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Carbon Inequality and Allometric Uncertainty in a Micro-Scale Campus Forest in East Java, Indonesia

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Abstract

Micro-scale urban green infrastructure provides localized ecosystem services, yet quantifying its carbon dynamics remains a methodological challenge due to satellite resolution limits and the structural assumptions of generalized models. This study evaluates carbon stock distribution across 68 individual trees within a heterogeneous 0.8-hectare institutional urban forest at a microcatchment resolution, analyzing the validity of pantropical allometry. The stand exhibits an estimated mean carbon density of 45.38 Mg C/ha, totaling 36.34 Mg. Critically, the high coefficient of determination value of 0.9422 primarily reflects structural dependency within the allometric formulation rather than independent ecological variability. Furthermore, the Gini coefficient value of 0.654 confirms severe structural biomass asymmetry. The carbon pool is disproportionately concentrated within a limited cohort of exactly 6 Large Old Trees with a diameter exceeding 60 cm, predominantly *Samanea saman*. Census data reveals that the top 5% of the largest individuals manage 28.3% of the vegetative carbon, while the top 10% and top 20% control 47.3% and 66.2% of the cumulative reservoir, respectively. Within this micro-forest, inverted J-shaped diameter distributions were insufficient to ensure evenly distributed carbon storage. Consequently, urban green planning must prioritize the targeted retention of dominant biomass anchors over raw sapling quantity. Preserving these established large trees contributes significantly to institutional carbon governance, providing an empirical framework for sustainability metrics such as the UI GreenMetric.

Keywords: Urban micro-forest; Carbon inequality; Large old trees (LOTs); Upstream watershed; Gini coefficient; Living lab; Allometric uncertainty

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INTRODUCTION

Urban green infrastructure (UGI) is a prerequisite for climate mitigation, with university campuses functioning as micro-spatial living laboratories for the Sustainable Development Goals (SDGs) (Vasenev et al., 2026). As higher education institutions respond to operational greenhouse gas emissions, campus forests assume strategic importance (Fani et al., 2025). The University of Muhammadiyah Malang (UMM) Campus Forest is particularly vital due to its location in the critical upstream area of the Brantas River Watershed, serving simultaneously as an active carbon sink and a localized hydrological regulator (Quaglia & Aalbers, 2026).

The capacity of these institutional forests to fulfill climate metrics varies fundamentally across climatic zones. In non-tropical and temperate biomes, mature urban stands such as historic campuses in Budapest provide stabilized, long-term carbon offsets driven by steady-state ecological succession (Király et al., 2025). Conversely, tropical urban landscapes, analogous to rapid-growth environments observed in Rio de Janeiro (Kurtz et al., 2024), exhibit highly aggressive biomass accumulation rates within structurally dynamic stands. However, this rapid tropical carbon sequestration potential is inherently vulnerable; it is highly susceptible to severe biomass loss resulting from flawed landscape management practices, as documented in other tropical institutional contexts (Kasikam et al., 2026).

Precise quantification of Aboveground Biomass (AGB) within these dynamic tropical micro-scales faces critical methodological challenges. Global carbon inventories predominantly rely on remote sensing technologies, whose spatial resolutions frequently fail to capture species heterogeneity and structural anomalies in sub-hectare areas (McGregor et al., 2025). This reliance obscures carbon asymmetry at the site level, necessitating high-precision terrestrial methodologies for ground-truth validation (Li et al., 2025). Furthermore, applying pantropical allometric models (Chave et al., 2014a) to multi-species urban micro-ecosystems often introduces structural biases (Reta et al., 2025). Beyond methodological constraints, current management paradigms falsely assume that tree quantity equates to carbon sequestration capacity. While an inverted-J diameter distribution is traditionally lauded as an indicator of ecosystem health, it frequently masks severe carbon inequality. In reality, mitigation capacity is disproportionately concentrated within a few Large Old Trees (LOTs), such as *Samanea saman*, which regulate carbon accumulation more significantly than mere species diversity (Zhu et al., 2026).

Despite these recognized dynamics, current literature remains fragmented across three distinct, unaddressed research gaps. First, an ecological gap exists regarding the precise distribution of carbon concentration within constrained urban green infrastructures; while macro-scale studies observe generic forest biomass, empirical data on how Large Old Trees (LOTs) generate intense biomass asymmetry and carbon inequality within small tropical campus forests is virtually absent. Second, a methodological gap persists due to the lack of structural validation for pantropical allometric formulations in highly managed, multi-species micro-ecosystems, where model-inherent mathematical dependencies and field-propagated errors are rarely decoupled. Third, a governance gap remains regarding how micro-scale carbon inventory data can actively guide institutional landscape policies; campus sustainability frameworks often default to raw sapling counts rather than evidence-based carbon budgeting anchored by dominant biomass anchors.

To systematically resolve these limitations, this study targets three corresponding objectives:

(1) to map micro-spatial biomass distribution and evaluate carbon inequality driven by LOTs cohort dominance, thereby bridging the ecological gap;
(2) to execute an error-propagation and diagnostic regression framework to dissect the structural validity of pantropical equations under micro-urban settings, addressing the methodological gap; and
(3) to translate these high-resolution terrestrial metrics into an evidence-based support system for institutional climate action plans and sustainability metrics such as the UI GreenMetric, effectively closing the governance gap.

METHOD

Study Area and Period

This research was conducted in April 2026 at the Campus Forest of the University of Muhammadiyah Malang (UMM), East Java, Indonesia, covering a delineated study area of 0.8 hectares (Figure 1). Spatially, this site is an institutional green open space located in the upstream region of the Brantas River Watershed. The biophysical characteristics of the area represent an urban micro-forest ecosystem dominated by heterogeneous artificial stands.

