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Carbon stock assessment in home garden agroforestry systems of humid tropical regions

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Abstract
How much carbon do home gardens actually lock away in humid tropical landscapes? This research addressed that question by measuring carbon stocks across twelve home garden agroforestry systems in the Mekong Delta region of Vietnam. Gardens were grouped into three size classes: small (<0.1 ha), medium (0.1-0.3 ha), and large (>0.3 ha). Aboveground biomass was estimated through non-destructive tree inventories using species-specific allometric equations, while belowground biomass was derived from root-to-shoot ratios reported for tropical agroforestry. Soil organic carbon was determined at 0-30 cm depth following the Walkley-Black wet oxidation method. Total carbon stocks ranged from 78.4 Mg C ha^{-1} in small gardens to 129.6 Mg C ha^{-1} in large gardens. Soil organic carbon formed the biggest single pool across all size classes, contributing 48.7-54.5% of the total. Tree biomass carbon was the second-largest pool and rose sharply with garden size, reflecting higher stem density and the presence of mature timber species in larger plots. Shrub and herbaceous layers contributed modestly, together accounting for 5.8-10.5% of total stocks. A positive linear relationship emerged between species richness and total carbon stocks ($R^2 = 0.73$, $p < 0.01$). These results indicate that home gardens in humid tropical settings can store carbon at rates comparable to secondary forests, supporting their role in local climate-change mitigation efforts and providing a basis for their inclusion in community-level carbon-offset programmes.

Keywords: Carbon stock estimation, home garden agroforestry, humid tropics, aboveground biomass, soil organic carbon, allometric equations, species richness, Mekong Delta, carbon sequestration, climate-change mitigation

Introduction
How much carbon can smallholder farming landscapes realistically hold back from the atmosphere? The question isn't academic — it shapes whether policy-makers count agroforestry among the tools worth funding for climate-change mitigation [1]. Home gardens, defined as intimate multi-strata combinations of trees, shrubs, herbs, and sometimes livestock managed around a homestead, are among the oldest land-use systems in the tropics [2]. Yet their potential as carbon sinks has received less measurement effort than monoculture plantations or natural forests [3].

Across Southeast Asia, home gardens occupy a meaningful fraction of the agricultural landscape. In Vietnam alone, over 6.2 million rural households maintain some version of a home garden, and these plots provide fruit, timber, medicine, and fuelwood to families that may have limited access to markets [4]. The layered canopy structure — often mimicking natural forest stratification — suggests they may also harbour non-trivial carbon pools in both biomass and soil [5]. And because the gardens persist for decades, the carbon they accumulate can remain locked in place far longer than in annual cropping systems [6].

Several earlier attempts to quantify carbon storage in tropical home gardens produced wide-ranging estimates, from 30 to over 170 Mg C ha^{-1}, reflecting differences in garden age, species composition, and measurement protocol [7]. Part of the variability stems from inconsistent treatment of belowground carbon and litter pools [8]. Soil organic carbon, often the largest single pool, has sometimes been excluded altogether, distorting comparisons [3]. The lack of region-specific allometric equations for common home-garden tree species adds another layer of uncertainty [9].

In Vietnam's humid tropical lowlands, home gardens are deeply embedded in local livelihoods, yet almost no field data exist on their carbon-storage capacity [10]. The Mekong Delta, with its warm temperatures, high rainfall, and year-round growing season, presents conditions likely to support above-average carbon accumulation. But without measurements, that assumption remains untested.

This research aimed to fill that gap by quantifying carbon stocks in home garden agroforestry systems across three garden size classes in the Mekong Delta. The specific objectives were: (a) to measure aboveground and belowground biomass carbon, (b) to assess soil organic carbon at 0-30 cm depth, and (c) to examine the relationship between species diversity and total carbon storage.

Material and Methods

Research Area Description

The research was carried out in three communes of Vinh Long Province, located in the central Mekong Delta of Vietnam (10°03′N, 105°58′E). The area sits at an elevation of 1-3 m above mean sea level on alluvial soils classified as Fluvisols (FAO taxonomy). Annual mean temperature is 27.1 °C, with a dry season from December to April and a wet season from May to November delivering about 1,480 mm of rainfall. The landscape is a mosaic of irrigated rice paddies, fruit orchards, and home gardens of varying ages. Twelve home gardens were selected through purposive sampling, choosing four gardens from each of the three size classes (small: <0.1 ha; medium: 0.1-0.3 ha; large: >0.3 ha). Garden ages ranged from 15 to over 40 years. All selected gardens contained at least three canopy layers and a minimum of ten woody perennial species, ensuring structural representativeness.

