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Tree size, species composition, and tree-related microhabitats: Implications for urban forest management in a Sub-Saharan African city

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ABSTRACT

Urban trees provide important benefits for cities' residents and host tree-related microhabitats (TreMs), which enhance structural complexity, support the sustainable provision of ecosystem services, and strengthen resilience against climate change and environmental stressors. However, a large number of biodiversity aspects remain understudied in rapidly urbanizing African cities that face climate change impacts. This study examines the structure, composition, functional traits, and tree-related microhabitats of the urban forest in Greater Kumasi, Ghana, a densely populated and rapidly growing city. From August to December 2022, we inventoried 644 trees across 236 plots, representing 93 species and 31 families. We compared tree species composition, functional traits, TreMs abundance, and type richness between land cover classes and identified critical drivers of TreM diversity. Results revealed a scarcity of large-diameter trees and a dominance of non-native species, while native and large-diameter trees were crucial for supporting a large number of TreMs, including ecologically valuable TreM types such as those found in epiphyte habitats. Differences in TreM abundance and richness between palms and trees, and between deciduous and evergreen species, as well as the discovery of new TreM types such as those found in termite and ant nests on trees, highlight the need for increased research to understand the unique ecological factors influencing TreM abundance and richness in tropical Sub-Saharan African cities. We recommend management strategies that integrate socio-economic perspectives, consider the protection of mature trees, and monitor the spread of non-native species to strengthen the biodiversity and resilience of African tropical urban forests.

1. Introduction

Urban trees and forests offer humans a wide range of ecosystem services and therefore make an important contribution to enabling a healthy life in the city. They reduce the temperature (Gangwisch et al. 2023), filter the air (Paoletti et al. 2004), and offer spaces for recreation and stress minimization (Beckmann-Wübbelt et al. 2021). Further, urban trees offer habitat for a large number of species by providing so called tree-related microhabitats (TreMs) (Shrestha et al. 2023; Großmann et al. 2020). TreMs are defined as "distinct and well-delineated structures occurring on living or standing dead trees, that constitute a particular and essential substrate or life site for species or species communities during at least a part of their life cycle to develop, feed, shelter or breed" (Larrieu et al. 2018). In literature, they are grouped based on morphological characteristics and their use by the associated taxa. Thereby, seven groups are generally distinguished based on Larrieu et al. (2018): "(i) cavities, (ii) tree injuries and exposed wood, (iii) crown deadwood, (iv) excrescences, (v) fruiting bodies of saproxylic fungi and slime moulds, (vi) epiphytic, epixylic and parasitic structures, and (vii) fresh exudates". Each of these has individual functions for the urban forest ecosystem. For instance, cavities can host hundreds of species, while more specialized TreMs, like dendrotelms - water-retaining concavities - support fewer but highly specialized organisms (Wesołowski, 2007; Kirsch et al. 2021). TreMs are considered an important supporting ecosystem service offered by urban trees as they play a critical role in maintaining the structural complexity of

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urban forests, which is closely linked to biodiversity (Großmann et al. 2020).

It is emphasized that a high diversity of urban forests is crucial for the provision of a large number of ecosystem services (Morgenroth et al. 2016). Past studies highlighted that numerous ecosystem services including the reduction of air temperature (Wang et al. 2023), pollution removal (Gaglio et al. 2022), rainfall interception (Aston, 1979), the abundance of bird populations (Humphrey et al. 2023) as well as negative effects, such as the abundance of invasive insects (Buenrostro and Hufbauer, 2022) depend on the morphological and physiological characteristics of individual species. In addition to a variety of tree species, Esperon-Rodriguez et al. (2020) also emphasize the importance of diverse structural characteristics and functional traits. The genetic, taxonomic, and functional diversity and structural complexity of the urban forest are also crucial for the functioning of the ecosystem (Weiskopf et al. 2024) and its resilience to climate change, incoming pests, pathogens, and other environmental influences (Raupp et al. 2006). Biodiverse urban forests will have a higher chance of reducing pest outbreaks (Tabassum et al. 2024), withstand global changes (Paquette et al. 2021), as well as other biotic and abiotic urban stressors (Carol-Aristizabal et al. 2023). Therefore, biodiverse urban forests may not only provide a large number of ecosystem services but are also likely to support their sustainable long-term provision. When managed well, urban forests serve as buffers for pest invasion and sentinels for native biodiversity in terrestrial and aquatic ecosystems of the rural hinterland, such as forests, lakes and rivers (Paap et al. 2017).

To enhance the resilience of urban forests and to ensure the sustainable provision of ecosystem services in the city and beyond, authors call for urban forest management strategies that support biodiversity (Raupp et al. 2006; Carol-Aristizabal et al. 2023). However, while the importance of urban biodiversity is also recognized in the objectives of the Convention on Biological Diversity (CBD), in the Kunming Declaration, and the Sustainable Development Goals (SDGs), numbers of urban forest management strategies to support biodiversity in the West African urban context, including in Ghana, remain low (Cobbinah et al. 2023). Besides challenges in related administrative and responsibility clarifications (Adjei-Poku et al. 2023), this may result from a lack of understanding of the species composition and structure of urban forests in many West African cities. Authors highlight that even though African countries suffer most from climate change and urban forests are exposed to numerous stressors, including rapid urbanization and land cover changes, there is a lack of comprehensive knowledge on urban biodiversity, particularly in West African cities (Agyapong et al. 2018; Aronson et al. 2017). In Greater Kumasi, Ghana, past studies focusing on remote sensing data and land use and land cover change detection have shown a rapid decrease in urban green spaces (Frimpong and Molkenthin, 2021), leading to increased surface temperatures (Mensah et al. 2020). A high proportion of impervious surfaces combined with other factors such as poor urban planning, further leads to more intense and severe flooding events in the city (Abass et al. 2020). These climate risks increase due to ever-decreasing urban green infrastructure and the number of trees in the rapidly growing city. Thereby, Greater Kumasi exhibits similar characteristics to numerous West and Sub-Saharan African cities.

In addition, few studies have assessed the structure and composition of the urban forest in Greater Kumasi, Ghana (Agyapong et al. 2018; Uka and Belford, 2016; Nero et al. 2018). These indicated a species richness loss from forest to built-up area and an increase in invasive species (Agyapong et al. 2018). Nero et al. (2018) point out the need for further research towards the structure, diversity and function of West African urban ecosystems in relation to ecosystem services.

Even though the significance of TreMs in biodiversity conservation has been widely recognized and methods for their assessment have been developed, particularly in temperate and Mediterranean regions of Europe (Kraus et al. 2016; Larrieu et al. 2018), no English-language study was found in the literature review that included a comprehensive TreMs survey in any Sub-Saharan African city. Much of the existing research has concentrated on forested landscapes in Europe, with fewer studies addressing the occurrence and ecological role of TreMs in tropical forests. Research on tree-related microhabitats in urban environments remains low in general (Großmann et al. 2020; Martin et al. 2022). At the same time, studies from tropical forests suggest differences in abundant TreM types in the tropical compared to temperate forests. They found higher numbers of as well as newly added TreM types such as carton nests built on the tree by termites and ants (Nußer et al. 2024). Further, past studies in tropical forests revealed a higher diversity of TreMs compared to temperate forests (Nußer et al. 2024). Authors suggest that these may be influenced by higher energy availability or higher environmental heterogeneity in tropical ecosystems. Differences in ecological processes, such as more efficient wound closure in tropical trees, could lead to reduced numbers of TreMs, such as rot holes (Nußer et al. 2024). However, a comprehensive understanding of TreM abundance and diversity in tropical forests as well as ecological factors influencing them yet awaits (Bianco et al. 2024). The tree species, traits, and structural characteristics that support the provision of tree-related microhabitats in tropical cities of West Africa remain unknown. This study aimed to compare the composition, functional traits, and tree-related microhabitat abundance of trees across urban and forest, and semi-natural tropical landscapes in Greater Kumasi, Ghana. It aimed to include important trait aspects such as the abundance of palms and trees, as well as evergreen and deciduous, and their influence on the abundance and richness of tree-related microhabitats. Although previous TreM studies have not focused on tree growth forms - mainly due to the lower diversity of growth forms in temperate forests compared to tropical ones - authors suggest it may hold potential for further investigation in tropical ecosystems that are characterized by a high diversity of tree species and a wide range of growth strategies (Bianco et al. 2024). The focus on different land cover classes simultaneously aimed to identify the potential influence of urbanization on urban biodiversity and TreM provision. Understanding the diversity of the Sub-Saharan African urban forest in different land cover classes and its relation to the provision of TreMs is crucial to developing management strategies to improve urban biodiversity.