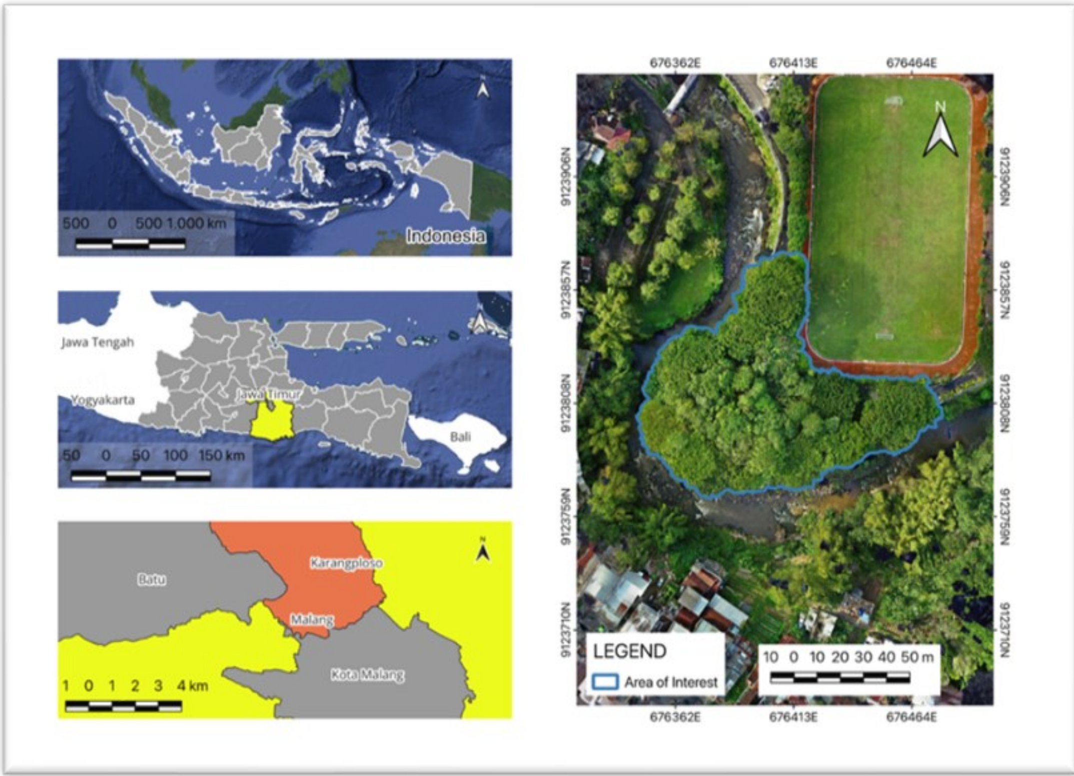

Figure 1. Geographic location of the study area in the University of Muhammadiyah Malang campus forest East Java Indonesia

Census Design and Terrestrial Data Collection

Given the micro-scale spatial extent of the site (< 1 ha), the application of remote sensing was excluded to prevent spatial resolution bias and canopy shadow effects. Alternatively, this study employed a 100% full-enumeration terrestrial census. The subjects of this study encompassed all living individual trees (ranging from pole to mature stages) that met the standard criteria for carbon inventory, specifically a Diameter at Breast Height (DBH) of ≥ 10 cm.

Primary field data acquisition utilized a precision diameter tape (phi-band) to measure trunk circumference at a height of 1.3 meters, and a Haga altimeter to measure total tree height (H). The circumference data (C) were geometrically converted into diameter (D) using the equation:

$$D = C/\pi. \qquad (1)$$

Trees with a DBH of less than 10 cm were excluded from the inventory, aligning with standard pantropical protocols (Chave et al., 2014) where smaller stems contribute negligibly to mature biomass pools. However, this exclusion limits the interpretation of early-stage sapling regeneration dynamics, filtering the scope specifically toward established carbon reservoirs.

Furthermore, in-situ taxonomic identification of species was conducted to facilitate the determination of species-specific wood density (ρ). The ρ values were extracted utilizing empirical data from the Global Wood Density Database (Chave et al., 2014; Zanne et al., 2009).

Biomass, Carbon Stock, and Carbon Sequestration Quantification

Above-Ground Biomass (AGB) was calculated exclusively using the pantropical allometric equation developed by Chave et al. (2014). This multivariable model is methodologically justified because the stand consists predominantly of broad leaved tropical angiosperms, such as *Samanea saman* and *Ficus racemosa*, whose architectures conform closely to the global calibration datasets. Furthermore, in the absence of local urban allometric equations, this model provides the most mathematically stable framework for small scale inventories. To align with the empirical limits of the data, any inferred hydrological contributions are evaluated strictly at a micro catchment resolution rather than a regional watershed scale, as these small scale stands function primarily to mitigate local storm runoff and regulate localized micro climates.

To maintain this specific scope, this study focused exclusively on AGB and aboveground carbon stocks. Belowground biomass (BGB) and soil organic carbon (SOC) pools were excluded due to the non-destructive constraints of urban landscape management and the study's focus on canopy-driven structures. Accordingly, structural biomass for each tree was quantified using the following mathematical formulation:

$$AGB = 0.0673 \times (\rho \times D^2 \times H)^{0.976} \quad (2)$$

where AGB represents the estimated biomass (kg); ρ is the wood density (g/cm^3); D is the diameter at breast height (cm); and H is the total tree height (m).

Carbon stocks (C) were estimated based on the percentage of organic carbon mass relative to dry biomass. Following national guidelines (BSN, 2019) and Intergovernmental Panel on Climate Change (2006) protocols, the carbon fraction was assumed to be 47% (0.47) of the total biomass:

$$C = AGB \times 0.47 \quad (3)$$

To evaluate the actual capacity of the stand in mitigating greenhouse gas emissions, absolute carbon stocks were converted into carbon dioxide equivalent (CO_{2eq}) sequestration units based on the molecular weight ratio (44/12):

$$CO_{2eq} = C \times 3.67 \quad (4)$$

The total estimates for biomass, carbon, and CO_{2eq} were subsequently converted into Megagrams (Mg) and normalized into carbon density ($Mg\ C/ha$) by dividing the total accumulated mass by the 0.8 hectare study area.

