Structure, Diversity, and Carbon Stocks of the Tree Community of Kumasi, Ghana

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Abstract: Urban forestry has the potential to address many urban environmental and sustainability challenges. Yet in Africa, urban forest characterization and its potential to contribute to human wellbeing are often neglected or restrained. This paper describes the structure, diversity, and composition of an urban forest and its potential to store carbon as a means of climate change mitigation and adaptation in Kumasi. The vegetation inventory included a survey of 470,100-m^2 plots based on a stratified random sampling technique and six streets ranging from 50 m to 1 km. A total of 3757 trees, comprising 176 species and 46 families, were enumerated. Tree abundance and species richness were left skewed and unimodally distributed based on diameter at breast height (DBH). Trees in the diameter classes >60 cm together had the lowest species richness (17%) and abundance (9%), yet contributed more than 50% of the total carbon stored in trees within the city. Overall, about 1.2 million tonnes of carbon is captured in aboveground components of trees in Kumasi, with a mean of 228 t C ha^{-1}. Tree density, DBH, height, basal area, aboveground carbon storage, and species richness were significantly different among green spaces ($p < 0.05$). The diversity was also significantly different among urban zones ($p < 0.0005$). The DBH distribution of trees followed a modified reverse J-shaped model. The urban forest structure and composition is quite unique. The practice of urban forestry has the potential to conserve biological diversity and combat climate change. The introduction of policies and actions to support the expansion of urban forest cover and diversity is widely encouraged.

Keywords: species richness; abundance; urban forest; green spaces; sustainability

1. Introduction

More than 50% of Ghana's population now reside in urban areas [1,2]. Kumasi, the second largest city in Ghana, is expanding rapidly in both land area and population. Its population and land area have respectively expanded from about 300,000 inhabitants and 25 km^2 in the 1950s to about 2.5 million and 254 km^2 today. Between 1986 and 2014, about 200 ha of Kumasi's green cover was lost annually to urban build-up and road infrastructure [3]. In spite of this massive loss, some 33% of the land area of the political metropolitan Kumasi is still predominantly vegetated, of which 65% is composed of woody tree/shrub cover [3,4]. This remaining natural land cover is a vital ingredient for environmental sustainability and a primary source of key ecosystem goods and services. Yet knowledge about the forest structure and composition, as well as its carbon storage potential, is limited.

Successful ecological management of the urban forest requires a thorough understanding of the structure and composition of remnant trees, forest patches, and the dynamic variability between and within green space types. This reveals inter-green space structural and compositional differences

and provides information on how to achieve conservation goals. The urban forest structure and composition is considerably unique and distinct from that of natural and plantation forests. Unlike the latter two, the urban forest exists as fragments of tree clusters of varying sizes scattered between grey infrastructures and may assume several shapes of varying dimensions [5]. The tree community is composed of planted and naturally regenerated species of both exotic and native origins, hence urban forest can be more diverse than forest in neighboring open landscape [6]. Species composition and diversity depend on the ecological zone. For instance, in West Africa, the species tolerant to droughts predominate in cities of the tropical dry savannah, while cities in the tropical high forest zone are composed of species adapted to moist and humid conditions [7]. The size-class distribution of the urban forest is a blend of plantation and natural forests and a mixture of small and large growing trees [6]. The extent, species composition, and structure are influenced by the city morphology, natural environmental characteristics, human management and city age [8], and the pre-development land use types [9]. The stratified levels of stress among green spaces [10] and the lack of or ineffective implementation of urban forestry policies in developing countries [7] affect the pattern of urban forest structure, diversity, and species composition.