Taking Greater Kumasi as an example, this study analyzed the structure, species, and trait composition of the tropical African urban forest, as well as their influence on the abundance and type richness of TreMs in two different land cover classes. It gives implications for developing management perspectives that support safeguarding the urban forest and its functionality in Greater Kumasi and other tropical African cities in the future. This study addressed two main research questions:

a) What characterizes the size structure, species, and trait composition of the urban forest in Greater Kumasi, and how do they differ between the urban area and the forest and semi-natural areas?
b) How do urban forest characteristics, including tree species composition, trait attributes, and size structure, both in stand-forming and individual trees, affect the abundance and richness of tree-related microhabitats?

2. Material and method

2.1. Study area

The study was conducted in Greater Kumasi, Ashanti Region, Ghana. The three million-inhabitant area of Greater Kumasi, including Kumasi Metropolitan and its surrounding municipalities (Fig. 1), is located in south central Ghana and is characterized by a high population density and growth rate (Ghana Statistical Service, 2021). Greater Kumasi is located in Ghana's humid semi-deciduous vegetation zone with favorable soil conditions conducive to agriculture and green vegetation. It is characterized by a tropical climate with wet summers (Nero et al. 2018).

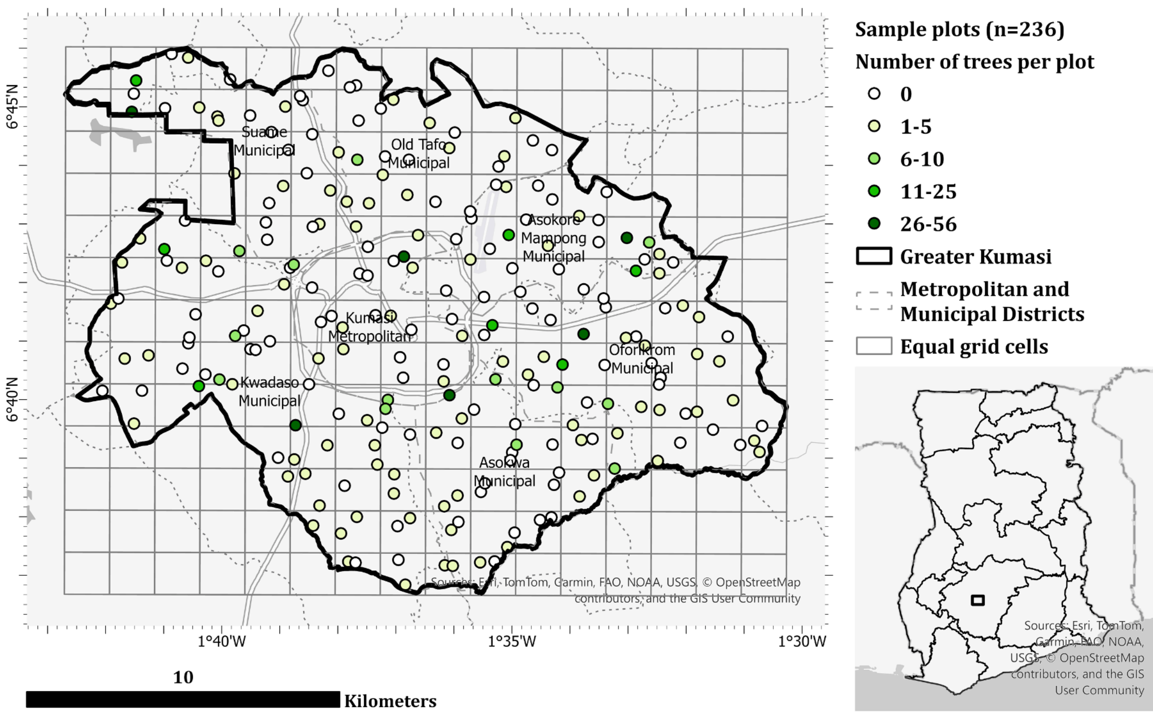


Fig. 1. Map showing the extent of the research area of Greater Kumasi (238 km^2), its location in south central Ghana, the non-stratified plot design taken in this study, the location of the 236 individual plots as well as the number of trees per plot.

As late as the 1960s, the city of Kumasi was considered the "Garden-city of West Africa" as approximately 60 % of the city was covered with green spaces (Mensah, 2014). However, especially since 2009, much of the green space in the city has been lost and remaining fragments of urban forest are under pressure from increasing urbanization (Nero, 2017). Thereby, Greater Kumasi represents the similar characteristics of numerous West and Sub-Saharan African cities.

2.2. Plot design and field data collection

A non-stratified random plot design and data collection protocol were selected based on the ground-based methodology proposed by Nowak et al. (2008a). Individual consultations with David Nowak from the USDA Forest Service were made before field data collection. A lack of reliable pre-field tree and land cover data had limited the feasibility of a robust pre-stratification. Therefore, random sampling was identified as the most methodologically sound and unbiased option that further benefits potential longitudinal studies and temporal comparison in future. To ensure systematic spatial coverage, a grid of equal-sized cells was generated based on the maximum extent of the study area. Within each cell, two circular plots were randomly located. The resulting point layer was then clipped to the actual boundary of Greater Kumasi. This clipping process led to some edge cells being only partially included in the study area, resulting in fewer than two plots in those cells. Thereby, 245 circular plots with a radius of 11.34 m were established. The number of plots was based on the assessment by Nowak et al. (2008b), who found that a minimum of 200 plots would reduce the relative standard error on the total number of trees to below 12 %. Fig. 1 shows the distribution of research plots.

The fieldwork took place between August and November 2022, during the rainy season. It resulted in a total of 236 accessible plots that were measured. Three data sheets were used to collect data for each plot and included in the analysis: general plot information, tree dendrometry inventory, and tree-related microhabitat survey. Table 1 shows the individual measures included in the data sheets with their measurement units. Woody vegetation with a DBH below 2.5 was considered as shrub. The attributes for the general plot information and the tree dendrometry inventory were adapted from the USDA Forest Service (2007). The TreMs survey was based on Larrieu et al. (2018). It was carried out for all woody species with a DBH larger than 20 cm. According to the preliminary observations in the field, ant mounts, ant channels, termite mounts and termite channels were added to the surveyed items in the group of epiphytic, epixylic, parasitic structures. Simultaneously, fire and lightning scars were excluded and cavitiy size categories were

Table 1
Summary of the individual variables per data sheet measured in the field. Three data sheets were included in the study: General Plot Information, Tree Dendromentry Inventory and TreMs Survey.

General Plot Information
Plot ID, Plot coordinates, Date, Time, Crew members, Plot Address, Plot Contact Info, Tree measurement point, Percent measured (%), Tree cover (%), Shrub cover (%),Plantable fraction (%), Land cover type (% per type – Artificial surface, forest and semi-natural, agricultural, wetland), Ground cover type (% per type), Comments
Tree Dendrometry Inventory (for all woody species with DBH > 2.5 cm)
Plot ID, Tree ID, Distance to center (m), Direction from center (°), Land cover, Street tree (yes/no), Species, DBH (cm), Total height (m), Life tree height (m), Height to live crown base (m), Live crown width N-S (m), Live crown width E-W (m), Canopy missing (%), Dieback (%), Crown light exposure (0–5), Impervious beneath canopy (%), Shrub cover beneath canopy (%), Defoliation (%), Discoloration (%)
Tree-related Microhabitat Survey (for all woody species with DBH > 20 cm)
Plot ID, Tree ID, Species, Percent observed, DBH, Kraft (1–5), Forked (Y/N), Vitality (0–3), 45 TreMs types of 15 groups based on Larrieu et al. (2018)

simplified as we encountered significant challenges in estimating cavity sizes, especially in tall trees with dense crowns and overlapping canopies. These adjustments resulted in a total of 45 TreM types grouped into 15 categories. The original data sheets were added to the supplementary material (S1).

As for the variables in Table 1, Kraft (1−5) represents the height cohort, with 1 representing dominant trees with exceptionally well-developed crowns and 5 representing low suppressed trees (Kraft, 1884). Crown light exposure (0−5) represents the light availability from up to four sides and the top of the crown. Vitality was scaled from 0 (not vital at all) to 3 (very vital) based on visual assessment.