Stand Structure Analysis and Carbon Asymmetry

To understand regeneration dynamics and validate the micro-scale carbon inequality phenomenon, all vegetation was classified into six DBH interval classes: 10–20 cm, 21–30 cm, 31–40 cm, 41–50 cm, 51–60 cm, and >60 cm. This frequency distribution was visualized to detect the presence of an *inverted-J* curve. Within this structural classification, individuals falling into the largest cohort exceeding 60 cm are operationally defined as LOTs, adopting the global macroecological baseline established by Lutz et al. (2018). Secondly, to quantitatively measure the degree of carbon asymmetry, the proportion of cumulative carbon accumulation at each percentile of individual trees was analyzed using the Gini Coefficient mathematical calculation (Zhu et al., 2026):

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |c_i - c_j|}{2n^2 \bar{c}} \quad (5)$$

where G is the Gini Coefficient (ranging from 0 to 1); c_i and c_j represent the carbon stock values of the i- th and j-th individual trees; n is the total tree population; and $\bar{c}$ is the mean carbon stock of the stand. The degree of this asymmetry was subsequently visualized through a Lorenz Curve (Moe et al., 2026). Furthermore, non-linear regression was applied to was applied as a diagnostic demonstration of model-inherent mathematical dependency between secondary stem growth (DBH) and carbon stock expansion, evaluated based on the strength of the coefficient of determination (R^2).

$$C = a \cdot DBH^b \quad (6)$$

Where C represents the estimated individual tree carbon stock (Mg), DBH is the diameter at breast height (cm), and a and b are the scaling coefficient and allometric exponent determined through non-linear power-law regression.

Hierarchical Functional Trait Classification

To objectively extract vegetation typologies without the bias of a priori assumptions, a computational algorithm based on Hierarchical Cluster Analysis (HCA) was implemented. Prior to the clustering process, the individual tree dataset was aggregated to generate species-level functional summaries. Multidimensional tree data, including mean DBH, mean H, and mean ρ per species, were transformed using the Z-score method. The clustering algorithm was executed employing the Euclidean distance metric and Ward's linkage method to minimize internal cluster variance. The entire modeling architecture was run within a Python programming environment, utilizing the SciPy and Scikit-learn scientific libraries. Practically, the results of this clustering are translated into a decision support system to formulate strategies for planting high-performance species and to develop the campus's institutional carbon budgeting documents.

Uncertainty and Model Limitation

Although the Chave et al. (2014) pantropical allometric model is widely accepted for tropical biomass estimation, several sources of uncertainty remain inherent in micro-scale urban forest applications. These uncertainties arise from field measurement inaccuracies, variability in species-specific wood density, and structural heterogeneity among urban tree stands. Furthermore, the model was originally developed from large-scale tropical datasets, which may not fully represent the architectural anomalies of highly heterogeneous urban micro-forests.

To address these methodological constraints, an error propagation parameter was acknowledged based on established forest inventory uncertainties. Assuming standard field measurement errors of up to ±5% for DBH, ±10% for altimeter-based tree height due to canopy occlusion (Larjavaara & Muller-Landau, 2013), and ±5% variance for literature-derived wood density (Réjou-Méchain et al., 2017), the mathematically propagated uncertainty indicates that the estimated total carbon stock may vary by approximately ±10–18% from the reported mean value (Chave et al., 2004).

$$U_{total} = \sqrt{(2 \times U_D)^2 + (U_H)^2 + (U_\rho)^2} \qquad (7)$$

Where U_{total} is the propagated cumulative relative uncertainty of the aboveground biomass estimation, U_D represents the standard field measurement error for DBH (±5%), U_H is the altimeter-based tree height error (±10%), and U_ρ accounts for the variance within the literature-derived wood density database (±5%). The multiplier of 2 assigned to U_D mathematically reflects the quadratic scaling nature of diameter (DBH^2) inside the generalized pantropical allometric framework.

By substituting the empirical field error thresholds (U_D = 0.05, U_H = 0.10, and U_ρ = 0.05) into Equation 7, the mathematically quantified baseline uncertainty yields exactly ±15% at the stand level, structurally validating the reported ±10-18% uncertainty bounds. A sensitivity analysis of this propagation model reveals that DBH variance acts as a dominant exponential driver. Because of its quadratic scaling inside the allometric formulation, a minor ±5% measurement error in DBH contributes just as heavily, 44.4% of the total variance as a much larger ±10% error in tree height, while wood density variance contributes the least 11.2%. Consequently, minor field measurement errors in the dominant LOTs disproportionately amplify the total stand-level carbon uncertainty. Therefore, all carbon stock and biomass values presented in this study should be interpreted as structural estimations within this recognized uncertainty range rather than absolute physiological measurements.

RESULTS AND DISCUSSION

Based on the full-enumeration terrestrial census within the 0.8-hectare UMM Campus Forest, the stand composition exhibits highly asymmetrical structural distributions in carbon stock contributions. Under the selected pantropical allometric assumptions proposed by Chave et al. (2014), the total estimated aboveground biomass across the 68 individual trees was approximately 77.29 Mg, which corresponds to a total estimated carbon stock of 36.34 Mg and translates to a stand-level carbon density of 45.38 Mg C/ha. The estimated stand-level carbon density of 45.38 Mg C/ha puts the UMM Campus Forest in a moderate-to-high carbon storage category compared to other urban green spaces and campus institutional forests in tropical developing regions, which typically range between 25 and 60 Mg C/ha (Yusoff et al., 2021). This elevated efficiency is heavily supported by the advanced maturity of its dominant keystone species cluster. As analyzed below, this accumulated carbon is heavily concentrated within specific taxa and structural cohorts rather than evenly distributed across the community, creating a distinct ecological and methodological paradox within the micro-urban ecosystem.