Assessing urban forest structure and composition involves measuring and recording information on every tree and the methods adopted are quite well-documented. A complete census of all trees is the most precise way of collecting data, but is cost- and time-consuming for larger tree populations. Random sampling techniques have been used by several studies in the past to assess urban forest structure and composition [11–15]. Other recent studies have used models such as the urban forest effects model, designed and used in several cities around the world, to evaluate urban forest structure, composition, function, and values [13,14]. Remote sensing techniques have also been used intensively to map and depict the distribution, structure, and function of urban forest at a citywide scale [16–19]. These studies depict the urban forest as a spatially- and vertically-stratified multifunctional entity composed of patches of different sizes, species compositions, tree densities, and tree sizes. Despite this progress, there is limited knowledge on the forest structure, species composition, and forest functions in urban areas in developing countries and urban and peri-urban forest resources are neglected in national forest policies and strategies in countries such as Ghana [20].

There have been several vegetation inventory studies conducted in the forest landscape of Ghana. For instance, between 1985 and 1989, the forest inventory project was implemented to provide data for sustained yield policy formulation and to establish inventory units [21]. This was continued under a new name, as the forest inventory and management project (1989–1997) [22]. The latter provided a more comprehensive national level estimate of the forest structure, species composition, and the yield potential of timber resources in forest inside and outside forest reserves. However, none of the past inventory programs have accounted for urban landscapes in the country, despite the potential of the urban forest to enhance urban sustainability and resilience. The present study contributes to this gap by assessing the tree species composition, diversity, and structure of the urban forest of Kumasi. More specifically, the study (1) describes the tree community structure, species diversity, and composition differences among green spaces of Kumasi; (2) establishes the linkage between urban forest structure, species diversity, and carbon storage (productivity); and (3) discusses the conservation relevance of the urban forest structure and composition of Kumasi.

2. Materials and Methods

2.1. Study Area

Kumasi metropolis is located in south central Ghana (6°41″ N, 1°37″ W, Figure 1). The climate is tropical, characterized by a bi-modal rainfall system. Mean annual rainfall and temperature are 1250 mm [23] and 26.4 °C [24], respectively. Kumasi's current population accounts for 10% of the total population of Ghana. It is the fastest growing and second largest city in the country, with a population density of 10,000 persons per km^2 and an annual growth rate of 4.8% [1,25]. It is a central transiting

point for travelers from within and beyond Ghana and hosts the largest open market in West Africa [26]. Kumasi's history as the "Garden City of West Africa", in addition to its rapid population growth rate, medium-size character, and location in the tropical high forest zone, make it an ideal city for the analysis of urban forest structure and composition. The metropolitan land area of Kumasi is about 254 km^2 (Figure 1) and is partitioned into ten sub-metropolises.
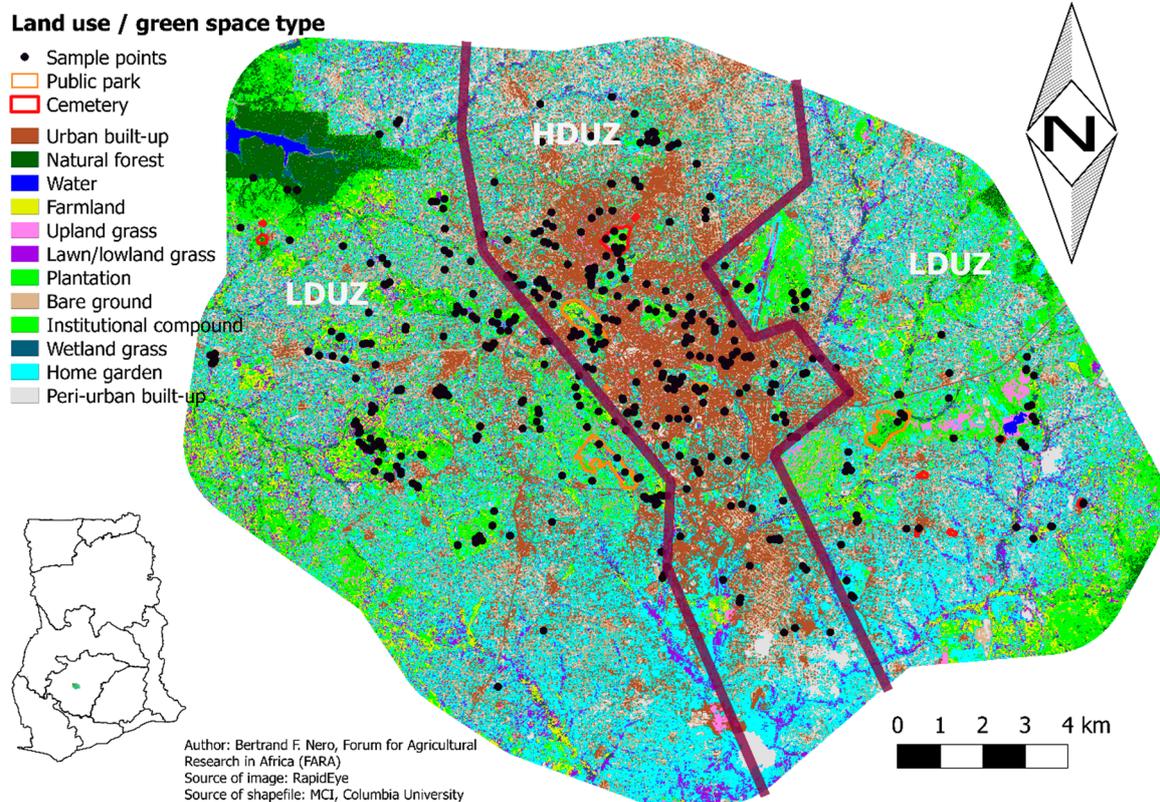