Before starting the field data collection, all qualified team members were trained and three test plot inventories were carried out. Certified botanists joined the team of four to six researchers and assistants for tree species identification. Whenever a tree species was not identified in the field, a sample was taken, which was identified afterward by botanists of the Forestry Research Institute of Ghana (CSIR-FORIG) who are experts in West African flora. A herbarium was created for documentation and is securely stored and accessible upon request at the CSIR-FORIG. Due to the high risk of subjectivity, tree-related microhabitat data were independently assessed from two researchers in the first ten plots and cross-validation took place. To minimize between-plot biases, TreMs were afterwards inventoried by the same leading researcher in each plot. In case of uncertainty, TreMs were photo-documented and individually discussed with experts. The data was collected on paper forms to avoid the risk of unstable network connections or technology. Raw datasheets were later digitalized for data analyses. To minimize transcription errors during data digitization, we implemented a quality control protocol whereby 20 % of the data sheets were randomly selected and cross-checked against the original records. This verification process did not reveal any discrepancies.

2.3. Data processing and statistical analysis

The DBH for multiple stem trees, the tree basal area, the mean crown radius, crown projected area, tree crown volume, tree stem volume, and the total tree volume were calculated using the formulas presented in Table 2 and added to the dataset.

Additionally, trait information on the identified species was collected from literature, whereby the database of Kew Botanic Gardens (www.kew.org), and the comprehensive collection of ecological profiles of Ghanaian forest trees by Hawthorne (1995) served as a main data source and were complemented by information from individual peer-reviewed studies. A detailed bibliography can be found in the supplementary material (S2).

TreMs variables assessed in percentage values were reclassified into 5 categories starting from 0 % and continuing in steps of 20 % to make them comparable with other variables that were either counted or binary. TreMs abundance and richness were calculated for each tree in the tree-related microhabitat survey. The TreMs abundance represents the total number of identified TreMs per tree, and the TreMs type richness represents the number of different TreMs types per individual. Originally, we assessed the percentage of land cover classes according to the CORINE land cover classes for each plot, as well as for individual trees, while collecting data in the field, considering artificial surfaces, forests, semi-natural areas, agricultural areas, and wetlands (see Table 1). For the data analysis, the sample was post-stratified into two categories: (1) artificial surface (referred to as “urban area” from here) and (2) forest and semi-natural areas. When applicable, the predominant land cover class was assigned. When the land cover was classified as agricultural or wetland in the field, plots were reassessed individually based on field notes and photos, and grouped into the two categories above to allow for larger group sizes in analysis.

Frequencies and mean values were estimated to provide a descriptive overview of the dataset, summarizing the structural and compositional values across land cover types. DBH distributions were calculated by individually aggregating values per land cover class and building the mean N/ha. We applied a weighting approach based on the standard error (SE) of tree measurements within and across plots to account for the nested structure of the data. For each plot, the within-plot SE was computed as the square root of the variance divided by the number of trees. The between-plot SE was calculated from the mean values of each plot. The weighting factor for each plot was defined as the inverse of the sum of the within-plot SE and the between-plot SE. This weighting factor was then applied to the original tree-level data to generate weighted values, which were subsequently used for further analysis. This approach ensures that variability at both hierarchical levels was appropriately considered while incorporating differences in sample size. Mann-Whitney U tests in SPSS were used to identify whether there were differences in the structural and trait characteristics between the forest and semi-natural and the urban area.

In order to investigate differences between woody species richness and TreMs type richness across land cover classes, rarefaction curves including observed and extrapolated values were created using the iNext package in R (Hsieh et al. 2022). iNext was further used to assess sample coverage in two land cover classes, based on the number of plots for the tree inventory and the number of trees for the inventory of tree-related microhabitats.

We applied a Linear Mixed Model (LMM) using the lme4 package in R (Bates et al. 2015) to analyze the factors influencing TreMs abundance and TreMs type richness. LMM was chosen as the dataset included hierarchical data, with individual trees nested within plots. Further, Generalized Linear Mixed Models (GLMM), which we explored in the early stage of the analysis, failed to meet the model assumptions as the

Table 2
List of variables that have been added to the data based on the measurements in the field, indicating their units and the formulas that have been used for the calculations.

Added item	Unit	Formula for calculation	Source
DBH for multiple stem trees	cm	$= \sqrt{\left((DBH1)^2 + (DBH2)^2 + (DBH3)^2 + (DBHn)^2 \right)}$	Bernhardt and Swiecki (2001)
Tree basal area	m^2	$= \pi * \left(\frac{\text{DBH}}{200}\right)^2$	Saugier et al. (1993)
Tree stem volume	m^3	$= \text{Height to live crown base(m)} * \text{Tree basal area(m)}$	
Mean crown radius	m	$= \sqrt{\left(\text{Live crown width N} - \text{S}\frac{\text{m}}{2}\right) * \left(\text{Live crown width E} - \text{W}\frac{\text{m}}{2}\right)}$	Pretzsch et al. (2015)
Crown projected area	m^2	$= \pi * \text{Mean crown radius(m)}^2$	Pretzsch et al. (2015)
Crown height	m	= Life tree height (m) - Height to live crown base (m)	
Correction factor for crown volume	none	$= \frac{100 - \text{Canopy missing(\%)}}{100}$	
Tree crown volume	m^3	$= \left(\frac{4}{3}\right) * \text{Crown projected area}(\text{m}^2) * \left(\text{Crown height}\frac{\text{m}}{2}\right) * \text{Correction factor for crown volume}$	
Total tree volume	m^3	=Tree stem volume (m^3) + Tree crown volume (m^3)	

residuals showed spatial autocorrelation. For the LMM, we included a random intercept for "Plot ID" to account for potential non-independence of observations within the same plot, and a weighting factor that included the number of trees per plot to account for the unequal distribution of trees within plots (Zuur et al. 2009). The Variance Inflation Factor (VIF) was used to identify multicollinearity in the predictors (Dorman et al. 2012). The input variables did not show multicollinearity. Normal distribution of residuals was assessed visually through Q-Q plots as well as using the Shapiro-Wilk test (Zuur et al. 2009). Homoscedasticity was examined using residual vs. fitted values plots (Zuur et al. 2009). The spatial independence of residuals was tested using Moran's I statistics to ensure residuals were not spatially autocorrelated (Bivand et al. 2013). Both response variables were square-root transformed to meet the assumption of normality of residuals. Additionally, the residuals of the non-transformed model exhibited heteroscedasticity, which improved after transformation. As no other study was yet known that analyzed influencing factors on TreMs abundance and type richness in any African city, the aim was to include a large number of potential predictors in the model without pre-selections of factors. Therefore, we initially constructed full models, incorporating all potentially relevant predictor variables as fixed effects (DBH, Height, Social class, Vitality, Land cover, Growth form, Leaf type, Nativeness, Dieback, Light availability, and Shurbcover beneath canopy). After, we applied stepwise backward elimination and identified the best model based on the Akaike Information Criterion (AIC) (Symonds and Moussalli, 2010). We initially tested whether the distribution of the continuous predictor DBH might bias model results by standardizing it (using z-score scaling) and comparing the model outputs. As the transformation had no effect on model structure, residual distribution, or interpretation, and since we do not aim to compare effect sizes across predictors or include interactions between continuous variables, we decided to retain the original scale of DBH. For all statistical analysis, we used thresholds of $p < 0.01$, $p < 0.05$, and $p < 0.1$ to assess statistical significance. Aditionally, actual p-values are reported to provide more detailed information.

3. Results

3.1. Size structure of the urban forest in Greater Kumasi

In total, we found 644 trees and palms of 93 species of 31 families in the 236 plots of the study area. The largest number of plots (131) did not contain any trees or palms. Of the plots containing woody individuals, a large number (95) were located in the urban area. 20 plots were located in the forest and semi-natural area. The distribution of the plots, including their number of trees, is represented in Fig. 1. Regarding the individuals of trees, 48.1 % of the measured trees were located in forest or semi-natural areas, and 51.9 % of the trees were located in built-up areas. Table 3 gives an overview of important size structural characteristics of the urban forest in the study area, as well as in the two assessed land cover classes.

The mean DBH of the measured trees was significantly higher in the urban areas than in the forest and semi-natural areas ($p < .001$). At the same time, the mean height of the measured trees was higher within the forest and semi-natural areas compared to the urban area (p = .024). The mean basal area of the measured trees was higher in the urban area than in the forest and semi-natural area ($p < .001$).

In both land cover classes, the share of trees with a small DBH of up to 10 cm was the highest (Fig. 2).

The mean dieback of all assessed trees was 3.69 %, whereby the mean dieback in the forest and semi-natural area was significantly higher than in the urban area ($p < .001$) (Table 3).

3.2. Species and trait composition of the Urban Forest in Greater Kumasi

The estimated overall woody species richness in the study area was 139, with a standard error of 18.70. The observed sampling coverage based on the number of plots was 86.53 %. Fig. 3 shows the rarefaction curve for the study area (global) and the two distinguished land cover classes.