Species Composition and Functional Efficiency of Dominant Taxa

The empirical data shows that *Samanea saman* (Jacq.) Merr. emerged as the structurally dominant taxon, accounting for an estimated 45.9% of the total carbon stock, which equals 16.66 Mg, despite comprising only 20.5% of the total population with a density of 14 individuals (Table 1). This disproportionate contribution indicates that the expansive crown architecture and dense wood profile of 0.490 g/cm^3 optimize aboveground biomass accumulation more efficiently than co-occurring broad-leaved taxa within this micro-urban space. A similar structural dominance was observed in *Ficus racemosa* L., where despite being represented by only two individuals, these specimens accounted for 16.1% of the total carbon stock, equivalent to 5.84 Mg, due to their advanced maturity as Large Old Trees.

Within this institutional stand, this macro-diameter cohort consists of exactly 6 mega-specimens spanning across these 2 dominant species. Remarkably, these 6 individual trees cumulatively sequester 20.61 Mg C, anchoring 56.7% of the entire campus forest's carbon reservoir. This highlights a profound structural pattern where a nominal fraction of large-diameter vegetation commands the absolute majority of vegetative carbon storage within highly constrained micro-urban spaces. These findings demonstrate that in constrained urban micro-ecosystems, carbon storage capacity is highly contingent upon the presence of structurally dominant keystone species that maximize spatial canopy utilization.

Table 1. Stand characteristics and carbon stocks of the recorded tree species

Species	N	Wood Density (g/cm^3)	Mean DBH ± SD (cm)	Mean Height ± SD (m)	Total AGB (Mg)	Total Carbon (Mg)	Carbon Density (Mg C/ha)	Contribution (%)
Samanea saman (Jacq.) Merr.	14	0.490	65.1 ± 22.1	21.1 ± 5.0	35.44	16.66	20.82	45.9
Ficus racemosa L.	2	0.363	114.1 ± 65.5	21.2 ± 2.4	12.43	5.84	7.3	16.1
Diospyros blancoi A.DC.	2	0.880	54.4 ± 49.1	15.4 ± 1.4	6.1	2.87	3.59	7.9
Talipariti tiliaceum (L.) Fryxell	8	0.450	29.9 ± 15.8	19.1 ± 4.0	4.38	2.06	2.57	5.7
Aleurites moluccana (L.) Willd.	2	0.380	57.5 ± 14.1	22.0 ± 0.7	3,01	1.42	1.77	3.9
Neolamarckia cadamba (Roxb.) Bosser	10	0.420	23.4 ± 8.6	18.9 ± 3.7	2.76	1.3	1.62	3.6
Leucaena leucocephala (Lam.) de Wit	1	0.683	59.8 ± 0.0	20.0 ± 0.0	2.54	1.19	1.49	3.3
Ceiba pentandra (L.) Gaertn.	3	0.305	37.9 ± 18.9	23.2 ± 3.1	1.82	0.86	1.07	2.4

Species	N	Wood Density (g/cm^3)	Mean DBH ± SD (cm)	Mean Height ± SD (m)	Total AGB (Mg)	Total Carbon (Mg)	Carbon Density (Mg C/ha)	Contribution (%)
Artocarpus elasticus (L.) Gaertn.	1	0.363	57.9 ± 0.0	25.2 ± 0.0	1.61	0.76	0.95	2.1
Pterospermum javanicum Jungh.	1	0.400	46.1 ± 0.0	24.5 ± 0.0	1.11	0.52	0.65	1.4
Schleichera oleosa (Lour.) Oken	1	0.897	32.8 ± 0.0	18.9 ± 0.0	0.97	0.46	0.57	1.3
Guazuma ulmifolia Lam.	1	0.519	46.8 ± 0.0	15.5 ± 0.0	0.94	0.44	0.55	1.2
Hevea brasiliensis (Willd. ex A.Juss.) Müll.Arg.	1	0.467	44.6 ± 0.0	17.5 ± 0.0	0.87	0.41	0.51	1.1
Syzygium cumini (L.) Skeels	1	0.673	35.0 ± 0.0	11.2 ± 0.0	0.5	0.23	0.29	0.6
Tectona grandis L.f.	4	0.601	16.2 ± 2.5	13.2 ± 1.6	0.48	0.22	0.28	0.6
Swietenia macrophylla King	3	0.520	18.2 ± 5.3	13.3 ± 1.9	0.41	0.19	0.24	0.5
Artocarpus camansi Blanco	1	0.433	29.0 ± 0.0	20.0 ± 0.0	0.4	0.19	0.23	0.5
Antidesma bunius (L.) Spreng.	1	0.629	25.8 ± 0.0	13.5 ± 0.0	0.31	0.15	0.18	0.4
Toona Sureni (Blume) Merr.	1	0.375	24.0 ± 0.0	22.5 ± 0.0	0.27	0.13	0.16	0.3
Cinnamomum burmannii (Nees & T.Nees) Nees ex Blume	2	0.490	18.3 ± 3.4	12.9 ± 0.5	0.24	0.11	0.14	0.3
Terminalia catappa L.	1	0.478	18.8 ± 0.0	17.8 ± 0.0	0.17	0.08	0.1	0.2
Spathodea campanulate P.Beauv.	1	0.351	15.0 ± 0.0	23.4 ± 0.0	0.1	0.05	0.06	0.1
Lagerstroemia speciosa (L.) Pers.	1	0.595	18.5 ± 0.0	8.1 ± 0.0	0.09	0.04	0.05	0.1
Parkia timoriana (DC.) Merr.	1	0.340	14.3 ± 0.0	20.5 ± 0.0	0.08	0.04	0.05	0.1
Pometia pinnata J.R.Forst. & G.Forst.	1	0.633	13.1 ± 0.0	12.3 ± 0.0	0.08	0.04	0.04	0.1
Terminalia mantaly H.Perrier	1	0.753	11.1 ± 0.0	13.2 ± 0.0	0.07	0.03	0.04	0.1
Annona squamosa L.	1	0.618	15.6 ± 0.0	8.1 ± 0.0	0.07	0.03	0.04	0.1
Durio zibethinus Rumph. ex Murray	1	0.516	10.2 ± 0.0	12.5 ± 0.0	0.04	0.02	0.02	0
Total Stand	68				77.29	36.34	45.38	100