Figure 1. Urban green space map of Kumasi showing the two urban zones. HDUZ—high density urban zone and LDUZ—low density urban zone.

2.2. Vegetation Sampling

Plots were located in Kumasi by a stratified random sampling design (Figure 1) in 2014 as part of the urban biomass study in Ghana [4]. The city was partitioned into two zones based on the normalized difference vegetation index (NDVI): High Density Urban Zone (HDUZ or core urban; mean NDVI $\leq$ 0.11) and Low Density Urban Zone (LDUZ or peri-urban; mean NDVI > 0.11) (Figure 1). About 12 land-use classes (including eight urban green space (UGS) types) were delineated using satellite imagery techniques [3]. The UGS types included: plantations, natural forest, home gardens, institutional compounds, farmlands, cemeteries/sacred grooves, public parks, and grasslands/rangelands (Figure 1). Forest (plantation or natural) refers to any extensive area of planted or naturally occurring trees, either managed or unmanaged and occupying an area of at least 0.5 ha with trees at least 5 m tall and a canopy cover of at least 80%.

A total of 470 sample points were randomly generated on the UGS map of Kumasi, Ghana, for the assessment of forest structure and biodiversity (Figure 1). A 10 × 10 m quadrat was established for each sampling point with the help of a compass, a distance tape measure, and ranging poles, except in home gardens, where the entire area of the garden was surveyed. All trees with a diameter at breast height (DBH = 1.3 m from ground) >5 cm within each plot were identified to the species level, counted by species, and the height and DBH were measured. For trees with multiple stems below the DBH mark, the diameter of each stem was measured and their combined mean estimated as the quadratic

mean of the individual stem diameters. At least six streets of lengths ranging from 50 m to 1 km were purposively selected and all trees along each road were counted by species and their heights and DBH measured. Purposive sampling was required here because the majority of streets in Kumasi are devoid of trees. The species identification was carried out with the aid of tree experts and published tree identification guides, such as those by Hawthorne and Gyakari [27] and Oteng-Amoako [28].

2.3. Data Analysis

Tree density, basal area, and size class distribution (SCD) were estimated and constituted the basis for describing the urban forest structure of Kumasi. Tree density is the number of trees per plot area, while basal area is expressed as $0.00007854 \times D^2$ (D = DBH in cm). An interval of 10 cm was maintained between successive diameter size classes, except for diameters above 90 cm, where larger intervals >10 cm were adopted. Species richness, abundance, and biomass in each DBH class were calculated for the entire city and for each green space type.