While the observed tree species richness was higher in the urban area (62) than in the forest and semi-natural areas (56), the estimated species richness was higher in the forest and semi-natural area (103) than in the urban area (97). The total number of estimated woody species in the study area was 139 (Fig. 3).

The most common species, based on the relative abundance of individuals per species, differed in the urban area compared to the forest and semi-natural area. Out of the 93 woody species found, 25 were abundant in both land cover classes. 37 species were uniquely found in urban areas, and 31 species were unique to the forest and semi-natural areas. Table 4 shows the most common species in both land cover classes.

In both land cover classes, most individuals were considered as trees, while there were also palms included in the sample. However, these represented no more than 13 % in the urban area and 6 % in the forest and semi-natural areas. A comparison of further traits in the two land cover classes showed that 81 % of the individuals in the urban area were evergreen species. In the forest and semi-natural, the share of evergreen species was 53 %, while 46 % of the individuals were deciduous trees. In both land cover classes, the share of non-native trees compared to native tree species was high. In the forest and semi-natural areas, the share of non-native tree species was 66 %. In the urban area, the share of non-native tree species was even higher: 75 %. In the forest and semi-natural areas, 96 % of the tree species were light-demanding species. In the urban area the share of light demanding species was 79 % while another 15 % were considered as partly light demanding. Further, in both land cover classes the highest share of tree species were fast growing trees. These made up 83 % in the forest and semi-natural area and 56 % in the urban area. Another 40 % of the tree species in the urban area represented moderately fast growing tree species. The minority of tree species in both land cover classes were slowly growing tree species.

3.3. Tree-related microhabitats

In total 144 individuals of 41 species were included in the TreMs survey. The most common TreMs group were cavities, followed by tree injuries and exposed wood, crown deadwood, and epiphytic, epixylic, and parasitic structures. The number of excrescences, fruiting bodies of saproxylic fungi and slime moulds as well as fresh exudates was

Table 3
Overview of important mean urban forest size and crown-dieback including their Standard Error (SE) of the urban forest in Greater Kumasi (global, all plots) and for the distinctive land cover classes: urban and forest and semi-natural areas.

	Mean DBH (cm)	(+/-) SE	mean Basal area (m^2) / ha	(+/-) SE	mean Stem volume (m^3) / ha	(+/-) SE	mean Crown volume (m^3) / ha	(+/-) SE	mean Crown dieback (%)	(+/-) SE
Global	17.53	0.76	7.34	1.08	19.22	3.79	19520.72	3495.23	3.69	0.61
Urban	20.53	1.11	5.70	0.86	12.77	2.14	14018.36	2669.03	1.11	0.45
Forest and semi-natural	14.31	0.98	15.16	4.27	49.84	17.72	45656.95	14206.97	6.47	1.14

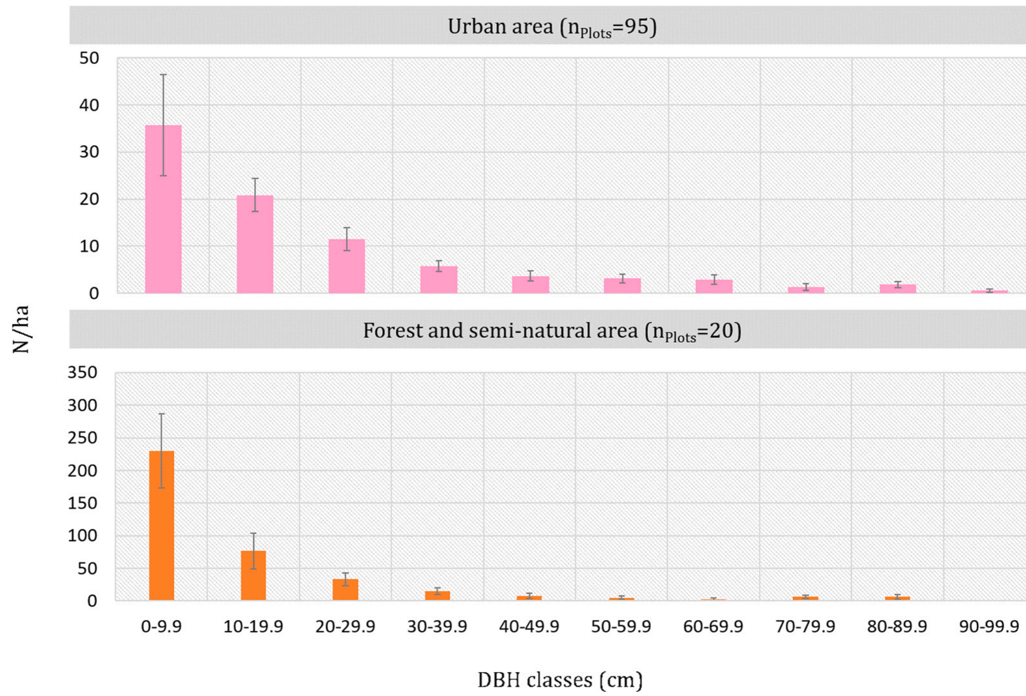
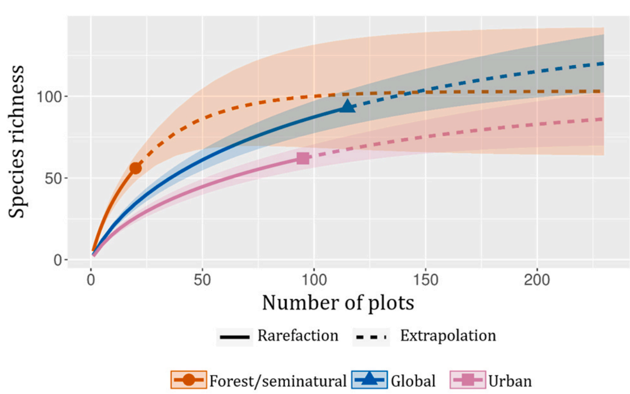


Fig. 2. DBH distribution in the two observed land cover classes based on the mean number of individual trees per ha in the research plots including standard errors (SE).



		Observed	Sample coverage	Estimator	Standard error	95% confidence level lower	upper
Forest/Seminatural	Species richness	56.00	69.05%	103.03	22.08	59.75	146.30
Global	Species richness	93.00	85.55%	139.29	17.49	105.01	173.56
Urban	Species richness	62.00	86.53%	96.67	17.63	62.11	131.24

Fig. 3. Rarefaction curve showing the woody species richness in Greater Kumasi study area (Global) and the distinct land cover classes included in the study along with the related statistics. The continuous line shows the observed species richness, while the dotted line represents the extrapolation.

significantly lower. Fig. 4 shows how the composition of TreMs groups differed for the two observed land cover classes and important trait characteristics. It became apparent that TreMs in palms were predominantly tree injuries and epiphytic structures, while they showed proportionally low numbers of cavities, excrescences, and fruiting bodies compared to trees. The proportional abundance of epiphytic structures was higher in native than in non-native species, while non-native trees supported a higher percentage of excrescences and fruiting bodies. Further, evergreen species showed a higher proportional abundance of tree injuries and exposed wood than deciduous trees that proportionally hosted more cavities.

The TreMs abundance per tree was significantly higher in the urban area than in the forest and semi-natural area ($p = .028$). The mean TreMs type richness per tree did not significantly differ between the forest and semi-natural and the urban area ($p = .338$).

Results of the rarefaction and extrapolation indicated a total observed as well as estimated number of TreMs types of 47 in the study area. The total number of TreMs types - observed and estimated - did not differ significantly between the two land cover classes. Fig. 5 shows the rarefaction results.

Trait comparisons showed that the TreMs abundance was significantly higher for native trees than for non-native trees ($p = .001$). The mean TreMs type richness was showed no significant difference for non-native trees as compared to native tree species ($p = .116$). The TreMs abundance did not significantly differ between trees and palms ($p = .900$). At the same time the TreMs type richness was higher for trees than for palms ($p < .001$). While the mean TreMs type richness was higher for deciduous trees than for evergreen species ($p = .041$), the mean TreMs abundance did not differ between the two ($p = .456$).

The regression analysis for the TreMs abundance identified DBH, vitality, and nativeness as the most important explaining variables. TreMs abundance increased with increasing DBH. Model predictions indicated that a tree with a DBH of 25 cm was expected to host approximately 9 TreMs, while a tree with a DBH of 50 cm was predicted to host around 18 TreMs. Thereby, the number of TreMs doubled. Further, TreM abundance decreased with increasing vitality. Trees classified as not vital at all (vitality score 0) were predicted to host approximately 37 TreMs. Trees with vitality scores of 1 and 2 were predicted to host 32 TreMs and 23 TreMs, respectively. Fully vital trees (vitality score 3) were predicted to host the fewest TreMs, with an estimated abundance of 14 TreMs. A tree being native had a positive effect on TreMs abundance. While model predictions indicated an abundance of 25 TreM for a native tree, non-native trees are predicted to host 15 TreMs. This illustrates a strong positive relationship between tree diameter and TreM abundance. Fig. 6 shows the effects of the variables that influenced TreMs abundance including their confidence interval. The results of the LMM are presented in Table 5.