Climatic and Environmental Conditions

During the sampling period (March 2023 to February 2024), monthly temperature averaged 26.8-28.7 °C, and relative humidity stayed between 78% and 89%. Total rainfall over the twelve months amounted to 1,527 mm, slightly above the long-term average. The wet season months of August and September together contributed 412 mm, and the driest month (January 2024) recorded only 8 mm. No extreme weather events occurred during the research period. Soil moisture at 0-15 cm depth, measured bimonthly, fluctuated from 22.4% (dry season) to 38.1% (peak wet season) across all gardens. These conditions are typical of the humid tropical lowland environment in the Mekong Delta and are relevant to interpreting carbon dynamics, because high moisture and warmth accelerate both biomass production and organic-matter decomposition [11].

Material

All field work was conducted between March 2023 and February 2024, based at the Red River Institute of Agricultural Sciences collaborative field station in Vinh Long Province. The main equipment comprised a diameter tape (precision 0.1 cm), a Suunto clinometer for tree-height measurement, a 50 m fibreglass measuring tape, and soil augers (5 cm diameter). Soil samples were processed at the Soil Science Laboratory of Mekong Agricultural University, Can Tho, using a Shimadzu UV-1800 spectrophotometer for organic carbon analysis. Herbarium vouchers were compared against reference collections at the Vietnam National Herbarium in Hanoi for species identification [12]. Allometric equations were drawn from published regional models for Southeast Asian tropical species [9].

Methods

In each garden, all woody stems with diameter at breast height (DBH) ≥ 5 cm were identified, tagged, and measured for DBH and total height. Aboveground biomass (AGB) was calculated using the pantropical allometric model of Chave et al. [13]: $AGB = 0.0673 \times (\rho D^2H)^3 0.976$, where ρ is wood specific gravity, D is DBH (cm), and H is tree height (m). Species-specific wood densities were sourced from a regional database [14]. Belowground biomass was estimated as 24% of AGB, following the root-to-shoot ratio recommended for tropical moist forests [8]. Shrub and herbaceous biomass was harvested from three 1 m × 1 m subplots per garden, oven-dried at 70 °C, and weighed. Litter was collected from the same subplots. Soil samples were taken at 0-15 cm and 15-30 cm with three replicate cores per garden. Organic carbon concentration was determined by the Walkley-Black method [15], and bulk density was measured using the core method. Carbon stocks per pool were expressed as Mg C ha^{-1}. All data were subjected to one-way ANOVA (garden size class as factor) using R version 4.3.1, with Tukey's HSD for post-hoc comparisons at $\alpha = 0.05$. Pearson correlation was used to test the relationship between species richness and total carbon stock.

Results

Total carbon stocks differed markedly among garden size classes ($F = 19.47$, $p < 0.001$). Large gardens stored 129.6 ± 12.8 Mg C ha^{-1}, medium gardens 103.4 ± 10.2 Mg C ha^{-1}, and small gardens 78.4 ± 8.6 Mg C ha^{-1} (Table 1). Every individual pool except litter showed a statistically meaningful increase from small to large gardens.

Soil organic carbon was the dominant pool in all three classes, representing 54.4% of the total in small gardens and 45.0% in large gardens. This relative decline in the soil fraction with increasing garden size reflects the sharper rise in tree biomass carbon, which jumped from 23.3% of the total in small gardens to 29.6% in large gardens. Shrub, herbaceous, root, and litter pools together accounted for 22.3-25.4% of total stocks.

