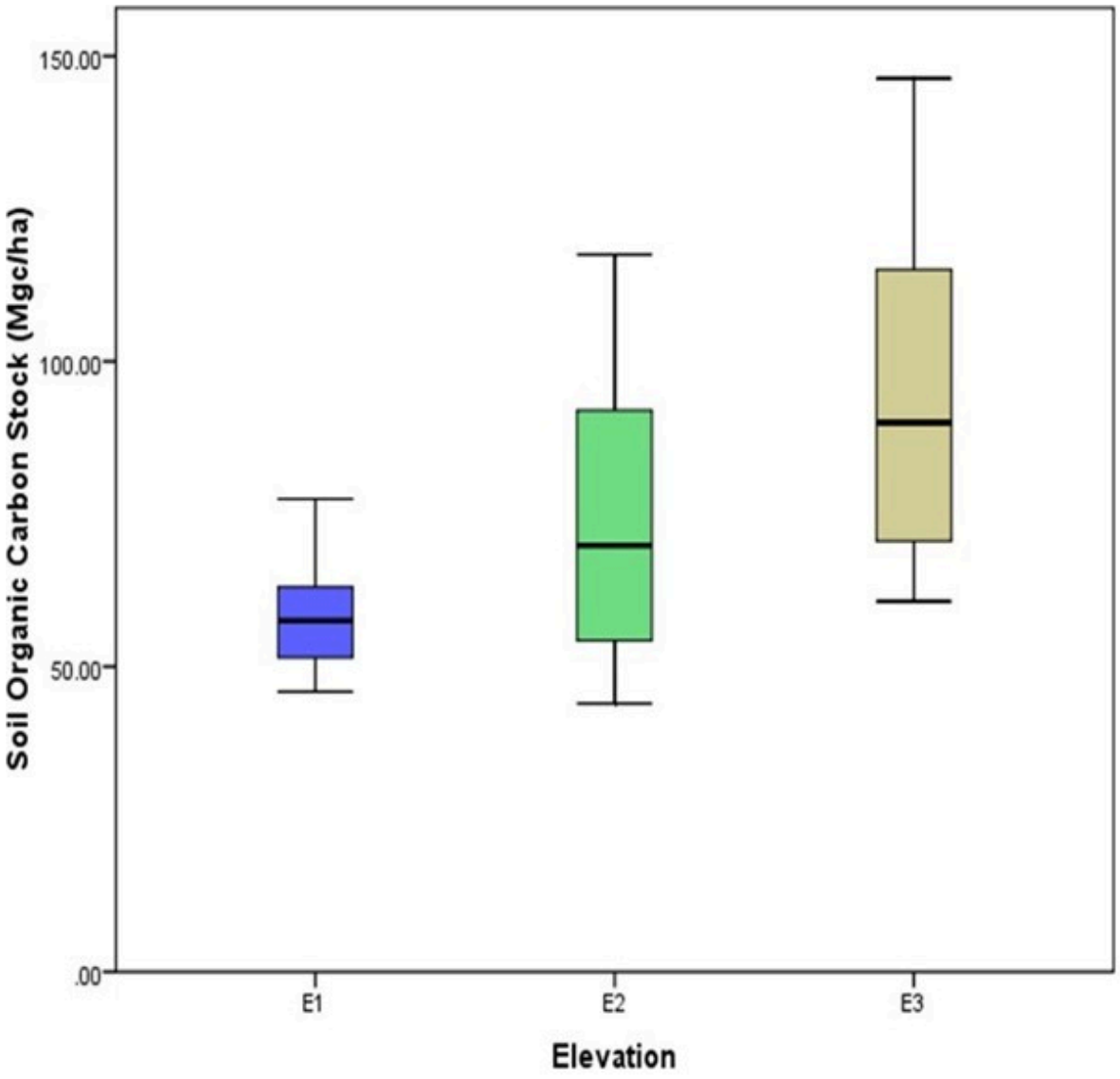


Figure 5

Soil Organic Stock (SOC) (0-60 cm depth) MgC ha^{-1} of Homegardens across altitudinal gradients in Subtropical Nagaland.