Growth form, DBH, vitality, and leaf type effected the TreMs type

Table 4
The most common woody species in the urban and forest area based on the sampled trees in Greater Kumasi, Ghana.

Landcover class	Tree species	Family	Common name	Number of individuals	Mean DBH (cm)	(+/- SE)	Mean life tree height (m)	(+/- SE)	Mean dieback (%)	(+/- SE)	Growth form	Growth speed	Leaf type	Light demandingness	Nativeness
Forest and semi-natural area	*Senna siamea*	Fabaceae	Siamese cassia	42	12.50	10.12	9.43	6.24	3.93	13.77	Tree	Fast	Evergreen	Light demanding	Non-native
	Leucaena leucocephala	Fabaceae	Jumbay	37	5.98	2.92	7.71	2.16	7.16	17.89	Shrub or small tree	Fast	Evergreen	Light demanding	Non-native
	Tectona grandis	Lamiaceae	Teak	28	16.02	4.97	12.31	3.00	6.61	18.87	Tree	Fast	Deciduous	Light demanding	Non-native
	Cedrela odorata	Meliaceae	West Indian Cedar	23	13.57	18.64	9.80	8.33	0.87	4.17	Tree	Fast	Deciduous	Light demanding	Non-native
	Delonix regia	Fabaceae	Royal poinciana	23	11.10	12.82	7.28	5.04	7.39	21.58	Tree	Fast	Deciduous	Light demanding	Non-native
	Broussonetia papyrifera	Moraceae	Paper mulberry	16	6.18	6.60	5.09	4.32	10.63	29.55	Tree	Fast	Deciduous	Light demanding	Non-native
	Elaeis guineensis	Arecaceae	African Oil Palm	15	59.21	26.88	8.38	2.50	0.33	1.29	Palm	Fast	Evergreen	Light demanding	Native
	Ficus sur	Moraceae	Cape Fig	13	11.28	6.34	9.15	3.26	7.69	27.74	Tree	Fast	Deciduous	Light demanding	Native
	Alchornea cordifolia	Euphorbiaceae	Christmas bush	9	5.33	1.29	2.79	1.56	28.89	43.72	Shrub or small tree	Moderate	Evergreen	Light demanding	Native
	Carica papaya	Caricaceae	Pawpaw	9	6.74	2.94	4.04	1.03	0.00	0.00	Tree	Fast	Evergreen	Light demanding	Non-native
Urban area	*Cascabela thevetia*	Apocynaceae	Yellow oleander	32	4.31	0.97	3.58	0.21	0.00	0.00	Shrub or small tree	Fast	Evergreen	Partly light demanding	Non-native
	Elaeis guineensis	Arecaceae	African Oil Palm	24	62.42	16.90	8.93	2.25	0.21	1.02	Palm	Fast	Evergreen	Light demanding	Native
	Mangifera indica	Anacardiaceae	Mango	23	24.28	20.30	7.02	3.06	0.00	0.00	Tree	Moderate	Evergreen	Light demanding	Non-native
	Polyalthia longifolia	Annonaceae	Indian mast tree	22	17.64	8.62	7.48	4.54	4.55	21.32	Tree	Fast	Evergreen	Light demanding	Non-native
	Persea americana	Lauraceae	Avocado	19	19.00	10.17	7.16	1.84	1.58	5.02	Tree	Moderate	Evergreen	Light demanding	Non-native
	Citrus x sinensis	Rutaceae	Sweet Orange	16	14.45	3.77	5.49	0.90	3.75	11.62	Shrub or small tree	Moderate	Evergreen	Light demanding	Non-native
	Carica papaya	Caricaceae	Pawpaw	15	7.13	2.99	3.46	0.97	0.00	0.00	Tree	Fast	Evergreen	Light demanding	Non-native
	Cocos nucifera	Arecaceae	Coconut palm	14	32.75	8.11	9.11	2.52	0.00	0.00	Palm	Moderate	Evergreen	Light demanding	Non-native
	Hallea ledermanii	Rubiaceae	Subaha	12	11.16	4.18	6.61	2.18	8.33	27.33	Tree	Fast	Evergreen	Light demanding	Native
	Theobroma cacao	Malvaceae	Cocoa tree	11	10.16	5.16	4.87	1.72	0.00	0.00	Tree	Moderate	Evergreen	Not light demanding	Non-native

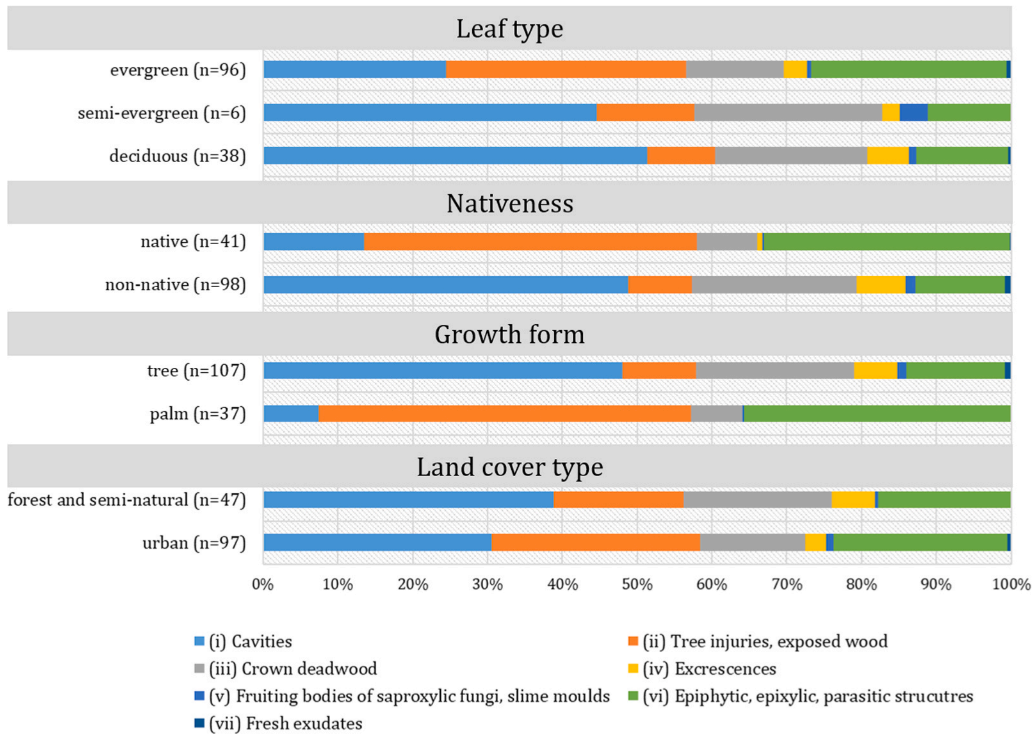
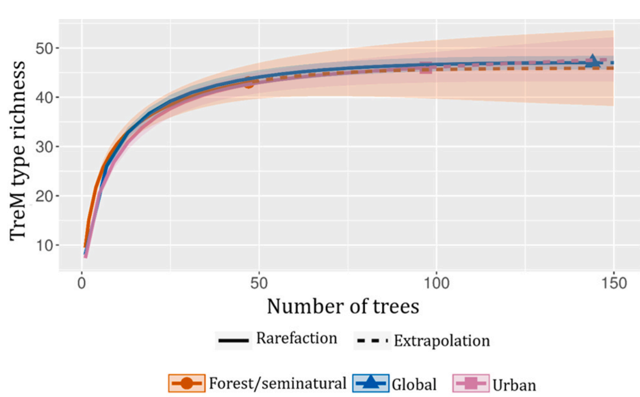


Fig. 4. Composition of identified TreMs forms for different land cover classes and trait characteristics. N represents the number of trees per category included in the survey.