The aboveground biomass of each tree was computed using the generalized biomass model developed for pantropical forest trees (Equation (1)) [29].

$$AGB = 0.0673 \times (\rho D^2 h)^{0.976} \qquad (1)$$

where AGB = aboveground biomass (kg), D = DBH in cm, h = height in m, and ρ = dry wood density of the tree species. For plants in the Arecaceae family, height was measured *and* specific biomass equations involving height used for the estimation of biomass, since the DBH of these trees are usually inaccessible and unmeasurable.

The dry wood density of each species was obtained from published literature and global databases [30,31]. The biomass was then multiplied by 0.474 to obtain carbon stocks per tree [32].

Species richness was expressed as the number of observed species for each DBH class of the sampled trees, while *Chao1* was used to estimate the potential species richness for the entire city, each UGS type, and each urban zone (Equation (2)). *Chao1*, the simplest nonparametric estimator, estimates the total number of species (Sest) by adding a term that only depends on the observed number of singletons (a), species each represented by a single individual) and doubletons (b), species each represented by exactly two individuals) to the number of species observed (Sobs) [33].

$$Sest = Sobs + \frac{a^2}{2b} \qquad (2)$$

Species accumulation curves were constructed based on the number of individuals and the sample size/number. Shannon's (H) and Simpson's (D) diversity indices and Pielou's (J) evenness were calculated. Chi-square statistics were used to establish significant differences in species richness and diversity among green spaces and urban zones.

Beta diversity analysis was performed to determine similarities in species composition among urban zones and UGS types. Beta diversity was estimated with the reformulated Sørenson's and Jaccard's indices instead of the binary techniques often employed [34]. These indices use a probabilistic approach which combines incidence-based indices with relative abundance data, thus minimizing bias and placing unequal weightings on rare and common species [34]. The computations of these indices are outlined in Chao et al. [34]. The values of both indices range between 0 and 1: with a value of 0 implying absolute dissimilarity and a value of 1 implying absolute similarity [33,35]. Thus, high values reflect a low beta diversity (high similarity) and low values reflect a high beta diversity (high dissimilarity). Bootstrap confidence intervals (CI) of the indices at 95% CI were estimated using 1000 iterations.

Correspondence analysis (CA) was performed to show the association between tree species, UGS type, and urban zone. CA graphically displays the relationship between variables which otherwise would not be detected using a pairwise test of associations. The graphs represent relative frequencies

based on the distance between row (green space or urban zone) and column (species) profiles and the distances to the average row and column profiles in a low-dimensional space. The distance is measured as a chi-square metric. CA, as well as the inferential chi-square and ANOVA test, were performed in SAS/STAT® 13.2 (SAS Institute Inc., Cary, NC, USA), while the dissimilarity and other qualitative analyses were performed in Microsoft Excel (Microsoft Inc., Redmond, WA, USA).

3. Results

3.1. Species Diversity and Composition

Overall, 176 species in 46 families were enumerated in Kumasi. Species richness differed significantly among green space types and urban zones. The species accumulation curves for the different green space types are presented (Figure 2), indicating the increment in the number of species with sampling effort. The study further indicates that sampling was adequately done. Home gardens, public parks, and institutional compounds were the most species rich; 80, 79, and 75, respectively (Figure 2, Table 1). The natural forest, however, had the highest species richness, as well as the highest Simpson's and Shannon's diversity indices (Table 1).
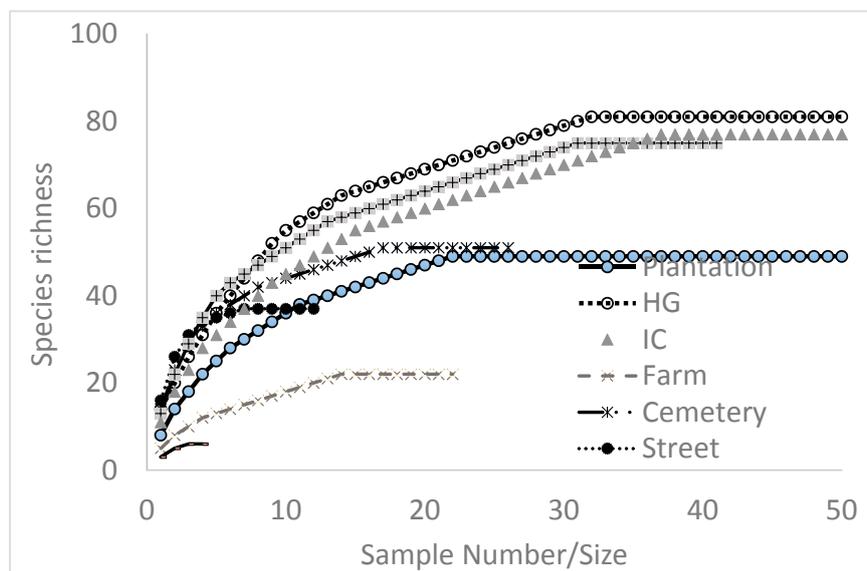