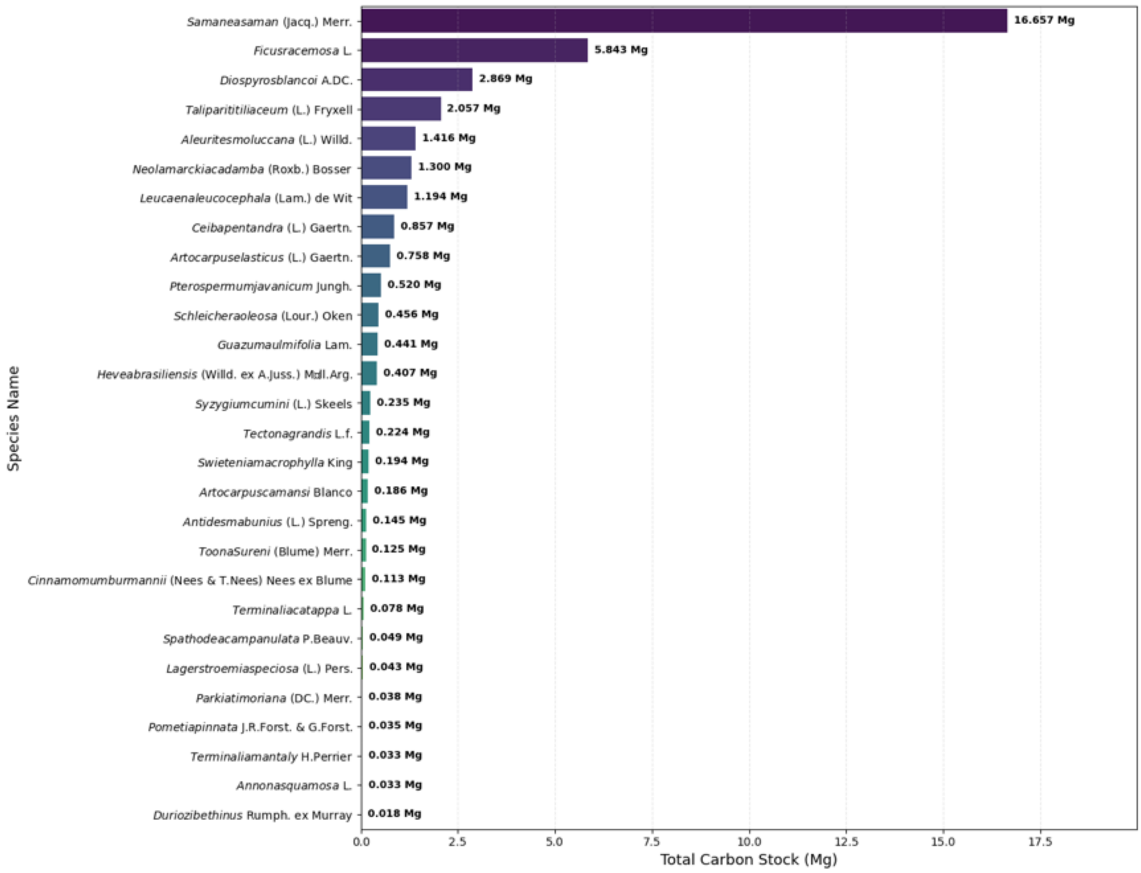

Figure 2. Carbon stock distribution among dominant species

This asymmetrical carbon distribution pattern is consistent with Suheriyanto et al. (2024), who identified the Fabaceae family as a primary carbon sink in urban ecosystems. The critical role of specific dominant vegetation in maintaining baseline carbon storage capacities and ecological functions has been well-documented across various critical environments (Rahardjanto et al., 2022). Although the extensive canopy architecture of *S. saman* (Zaki & Munawaroh, 2025) provides substantial localized emission mitigation, this extreme taxonomic dominance introduces significant ecological vulnerabilities. While this concentration facilitates immediate high-capacity carbon sequestration, it structurally resembles a Functional carbon centralization within the local catchment area. Consequently, the introduction of a species-specific pathogen or environmental stressor could severely degrade the carbon storage resilience of this localized ecological buffer. Because species diversity is a fundamental driver of long-term carbon stability in tropical contexts (Jose et al., 2025), institutional UGI management must prioritize the targeted diversification of taxa with high wood density profiles comparable to the structural benefits observed in *Larix olgensis* (Zhang et al., 2022) to ensure the long-term functional resilience of the institutional stand.

Demographic Stand Structure and the Paradox of Carbon Inequality

Demographic structural analysis of the stand confirms a reverse J-shaped distribution curve, as shown in Figure 3, signaling an active structural regeneration profile where smaller-diameter classes numerically dominate the community. Specifically, the DBH interval between 10 and 20 cm constitutes the largest structural cohort with 34 individual stems, representing 50% of all recorded trees. However, a clear structural dichotomy appears when comparing numerical density against functional carbon storage capacity. While small-diameter cohorts dominate the demographic count, the estimated carbon mass is highly concentrated within the mature structural classes exceeding 60 cm DBH.