		Observed	Sample coverage	Estimator	Standard error	95% confidence level lower	upper
Forest/Seminatural	TreM richness	43.00	98.71%	45.94	6.46	43.00	58.59
Global	TreM richness	47.00	100%	47.00	1.83	47.00	50.58
Urban	TreM richness	46.00	99.44%	49.96	4.74	46.00	59.26

Fig. 5. Rarefaction curve showing the TreMs type richness in Greater Kumasi study area (Global) and the distinct land cover classes included in the study along with the related statistics. The continuous line shows the observed species richness, while the dotted line represents the extrapolation.

richness. Thereby, trees were associated with a TreMs type richness of 8, while palms were predicted to host 2 TreM types. DBH has a positive, and vitality has a negative effect on TreMs type richness. Fig. 7 shows the fixed effect of the variables that influence TreMs type richness. Additionally, detailed results of the LMM are presented in Table 5. Next to the fixed effects, the random effect Plot ID was significant for TreM abundance as well as TreM type richness. The land cover did not significantly influence neither of the two variables.

4. Discussion

4.1. *Species composition of the urban forest in Greater Kumasi*

We found 644 trees and palms of 93 species of 31 families in the 236 plots in Greater Kumasi, Ghana. Thereby, the detected tree species richness in the study area was higher in our study than compared to Agyapong et al. (2018), who found 76 species in their 68 plots in Greater Kumasi in their field campaign in 2017. It was also high in comparison to other studies in West African cities (e.g. Atchadé et al. 2023). This may be due to the higher sample coverage in this study, which increases the number of rare species detected. Furthermore, Atchadé et al. (2023) identified poor soil conditions as a reason for lower species richness in Cotonou compared to Greater Kumasi. Polorigni et al. (2014) found a similar species richness to the one detected in our study in their assessment in the city of Lomé: 93 species of 47 families.

Agyapong et al. (2018) detected a higher tree species richness in the forest area as compared to the urban area in Greater Kumasi. The effect was not visible in our sample, possibly due to a lower sample coverage in forest and semi-natural areas. The extrapolations showed higher species richness in the forest and semi-natural area compared to the urban area.

Further, a predominance of non-native species over native ones in urban areas has been reported in other studies in Sub-Saharan African cities (e.g. Dangulla et al. 2020; Atchadé et al. 2023). In our study, we found a 75 % share of non-native trees in the urban area, which supports previous findings. This may be because urban areas are dominated by socio-ecological factors and human actions through species introduction and landscape heterogeneity (Atchadé et al. 2023). The dominant human influence is shown in the individual introduced species such as *Mangifera indica*, *Persea americana*, and *Polyalthia longifolia* in the urban area, which have a high economic value through providing food.

However, a high share of non-native species, representing 66 %, was also detected in the forest and semi-natural areas. The dominance of *Senna siamea*, *Leucaena leucocephala*, and *Tectona grandis* indicates a high economic value from timber production and an anthropogenic influence

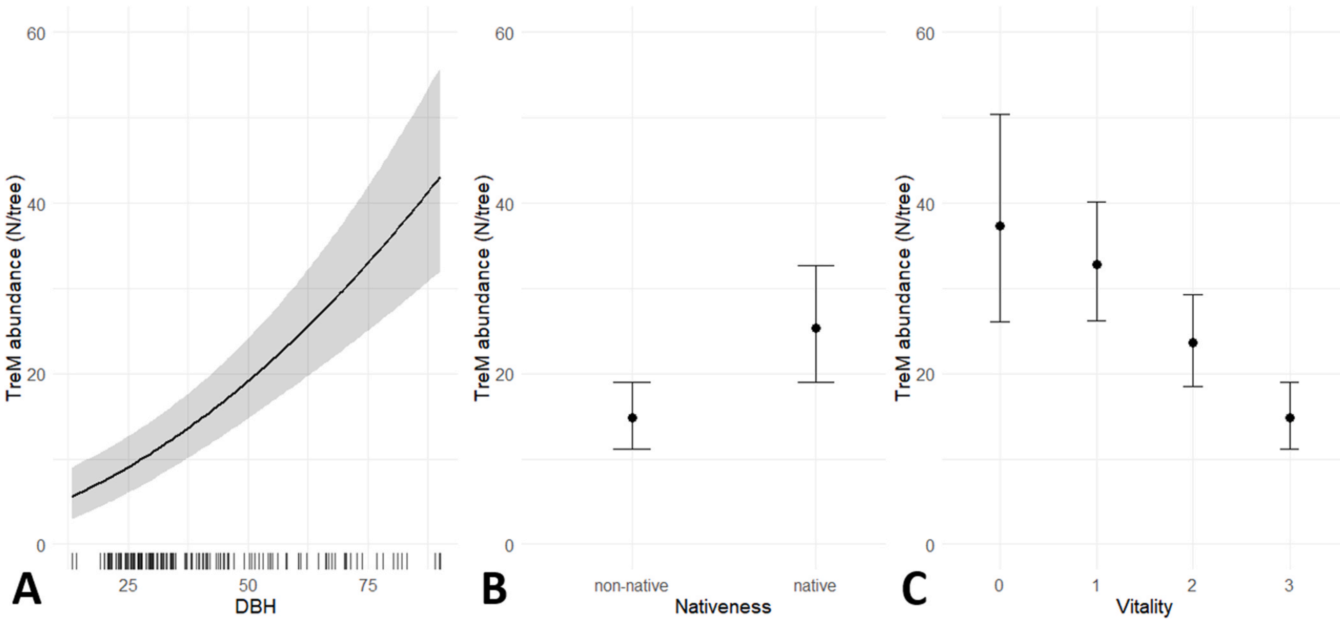


Fig. 6. TreMs abundance versus independent variables (A) DBH, (B), Nativeness, and (C) Vitality. The gray band in (A) indicates the 95 % confidence interval of the standard error of the model estimates. (B) and (C) display the mean values (±SE) of TreMs abundance across nativeness and vitality, respectively.

Table 5
Results of the linear mixed-effects models (LMM) predicting TreMs abundance and TreMs type richness. Displayed are the estimated effects (Estimate), standard errors (SE), 95 % confidence intervals (CI), and p-values for the fixed effects included in the final models as well as the variance and significance of the random effect Plot ID. The values for the fixed effects were back-transformed from the square-root scale to the original scale for interpretation.

					95 % Confidence interval		
			Estimate	SE	lower	upper	Sig.
TreM abundance	DBH		0.003***	0.001	0.002	0.005	0.000
	Nativeness						
		non-native					
		native	1.410***	0.806	0.273	3.432	0.000
	Vitality						
		0					
		1	−0.144	0.391	−1.931	0.398	0.462
		2	−1.561**	1.259	−5.005	−0.068	0.013
		3	−5.089***	2.340	−10.708	−1.536	0.000
	Random effect: Plot ID		Var = 0.658***	-	-	-	0.000
TreM type richness	DBH		0.000***	0.000	0.000	0.000	0.000
	Growthform						
		tree					
		palm	−1.865***	0.340	−2.592	−1.258	0.000
	Vitality						
		0					
		1	−0.023	0.051	−0.292	0.030	0.358
		2	−0.099*	0.104	−0.409	−0.000	0.059
		3	−0.552***	0.254	−1.163	−0.167	0.000
	Leaftype						
		deciduous					
		semi-evergreen	0.272**	0.234	0.007	0.926	0020
		evergreen	0.061**	0.050	0.002	0.200	0.015
	Random effect: Plot ID		Var = 0.074***	-	-	-	0.000

* $p < 0.1$,
** $p < 0.05$,
*** $p < 0.01$

on the urban forest species composition. The results suggest that the anthropogenic influence accompanying urbanization effects not only affects the built-up area but also the forest and semi-natural areas in Greater Kumasi, Ghana.