Figure 2. Rarefaction curves of woody species among green spaces in Kumasi. IC = Institutional compound, HG = home garden.

Table 1. Tree species abundance, richness, and diversity indices in different green space types within Kumasi. Chi-square analysis of richness indicates significant differences ($p < 0.0001$, $n = 8$, $X^2 = 139.4$).

Greenspace Type	Number of Individuals	Observed Richness, S	Estimated Chao1, Sest	Shannon H	Simpson 1-D	Pielou J (Evenness)
Plantation	630	48	73.6	2.561	0.854	0.66
Natural forest	980	96	105	3.840	0.969	0.84
Home garden	1095	80	98.6	3.158	0.919	0.72
Institutional Compound	715	79	101.3	3.502	0.951	0.80
Farm	100	23	47.0	2.269	0.821	0.72
Cemetery	266	51	81.3	3.242	0.935	0.82
Street	565	37	57.2	2.809	0.903	0.78
Public park	334	75	127.7	3.521	0.952	0.82
Grassland	39	6	8.3	0.749	0.328	0.42
Total	3757	176	222.4	3.716	0.956	0.72

Table 2 provides a list of the five most common species in each of the green space types. Mostly edible tree species are found in the home gardens, whereas species of aesthetic and shade values predominate along streets and within institutional compounds. Correspondence analysis reveals similarity among several green space types (Figure 3). About 51% of the association was well-represented in two dimensions. Dimension 1 (*x*-axis) representing the UGS type explained 28.5% of the total variation. Cemetery and natural forest were more similar in species composition courtesy of the predominance of native species, while home gardens (HG) and farmlands are also more similar in species composition due to the dominance of fruit and other agroforestry tree species. Common ornamentals and readily establishing exotic species result in species composition similarity among streets, plantations, institutional compounds (IC), and public parks (Figure 3, Table 2). Dimension 2 (*y*-axis), representing species, accounted for 22.1% of the total variation. The rule of thumb for the interpretation of the biplot is that species near each other are the most similar, UGS near each other are also the most similar, and species near a particular UGS type are most closely associated with or occur in that UGS type.

Table 2. Top five most common (abundant) species in each green space type in Kumasi.