This structural asymmetry represents a significant pattern of localized carbon inequality, which is mathematically confirmed by a Gini coefficient value of 0.654. This high degree of concentration is structurally mapped via the Lorenz curve in Figure 4, which reveals that a small fraction of large-diameter individuals manages the majority of the institutional carbon reservoir. To further deconstruct this functional concentration and directly address the structural distribution of biomass, the individual-level census data indicates that the top 5% of the largest trees which equals 3 individuals sequester 28.3% of the total biomass carbon, while the top 10% which equals 7 individuals and top 20% which equals 14 individuals control 47.3% and 66.2% of the cumulative carbon reservoir, respectively.

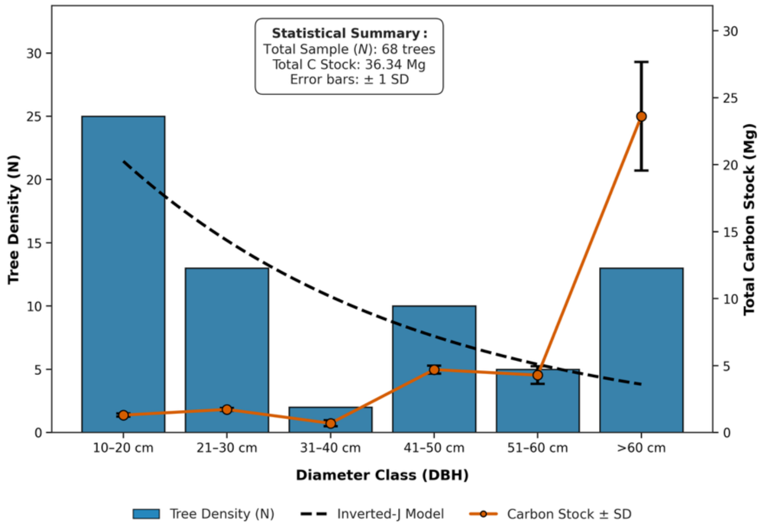

Figure 3. Tree density and carbon distribution per diameter class

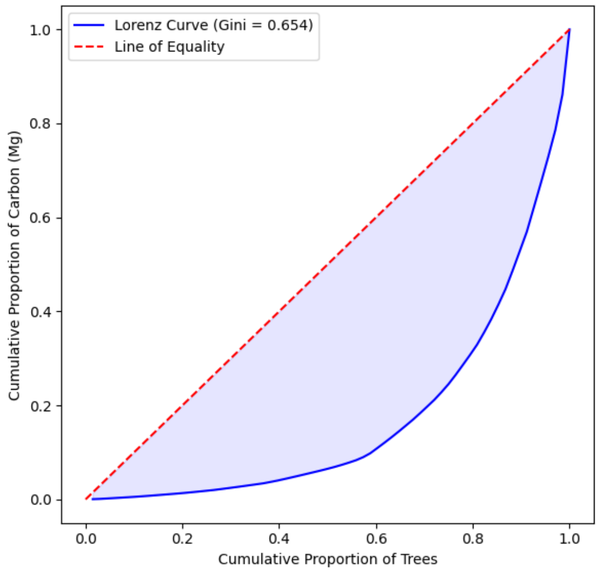

Figure 4. Lorenz curve and Gini coefficient (G=0.654) for carbon inequality

These results indicate a structural paradox where the demographic health of the forest conventionally interpreted as an indicator of healthy stand regeneration does not guarantee functional parity in its ecological contribution. Instead, the majority of the carbon storage capacity within this local stand is disproportionately concentrated in a limited cohort of LOTs with a DBH exceeding 60 cm. This aligns with macroecological patterns where the top 1% of the largest trees contribute up to 50% of the total forest biomass (Lutz et al., 2018).

Consequently, this structural asymmetry suggests that institutional landscape management strategies could pivot from expanding sapling quantities toward the targeted preservation of existing LOTs. While newly implemented sapling planting initiatives require substantial temporal buffers to achieve equivalent ecological mitigation thresholds, the targeted preservation of established LOTs ensures immediate, high-capacity carbon retention for local micro-climate governance. Because LOTs are integral to maintaining localized ecosystem services and stabilizing the Resource Nexus (Makwinja & Njiwawo, 2025), their conservation potentially supports institutional sustainability frameworks and may contribute to the resilience of urban watersheds.

Allometric Model Dependency, Sensitivity, and Estimation Uncertainty

The empirical relationship between secondary stem expansion and estimated carbon stocks was evaluated via non-linear regression as demonstrated in Figure 5, which yielded a high $R^2 = 0.9422$. Rather than an independent ecological validation, this correlation demonstrates a model-inherent mathematical circularity, given that DBH is already the primary exponential driver in the Chave et al. (2014) equation. Stepwise diagnostic analysis shows that a DBH-only relationship governs the curve's core geometric skeleton, yielding an $R^2 > 0.91$. Factoring in height, introduces vertical stratification, while wood density, anchors the final baseline to species traits without altering the power-law trajectory. Furthermore, species-level residuals reveal that generalized formulations flatten local anomalies: dense-wooded anchors plot consistently above the curve, whereas light emergent taxa plot below it. Crucially, the model's apparent stability is highly sensitive to the leverage of Large Old Trees (LOTs), as simulating the exclusion of the top 6 largest individuals severely deflates the overall explanatory power.