At the same time, the overlap of individual species between both land cover classes was small. Only one-third of all identified species were found in both land cover categories. Several studies in Sub-Saharan African urban settings highlighted the importance of urban trees for providing fuel wood, fruits and leaves for food, wood for building, as well as barks and roots for medicine (Kaoma and Shackleton, 2014; Mollee et al. 2017). The high number of non-native, economically exploited species in the study area highlights the highly anthropocentric composition and stresses the importance of considering the urban forest as a socio-ecological system, which is also highlighted by Hallett et al. (2024). Further studies into the unique use of urban trees in urban as well as forested areas and their implication on the preference of species

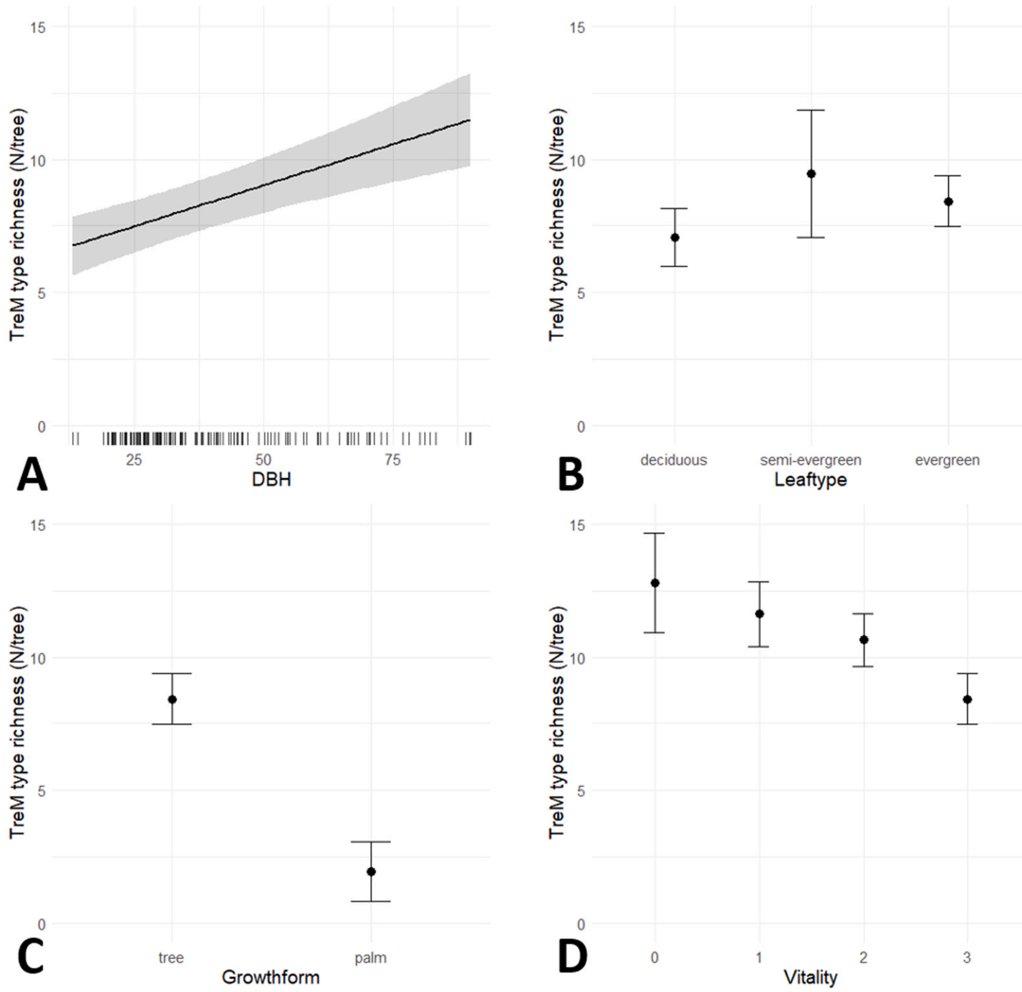


Fig. 7. TreMs type richness versus independent variables (A) DBH, (B), Leaftype, (C) Growthform, and (D) Vitality. The gray band in (A) indicates the 95 % confidence interval of the standard error of the model estimates. (B), (C) and (D) display the mean values (±SE) of TreMs type richness across leaftype, growthform and vitality, respectively.

might offer valuable explanations for the unique species composition.

4.2. Size structure of the urban forest in Greater Kumasi

The DBH distribution in both land cover classes in the study area showed a reverse J-shaped size class distribution with the majority of trees found in the smaller diameter classes. Besides low numbers of old trees, especially in the forest and semi-natural areas, we found high numbers of fast-growing and light-demanding pioneer species. The findings, while additionally considering the above-mentioned species composition, suggest that the forest areas we investigated in Greater Kumasi are not primary tropical forests but anthropogenic secondary forests. Cobbinah et al. (2023) highlight that unsustainable or unmanaged cutting of large trees is often prevalent in West African cities. As such, the low numbers of old trees may also result from too few protection measurements. At the same time, trees of the smallest diameter class can often be explained by a mix of natural regeneration as well as tree plantings in cities. According to Nowak (2012) about one of three trees is planted in cities in the US. It is not known what role tree plantings play in the West African urban context in regards to number of individuals. However, Lobe Ekamby and Mudu (2022) highlight the intensity of planting activities in African cities, where identified as an important tool by many urban administrations and governments to address air pollution challenges, heat, and enhance human well-being. At the same time, an inverted J-shaped size class distribution is commonly found in tropical forests (Jiménez et al. 2016) and may indicate a stable population in mature stands (Gonçalves et al. 2017). It ensures the replacement of trees with larger diameters. This pattern is an indicator of healthy recruitment in the tropical forest (Jiménez et al. 2016). It is yet to be understood how human activities and management influence the DBH distributions and size structure of the tropical urban forest and whether they represent healthy recruitment.

4.3. Tree-related microhabitat abundance and richness in Greater Kumasi

Cavities and rot holes emerged as this study's most prevalent TreMs types. These TreMs are frequently highlighted in the literature for their ecological importance. For instance, Basile et al. (2020) found strong associations between rot holes and the abundance of bats, birds, and insects. Additionally, rot holes have been shown to benefit threatened epiphytes in beech forests (Fritz and Heilmann-Clausen, 2010). Woodpecker cavities, alongside rot holes, are also crucial for providing roosting sites for bats (Kotowska et al. 2020).

In addition to cavities, a considerable number of epiphytic structures were observed in the study area. Epiphytes play a vital role in forest ecosystems' health by contributing to species richness and influencing ecological processes and interactions (Taylor et al. 2022). Epiphytes provide nutrients for other organisms and are highly sensitive to changes in microclimate (Gradstein, 2008). They contribute significantly to ecosystem functioning by producing organic matter and fixing atmospheric nitrogen (Nadkarni, 1984). Epiphytes also play an integral role in some urban ecosystems in Africa (Bhatt et al. 2015). We found that in Greater Kumasi, non-native trees supported fewer epiphytes than native species. This reflects findings by Laube and Zotz (2006), who noted that host tree species often harbor distinct epiphyte communities, even though most epiphyte species were not restricted to an individual host.

The proportions of ecologically valuable TreMs groups did not differ significantly between land cover classes. This supports the notion of significant urbanization effects on both land cover classes, including the number and composition of TreMs types. Even though the tree species composition differs between urban and forest and semi-natural areas, human influence is prevalent in both land cover classes and other factors played a more important role in the provision of TreMs than land cover.

The regression analysis further revealed that tree nativeness significantly influenced TreMs abundance. Native trees showed higher TreMs abundance than non-native trees. This is in line with other studies, such as Humphrey et al. (2023) who found a positive influence of native species on the abundance of bird populations in the urban area of Melbourne, Australia. Laux et al. (2022) found that native oak trees in Karlsruhe, Germany, attract a specific group of bats (Plecotus) more than non-native oaks due to specific types of tree-related microhabitat, which are more abundant in native oaks. Richards (1993) stressed that while focusing on the biodiversity of urban forests, the role of large numbers of non-native species in European (Bayón et al. 2021) and American (Potter et al. 2022) cities need to be considered. While these lead to increased overall species diversity, numerous studies highlight the importance of native species in urban areas (Tartaglia and Aronson 2024) that may be outcompeted by non-native and invasive species if not managed well (McKinney, 2006).

Larrieu et al. (2022) and others have shown that factors such as tree species, diameter at breast height (DBH), and tree status (living or dead) are critical drivers of TreMs occurrence and abundance. In our study, DBH and tree vitality significantly influenced TreMs abundance and richness. Furthermore, TreMs richness was influenced by growth form, with trees and palms showing distinct patterns. Palms, particularly *Elaeis guineensis*, exhibited higher TreMs abundance but lower TreMs type richness than trees. This could be attributed to the rough bark structure of *E. guineensis* due to excessive anthropogenic use and cutting, which facilitates the formation of bark pockets and bark soil - abundant and ecologically relevant yet less diverse TreMs types. Lastly, the leaf type was identified as an influencing factor for TreMs type richness, with evergreen trees showing higher TreMs type richness than deciduous trees.