UGS	Species
Home garden	Oil palm—*Elaeis guineensis* Jacq., Mango—*Mangifera indica* L., Pear—*Persea americana* Mill., Orange—*Citrus sinensis* (L) Osbeck, Coconut—*Cocos nucifera* L.
Street	Cassia—*Cassia siamea* Lam., Copper pod tree—*Peltophorum pterocarpum* (DC.) Backer ex K. Heyne, Cedrela—*Cedrela odorata* L., Indian almond—*Terminalia catappa* L., Flamboyant- *Delonix regia* (Bojer ex Hook).
Plantation	Teak—*Tectona grandis* L. f., Cocoa—*Theobroma cacao* L., *Cassia siamea*, *Elaeis guineensis*, White teak—*Gmelina arborea* (Roxb)
Institutional compound	*Cassia siamea*, *Millettia thonningii* (Schumach.) Baker, Weeping willow—*Polyalthia longifolia* (Sonn.) Thwaites, *Elaeis guineensis*, *Casuarina equisetifolia* L.
Cemetery	*Elaeis guineensis*, Brimstone tree—*Morinda lucida* (Benth.), *Cassia siamea*, *Mangifera indica*, Quickstick-*Gliricidia sepium* (Jacq.) Kunth ex Walp.
Public park	*Cassia siamea*, *Elaeis guineensis*, *Millettia thonningii*, *Pelthophorum pterocarpum*, *Delonix regia*
Farmland	*Elaeis guineensis*, *Morinda lucida*, *Mangifera indica*, African tulip—*Spathodea campanulata* P. Beauv, Kapok tree—*Ceiba pentandra* (L.) Gaertn.
Grassland	*Ceiba pentandra*, *Pithecellobium dulce* (Roxb.) Benth., *Cedrela odorata*, *Mangifera indica*, *Morinda lucida*
Natural forest	*Cedrela odorata*, *Elaeis guineensis*, Wawa—*Triplochiton scleroxylon* K. Schum., *Funtumia elastic* (Preuss) Stapf, *Trichilia monodelpha* (Thonn.) J. de Wilde

3.2. Urban Forest Structure and Diversity

The estimated total tree population in the study area is about 3,564,277 $\pm$ 27,888, with a mean of 377 trees ha^{-1}. The number of trees per unit area differed significantly among the green space types (Table 3, $p < 0.0001$). Plantations had the highest tree density of 825 trees ha^{-1}, followed by public parks with 383 trees ha^{-1} and by institutional compounds with 321 trees ha^{-1}. Farmlands had the lowest tree density of 175 trees ha^{-1}.