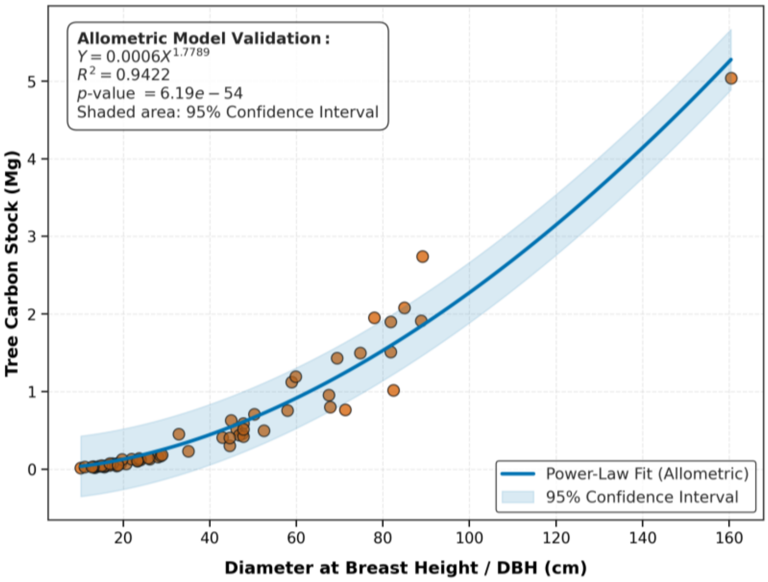

Figure 5. Regression analysis between DBH and tree carbon stock

This inherent mathematical endogeneity underscores that while DBH remains a highly practical terrestrial proxy for rapid carbon mapping, generalized pantropical formulations are highly sensitive to initial measurement inputs. To address the required error propagation analysis across different structural cohorts, Table 2 delineates the simulated impact of a standard field measurement error tier comprising ±5% for DBH, ±10% for tree height due to urban canopy occlusion, and ±5% for literature-derived wood density across the stand's key diameter classes.

Table 2. Error propagation and absolute uncertainty contributions by diameter class

DBH Class (cm)	Stems (N)	Mean AGB (Mg)	Target Carbon (Mg)	Propagated Uncertainty Range (%)	Absolute Carbon Error Variance (± Mg C)	Primary Error Driver
10–20	34	4.31	2.03	±10.2%	±0.21	Tree Height
21–30	11	4.65	2.19	±11.5%	±0.25	Tree Height and DBH
31–40	7	4.79	2.25	±12.8%	±0.29	DBH Variance
41–50	7	10.63	5.00	±14.1%	±0.71	DBH Variance

DBH Class (cm)	Stems (N)	Mean AGB (Mg)	Target Carbon (Mg)	Propagated Uncertainty Range (%)	Absolute Carbon Error Variance (± Mg C)	Primary Error Driver
51–60	3	9.06	4.26	±15.6%	±0.66	DBH Exponential Tail
>60	6	43.85	20.61	±17.8%	±3.67	DBH Exponential Tail
Total Stand	68	77.29	36.34	±10.0–17.8%	±5.79	DBH in Large Trees

This mathematical dependency implies that while DBH remains a highly reliable terrestrial proxy for monitoring micro-scale carbon accumulation, the model's absolute sensitivity to stem diameter frequently obscures the true estimation uncertainties present in highly heterogeneous urban stands. As established in the methodological uncertainty framework and quantified across diameter cohorts in Table 2, micro-scale estimates are inherently subject to a variance between 10.0% and 17.8% due to field measurement limitations and generic assumptions in species-specific wood density noted by Chave et al. (2004)Specifically, assuming standard field measurement errors of up to 5% for DBH, 10% for altimeter-based tree height due to canopy occlusion as discussed by Larjavaara & Muller-Landau (2013), and 5% variance for literature-derived wood density documented by Réjou-Méchain et al. (2017), a sensitivity analysis of the allometric formulation reveals that DBH variance contributes the most disproportionate error to the final Aboveground Biomass estimation. Because DBH acts as an exponential driver and a squared parameter in the pantropical equation, even a minor 5% measurement error in the dominant Large Old Trees cohort amplifies the total stand-level carbon uncertainty far more significantly than a 10% variance in tree height or wood density.

While advanced spatial technologies, such as UAV RGB mapping, are increasingly utilized to evaluate dense canopy structures and community mapping (Husamah, Rahardjanto, et al., 2026), these remote sensing approaches still struggle to resolve structural biomass uncertainties at the individual tree level. Furthermore, as cautioned by Ameztegui et al. (2022), estimation biases increase sharply in large-diameter trees, particularly when applying generalized global models that lack site-specific calibration. Relying exclusively on pantropical models without rigorous terrestrial verification introduces systematic overestimation risks in institutional carbon reporting. To achieve structural accuracy and provide precise volumetric assessments to support local conservation strategies, future inventories must transition toward advanced non-destructive methods, such as Terrestrial Laser Scanning (TLS), which mitigate the mathematical endogeneity found in traditional equations (Chen et al., 2019). Therefore, while the strong coefficient of determination confirms the utility of DBH measurements for immediate institutional reporting frameworks, it underscores the need for continuous local structural validation when scaling predictive models to more complex, multi-layered urban canopy spaces. All carbon values presented should be interpreted as structural estimations within this recognized uncertainty range rather than absolute physiological measurements.

Functional Typology and Institutional Integration as a Living Lab

To objectively categorize the urban stand without pre-existing taxonomic assumptions, Hierarchical Cluster Analysis was performed using standardized structural and functional metrics including DBH, tree height, wood density, and estimated carbon stocks. The resulting partitions of the 28 species into two distinct functional clusters based on their Euclidean distance linkages are illustrated in Figure 6.