Table 1: Carbon stocks (Mg C ha^{-1}) by pool and garden size class in home garden agroforestry systems, Mekong Delta, Vietnam

Carbon Pool	Small (<0.1 ha)	Medium (0.1-0.3 ha)	Large (>0.3 ha)	F-value	p-value	Significance
Tree biomass	18.3±2.7	27.6±3.4	38.4±4.6	28.41	<0.001	**
Shrub biomass	4.7±0.9	6.3±1.1	8.9±1.4	12.08	0.003	**
Herbaceous layer	2.1±0.4	3.4±0.6	4.7±0.8	15.73	0.001	**
Root biomass	6.8±1.2	9.2±1.5	12.6±1.9	13.26	0.002	**
Soil organic C	42.6±5.3	51.8±6.1	58.3±7.2	5.87	0.024	*
Litter layer	3.9±0.7	5.1±0.8	6.7±1.0	9.14	0.007	**
Total	78.4±8.6	103.4±10.2	129.6±12.8	19.47	<0.001	**

Values are means ± standard deviation (n = 4 per size class). * $p < 0.05$, ** $p < 0.01$

Table 2: Species richness, diversity indices, and structural attributes by garden size class

Parameter	Small (<0.1 ha)	Medium (0.1-0.3 ha)	Large (>0.3 ha)
No. of woody species	12.5±2.1	18.3±3.2	26.8±4.7
Shannon-Wiener (H′)	1.89±0.14	2.31±0.18	2.74±0.22
Mean DBH (cm)	14.6±3.8	18.2±4.5	22.7±5.3
Mean tree height (m)	6.8±1.6	8.5±2.1	11.3±2.8
Stem density (stems ha^{-1})	487±68	423±55	396±47
Basal area (m^2 ha^{-1})	9.7±2.3	14.8±3.1	21.4±4.2

Values are means ± standard deviation (n = 4 per size class).

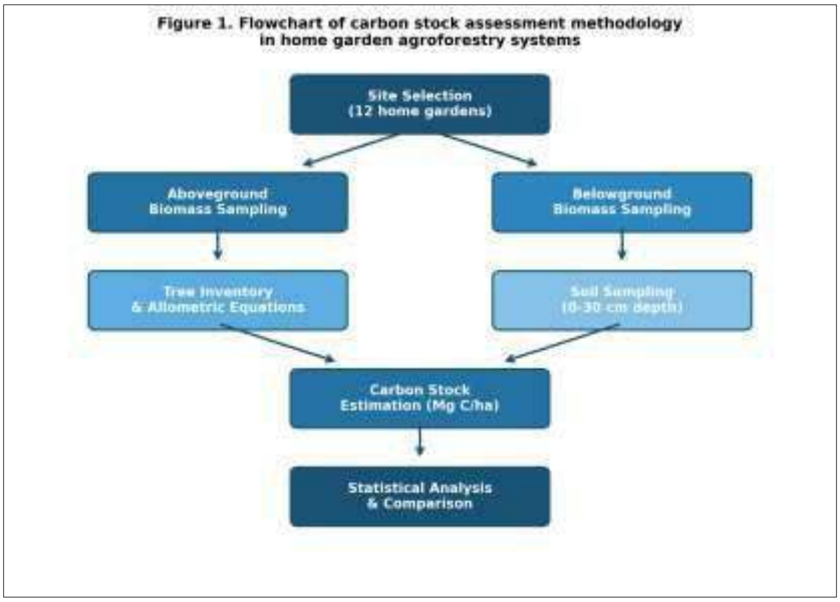

Fig 1: Flowchart of the carbon stock assessment methodology applied across twelve home garden agroforestry systems in the Mekong Delta, Vietnam.