Basal area and DBH were also significantly different ($p > 0.0001$) among green spaces and urban zones. The mean DBH and basal area of the studied plots were 33.3 cm and 55.5 m^2 ha^{-1}, respectively. Public parks, natural forest, cemeteries, and institutional compounds had the largest stand basal areas, while grassland, home gardens, and farmland had the smallest basal areas. The natural forest had the largest sized trees, with a mean DBH of 47.5 cm (Table 3).
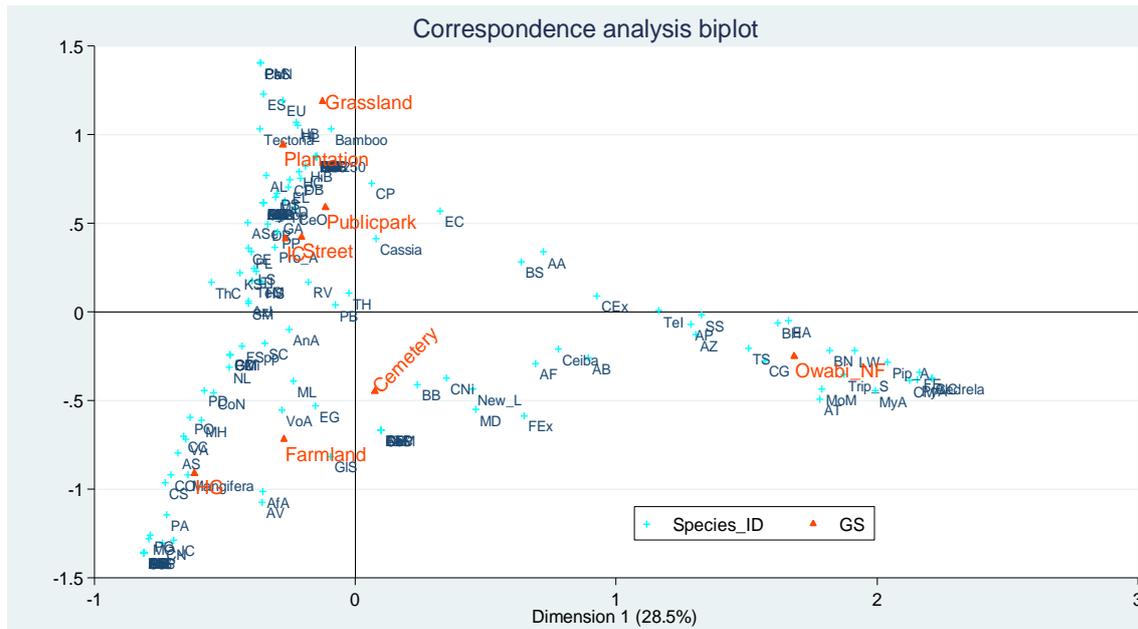
Figure 3. Output of correspondence analysis for the tree species in different green spaces (GS) in Kumasi metropolis. Dimension 1 represents green spaces while dimension 2 represents plant species. Chi-square = 11,169.8, Degrees of freedom = 2624. **Species names include**: AL, *Albizia lebbeck*; ASe, *Acasia senegale*; ASo, *Acalypha sonderina*; AD, *Adansonia digita*; AdP, *Adenanthera pavonina*; AfA, *Afzelia africana*; AF, *Albizia ferruginea*; AA, *A. adianthifolia*; AZ, *A. zygia*; AiC, *Alchornea cordifolia*; AlP, *Allanblackia parviflora*; AB, *Alstonia boonei*; AP, *Amphimas pterocarpoides*; AO, *Anacardium occidentale*; AM, *Annona muricata*; AS, *A. squamosal*; AnA, *Antiaris africana*; AT, *A. toxicaria*; AC, *Araucaria columnaris*; AI, *Artocarpus incisis*; AzI *Azadirachta indica*; AN, *Anthocleista vogelii*; AV, *A. nobilis*; Bamboo, *Bambusa vulgaris*; BN, *Baphia nitida*; BaS, *Baphia* spp.; BT, *Bauhinia tomentosa*; BS, *Blighia sapida*; BB, *Bombax buonopozense*; CaC, *Callitris cupressiformis*; CaP, *Calotropis procera*; CO, *Cananga odorata*; CP, *Carapa procera*; CaN, *Cassia nodiflora*; *C. siamea*; CE, *Casuarina equisetifolia*; CeP, *Cecropia peltata*; CeO, *Cedrela odorata*; Ceiba, *Ceiba pentandra*; CM, *Celtis mildbraedii*; CEx, *Chlorophora excelsa*; CZ, *Cinnamomum zeylanicum*; CL, *Citrus limon*; CN, *C. nobilis*; CS, *C. sinensis*; ClP, *Cleistopholis patens*; CF, *Cnestis ferruginea*; CoN, *Cocos nucifera*; CV, *Codiaeum variegatum*; CG, *Cola gigantea*; CoM, *C. millenii*; CNi, *C. nitida*, CA, *C. acuminata*; CMi, *Cordia millenii*; Cot, *Gossypium* spp; CC, *Crescentea cujete*; DO, *Daniella ogea*; DR, *Delonix regia*; DE, *Duranta erecta*; DG, *Dialium guineense*; DB, *Distemonanthus benthamianus*; DM, *Duboscia macrocarpa*; EG, *Elaeis guineensis*; FEx, *Ficus exasperata*; FSpp, *Ficus* spp.; FU, *F. umbellata*; FE, *Funtumia elastica*; GM, *Garcinia mangostana*; GlS, *Gliricidia sepium*; GA, *Gmelina arborea*; HL, *Hallea ledermannii*, HS, *H. stipulosa*; HB, *Hevea brasiliensis*; HiB, *Hildegardia barteri*; HF, *Holarrhena floribunda*; HyA, *Hymenostegia afzelii*; HA, *Hymenostegia aubrevillei*; JC, *Jatropha curcas*, KC, *Khaya cordifolia*; KS, *K. senegalensis*; LS, *Lagerstroemia speciose*; LaS, *Lannea schimperi*; LW, *L. welwitschii*; L_Spp, *Livingstonia* spp; MB, *Macaranga barteri*; MH, *M. heudelotii*; ME, *Maesopsis eminii*; MA, *Mammea africana*; *Mangifera indica*; MD, *Margaritaria discoidea*; MC, *Michelia champaca*; MT, *Millettia thonningii*; MH, *Millingtonia hortensis*; MM, *Monodora myristica*; ML, *Morinda lucida*; MO, *Moringa oleifera*; MoM, *Morus mesozygia*; MyA, *Myrianthus arboreus*; NL, *Nauclea latifolia*; New_L, *Newbouldia lavis*; OS, *Oncoba spinosa*; PB, *Parkia biglobosa*; PaS, *Parkinsonia speciosa*; PP, *Pelthophorum pterocarpum*; PA, *Persea americana*; PC, *Pinus caribaea*; Pip_A, *Piptadeniastrum africanum*; PD, *Pithecellobium dulce*; PS, *P. saman*; PlA, *Plumera alba*; PL, *Polyalthia longifolia*; PO, *P. oliveri*; Pro_A, *Prosopis africana*; PM, *Pseudospondias mombin*; PG, *Psidium guajava*; PsS, *Psydrax subcordata*; PH, *Pteleopsis hylodendron*; PyA, *Pycnanthus angolensis*; RV, *Rauwolfia vomitoria*; RL, *Rothmannia longiflora*; SD, *Samanea dinklagei*; SE, *Solanum erianthum*; SC, *Spathodea campanulata*; SM, *Spondias mombin*; SS, *Sterculia* spp.; TI, *Tamarindus indica*; Tectona, *Tectona grandis*; TeI, *Terminalia ivorensis*; TM, *T. montalis*; TeC, *T. catappa*; TS, *T. superba*; TA, *T. angolensis*; TT, *Tetrapleura tetraptera*; ThC, *Theobroma cacao*; TO, *Thuja orientalis*; TH, *Trichilia heudelotii*; Trip_S, *Triplochiton scleroxylon*; VA, *Vernonia amygdalina*; VoA, *Voacanga africana*. **GS type**; Owabi_NF = Natural forest, HG = Home garden, IC = Institutional compound.