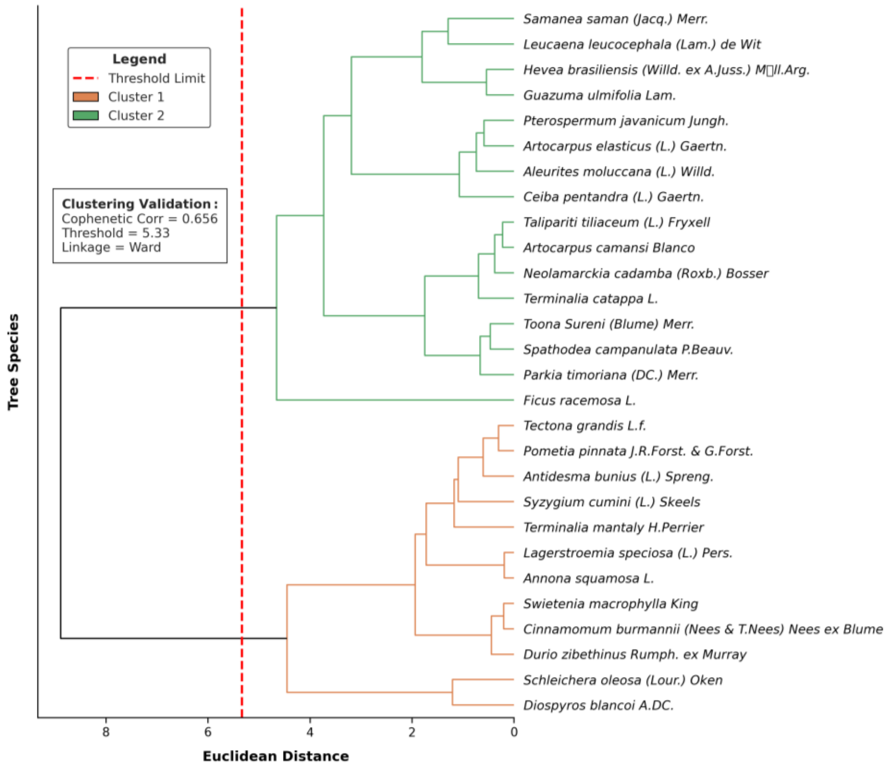

Figure 6. Dendrogram of species clustering based on functional traits

The first functional group, represented by Cluster 2, isolates high-performance carbon sinks and large-capacity structural taxa, including species such as *Samanea saman*, *Ficus racemosa*, *Talipariti tiliaceum*, and *Aleurites moluccana*. These species are defined by massive individual structural dimensions, broad canopies, and high individual carbon yields, acting as the structural core of the stand's carbon storage capability. Conversely, the second group, designated as Cluster 1, represents moderate-capacity and regeneration cohorts. This cluster is dominated by hardwood species and smaller-diameter or juvenile trees like *Tectona grandis*, *Swietenia macrophylla*, *Diospyros blancoi*, and *Cinnamomum burmannii*. While these individuals exhibit lower individual carbon accumulation at this current growth stage or possess denser but slower-growing biomass traits, they provide vital structural stability and form the future recruitment pool for the stand.

Integrating these structural data into institutional governance establishes the campus as a Living Lab, bridging academic research with operational praxis and accelerating students' environmental knowledge creation (Evans et al., 2015; Husamah, Romadoni, et al., 2026). To operationalize this framework, the empirical metrics must directly guide campus climate governance. The established carbon stock baseline of 36.34 Mg C can substitute generic default values in UI GreenMetric reporting, while a tree preservation priority map can be developed to flag the 6 LOTs which secure 56.7% of the carbon pool as absolute infrastructure exclusion zones. Furthermore, the extreme carbon asymmetry (G = 0.654) informs future species selection by prioritizing dense-wooded taxa for enrichment planting, which simultaneously supports a localized carbon risk assessment that recognizes the vulnerability of losing ~10% of the total carbon asset from a single mega-specimen. Ultimately, locking in this customized framework establishes a standardized monitoring protocol for future biennial carbon inventories to track institutional net-zero progress.

By executing these evidence-based pathways, Urban Green Infrastructure (UGI) extends beyond aesthetics to provide measurable ecosystem services like micro-climate regulation (Jeyachandran & Lee, 2024). Aligning empirical biomass data with frameworks like the UI GreenMetric transitions institutional sustainability from generalized estimations to structurally verified governance (Atici et al., 2021), enabling Higher Education Institutions to systematically contribute to SDG 13 and local microcatchment resilience (Da Silva et al., 2023).

CONCLUSION

This study confirms a clear structural dichotomy between numerical tree density and functional carbon storage within the institutional forest. While the stand exhibits a healthy, reverse J-shaped distribution dominated by smaller trees, mathematical assessment via the Gini coefficient yields a value of 0.654, proving severe carbon inequality. This reservoir is heavily concentrated in exactly 6 LOTs, predominantly driven by the dominance of *Samanea saman,* which command 56.7% of the total carbon, while the top 5%, 10%, and 20% of the largest individuals control 28.3%, 47.3%, and 66.2% of the cumulative biomass, respectively. Although the predictive model shows a high coefficient of determination, this alignment primarily reflects an inherent mathematical dependency within the DBH-driven allometric formulation rather than independent ecological variance. Consequently, standard error propagation quantified at $\pm 15\%$ is highly sensitive to the large diameter cohort, meaning that minor field measurement errors in these dominant trees disproportionately alter the stand-level carbon budgeting. To improve local carbon governance, campus management frameworks should pivot from simple tree planting numbers toward the strict conservation of these established large-diameter biomass anchors to secure the institutional carbon asset. Future inventories should transition toward advanced tools such as terrestrial laser scanning to mitigate traditional model endogeneity and provide precise volumetric data for institutional sustainability.

RECOMMENDATION

Campuses need strict preservation protocols for Large Old Trees, taxonomic diversification, and UI GreenMetric integration to ensure that urban green infrastructure remains an ecological capability builder rather than a mere aesthetic asset. Future studies should validate this model using Terrestrial Laser Scanning across broader urban canopy populations.

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AUTHOR CONTRIBUTIONS STATEMENT

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Abdulkadir Rahardjanto	✓		✓	✓			✓			✓	✓	✓	✓	
Husamah	✓		✓	✓			✓			✓	✓	✓	✓	
Atok Miftachul Hudha						✓	✓							
Tutut Indria Permana						✓								
Samsun Hadi					✓			✓						
Ludwick Satria Romadoni			✓		✓			✓			✓			

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The individual-tree census dataset supporting the findings of this study including taxonomic species names, diameter at breast height (DBH), tree height, wood density, aboveground biomass (AGB), and estimated carbon stocks is provided within the article as Supplementary Material (https://doi.org/10.5281/zenodo.20753747).

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