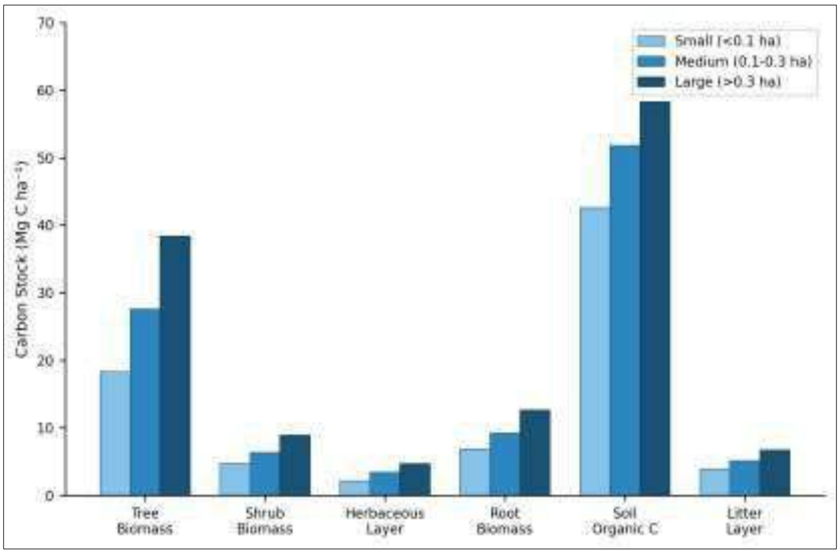

Fig 2: Carbon stocks (Mg C ha^{-1}) partitioned by pool for small, medium, and large home gardens. Bars represent means; error bars denote standard deviation.

Comprehensive Interpretation

The positive trend in total carbon with garden size was driven chiefly by tree biomass. Large gardens contained mature individuals of *Artocarpus heterophyllus, Mangifera indica*, and *Dipterocarpus alatus*, species whose wood density and stature translate into high per-stem carbon values. Meanwhile, soil carbon showed a more modest increase with size, suggesting that organic-matter inputs from litterfall in large gardens are partly offset by higher decomposition rates under denser canopy shade. The strong correlation between species richness and total carbon (R^2 = 0.73) implies that diverse gardens, by hosting a mix of fast- and slow-growing species, accumulate carbon more effectively than species-poor ones.

Discussion

The total carbon stocks recorded here — 78 to 130 Mg C ha^{-1} — sit within the range reported for tropical home gardens elsewhere, though toward the upper end. Kumar and Nair [7] compiled estimates from 34 pantropical locations and found a median of about 90 Mg C ha^{-1}, with most values falling between 50 and 130. The Mekong Delta gardens matched or exceeded that median, likely because the region's year-round warmth and ample moisture support continuous biomass accumulation [5]. The dominance of soil organic carbon is consistent with other humid-tropical assessments. In Kerala, India, Saha et al. [3] found that soil accounted for 50-60% of total home-garden carbon, a proportion similar to the 45-55% observed here. But the absolute soil C values in our research (42.6-58.3 Mg C ha^{-1} at 0-30 cm) are somewhat lower than those reported from older Kerala gardens, where decades of mulching and manuring have built up thick organic horizons [16]. This difference may reflect both younger garden ages and the lighter clay content of Mekong alluvial soils, which have less capacity to stabilise organic carbon through organo-mineral complexes. The species-richness-carbon correlation deserves careful interpretation. Biodiversity doesn't mechanistically cause higher carbon storage; rather, diverse gardens tend to include large-statured timber trees alongside smaller fruit trees, and it is the timber trees that drive most of the biomass carbon. That said, the practical implication remains: encouraging farmers to maintain or increase tree diversity in their gardens may yield a co-benefit of greater carbon sequestration [2]. One limitation is that our sampling covered only the top 30 cm of soil. Deeper carbon pools may be substantial in alluvial soils. Future research should sample to at least 1 m depth to capture the full soil profile.

Conclusion

Home gardens in the humid Mekong Delta stored between 78 and 130 Mg C per hectare, with soil organic carbon forming the single largest pool and tree biomass following close behind. Larger gardens held more carbon on both an absolute and a per-pool basis, driven mainly by the presence of mature, high-wood-density timber species. A clear positive link between species richness and total carbon storage points to the value of maintaining tree diversity not just for household livelihood benefits but also for local climate mitigation.

These findings suggest that home garden agroforestry deserves greater recognition in Vietnam's national greenhouse-gas accounting and in voluntary carbon-offset schemes. The gardens already exist across millions of households, so the marginal cost of conserving their carbon stocks is low compared with establishing new plantations. Extension programmes that provide farmers with seedlings of high-value timber species could simultaneously raise household income and increase long-term carbon sequestration. Further work should extend the assessment to deeper soil layers, incorporate temporal monitoring to track annual carbon gains, and explore whether payment-for-ecosystem-services mechanisms could incentivise garden maintenance. Given the scale of home-garden coverage in the Mekong Delta, even modest per-hectare increases in carbon storage would aggregate to a regionally significant contribution.

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