4.4. Implications for urban forest management

Some implications for urban forest management may be drawn from this study that can help secure the urban forest's biodiversity in Greater Kumasi, Ghana:

Firstly, preserving old trees is essential for maintaining the abundance and diversity of TreMs, as the DBH has a substantial effect on TreMs. In this study, we found that there were very few old trees in both land cover classes. Reasons need to be identified, and options for the protection of old trees should be developed. The ability of cities to support large, long-lived tree species often necessitates active human intervention through strategic tree planting and ongoing maintenance efforts. Such measurements should complement existing planting actions in order to safeguard the urban forest. In the Kumasi Metropolitan Development Plan (2018–2021), loss of tree cover is recognized as one of the leading causes for climate change impacts for Greater Kumasi (Kumasi Metropolitan Assembly, 2018). To address this identified challenge, tree planting activities are included in the 2018 as well as in the 2025 action and budget plan (Kumasi Metropolitan Assembly, 2018; Kumasi Metropolitan Assembly, 2024). These include concrete indicators regarding the numbers of trees to be planted. Thereby, the government aims to restore the city's status as a garden city and to reduce the impacts of climate change. However, the development plan does not include a statement or concrete indicator in regards to the protection of existing and old trees. The importance of urban biodiversity and urban trees in supporting urban biodiversity is not considered. The findings argue for an integration of these in future development plans. The Kumasi Metropolitan Assembly (KMA)'s bye-laws protect economic trees within the metropolis (Section 79 of the Local Government Act, 1993 (Act 462)). These bye-laws require individuals to obtain a permit from the KMA or the Lands Commission for timber concessions before cutting down any economic tree. Furthermore, those granted a permit are required to replant a tree of the same or a similar species within 30 days at the original location or a nearby location. Such laws could be extended to not only economically but also ecologically valuable trees.

Secondly, native trees showed higher abundance of TreMs and played a more critical role in providing epiphytic structures and nests than non-native tree species. Epiphytes support enhancing urban biodiversity. This calls for designing a control mechanism for introducing non-native and invasive species. Nowak (2012) suggests that without tree planting and management, the urban forest composition will likely shift toward more pioneer or invasive tree species, which are already present in the study area. Therefore, a check and watch approach for exotic tree species may be introduced to further examine the development of non-native and native populations.

Thirdly, besides monitoring the potential increase in numbers of non-native trees, identifying key characteristics such as nativeness or evergreen status - which contribute to TreM abundance and richness - can support more informed species selection during ongoing planting efforts in Kumasi and across Ghana. Besides the KMA Action Plans, these include activities under the Green Ghana Project, a national campaign introduced by the Ministry of Lands and Natural Resources together with the Forestry Commission in Ghana (www.greenghana.mlnr.gov.gh). Thereby, the findings of the study may contribute to existing efforts of restoring degraded landscapes and enhancing biodiversity.

Fourthly, strengthening urban forest management to consider the diverse demands on urban forests is essential and needs to consider occurring trade-offs. The results of the study showed an increase in TreM abundance and type richness with decreasing vitality. At the same time, the analysis on species compositions showed a large number of species with high economic value for their wood and food provision, which may decrease with decreasing vitality. It is also important to explore trade-offs between safety aspects (Fröhlich et al. 2024), cultural and aesthetic values, such as deciduous versus evergreen species, and biodiversity. The aim should be to identify management strategies that take into account the needs for biodiversity that are highlighted by this study, as well as the needs for ecosystem services provision and human well-being. This may include the identification of priority areas for protecting TreMs and biodiversity. Furthermore, it emphasizes the importance of engaging multiple stakeholders to consider diverse needs.

4.5. Future research directions

Firstly, TreM surveys offer a vital tool to determine which trees to retain as habitat trees (Basile et al. 2020). Therefore, the results of this study, that identify influencing factors for TreMs abundance and type richness, can provide a valuable framework for considering which structural and compositional aspects to consider when identifying trees that are of particular importance in safeguarding urban biodiversity in Greater Kumasi. Besides morphological and structural aspects, several location-specific characteristics may influence TreMs variation (Larrieu et al. 2022). While land cover did not impact either TreMs abundance or type richness in the study area, the variance explained by the random effect Plot ID was significant. Since trees within a plot are spatially proximate and share similar environmental conditions, this may lead to a higher similarity in TreMs abundance and type richness within plots, reflected in the significant random effect. This further suggests that there may be specific differences between plots that are not captured by the recorded variables. Such differences could arise from varying environmental conditions, soil properties, or different human interventions in the plots. These unaccounted factors could be important drivers of TreMs abundance and type richness and should be further investigated in future studies. Another potential factor contributing to the significant variance between plots could be the differing tree species composition within the plots. Certain tree species or densities might be more favorable for TreMs colonization, explaining the observed variation. Future analyses should specifically examine the influence of individual tree species on TreM abundance and type richness.

Secondly, studies have demonstrated that TreMs are valuable indicators for forest biodiversity (Paillet et al. 2018; Basile et al. 2020), while the precise relationship between TreMs and species occurrence at the stand scale remains to be fully clarified (Asbeck et al. 2021). Some specific interactions between forest-dwelling species and TreMs are well-known in the American and European contexts. For example, relationships between living TreMs such as fungal communities and woodpeckers (Jusino et al. 2022) or between invertebrates and lichens (Miranda-González et al. 2023) have been documented. Non-living TreMs, such as rot holes and cavities, are often used by species including lichens, bryophytesbats and birds (Fritz and Heilmann-Clausen, 2010). Further studies show a weak but positive relationship of TreMs abundance with the species richness of saproxylic beetles, bats and birds (Basile et al. 2020). In the West African as well as overall Sub-Saharan African context, no published research has been found on TreMs in urban forests to date. It is therefore difficult to compare results to other studies and make predictions of the actual abundance and richness of species. Studies on the relationship between TreM abundance and the abundance of forest organisms from Germany show, that potential habitat may not serve as a general indicator of the species abundance, however, individual significant links were identified (Basile et al. 2020). More studies are needed to investigate these relation in the Sub-Saharan African urban setting.

Thirdly, many TreMs represent tree weaknesses and poor sanitary condition (Maxence and Raymond, 2019) that may decrease the current and future commercial value of trees. In the study, the top ten tree species in urban and forest areas are known for their economic value in providing ecosystem services, including fruit and wood. This can potentially lead to trade-offs between the financial and biodiversity benefits of urban trees. Further, trade-offs may occur between increased TreM type richness in evergreen species and higher aesthetic values for deciduous species due to foliage colorations and differences in their seasonal appearance (Roy et al. 2012; Salmond et al. 2016). More studies are therefore needed that focus on the multi-functionality of urban trees in tropical African cities and the provision and demand of ecosystem services. Studies on the perception and use of individual tree species may also improve understanding the unique species composition in the identified urban forest and semi-natural areas.

4.6. Limitations of the study

This study can be considered a first-time explorative investigation into tree-related microhabitats in the Sub-Saharan African urban context. The results provided valuable insights into TreMs abundance and type richness in Greater Kumasi and can inform a more biodiverse urban forest management in further tropical African cities. However, the findings will need to be replicated in other cities in the region to validate their accuracy. The presented results are based on a single sampling period. As TreMs are dynamic and develop over time this approach may miss temporal variation in habitat features. Further, it will need replications in diverse seasons (i.e. dry season) as some TreMs, like dendrotelms are known to be periodically unavailable (Kraus et al. 2018). The presence of dense foliage may reduce the visibility of TreMs such as bird nests. Seasonality may also influence the use of TreMs by different species (Basile et al. 2017). We call for the creation of a long-term ecological monitoring and research network for urban trees and ecosystems in Greater Kumasi and other cities in Africa. Further, the small sample size in forest and semi-natural area may be a limitation. However, including extrapolations to analyze the existing data limited the bias in the comparison between two land cover classes and provided an idea of total species richness in the forest and semi-natural area. In this study, we did not apply a spatial buffer surrounding the sample plots to account for the potential influence of neighboring land cover types. While the predominant land cover class within the 1.34 m radius plot was used for classification, incorporating a buffer could help capture edge effects or transitional influences, especially in fragmented or heterogeneous landscapes. Future studies may benefit from integrating such spatial context to refine land cover classification and its ecological interpretation.

5. Conclusion

A high species diversity and a large number of cavities and epiphytes indicate the high ecological importance of the urban trees for the city's biodiversity. At the same time, low numbers of old habitat trees stress the need for improved protection that complements already existing measures of planting activities. The results further emphasize the importance of conserving native trees to protect ecologically valuable epiphytes. A high number of non-native, economically exploited species in the study tends to lower the number of tree-related habitats. Trade-off analysis between biodiversity needs and urban trees' economic and cultural use should be integrated into the newly developing fields of urban planning, urban forestry, arboriculture, and urban silviculture in West Africa to enhance biodiversity, ecosystem services provision, and human well-being simultaneously.

CRediT authorship contribution statement

Sebastian Schmidtlein: Writing – review & editing, Methodology. **Somidh Saha:** Writing – review & editing, Funding acquisition, Supervision. **Shalom Daniel Addo-Danso:** Writing – review & editing, Investigation. **Angela Beckmann-Wübbelt:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare no competing financial or non-financial interests.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.128994.

Data availability

The data that support the findings of this study are available from the corresponding author (angela.beckmann-wuebbelt@kit.edu) upon request.

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