Table 3. The structural attributes of the urban forest in Kumasi. Numbers in the same column followed by the same letter are not significantly different at *p* = 0.05.

UGS	Tree Density No. ha^{-1}	DBH cm	Height m	BA m^2 ha^{-1}	H:DBH m/cm
Streets		44.1ab	15.2bc		0.34
Cemeteries	261cd	44.0ab	13.2cde	83.8a	0.30
Farmlands	175d	45.5ab	11.4de	38.6c	0.25
Grasslands	200d	33.0cd	12.9cde	23.4c	0.39
Home gardens	240d	27.1cd	10.0e	24.0c	0.37
Institutional compounds	321c	35.3bc	13.6cd	71.3ab	0.39
Natural forest	246d	47.5a	44.5a	83.5a	0.94
Plantations	825a	23.2d	14.4bcd	65.0b	0.62
Public parks	484b	35.6bc	17.1b	84.9a	0.48
Mean	377	33.3	13.0	55.6	0.39
Least Square Difference		10.6	3.5		

Analysis of the diameter-size class distribution of the urban forest of Kumasi revealed a modified reverse J-shaped curve (Figure 4). Trees with extremely small girth sizes (DBH < 10 cm) were few, since the urban forest in many cases lacks understory vegetation. However, the medium diameter class (DBH > 10 cm) peaked at the DBH = 20 cm with over 400 trees and declined progressively till DBH = 50 cm, where the number of trees per DBH class appears to stabilize. Among green space types, some, such as plantations, institutional compounds, and streets, depicted a similar modified reverse J-model in their diameter distributions, while in others, such as cemeteries and home gardens, the reverse J-shaped model was clearly depicted (Figure 5). This suggests that the reverse J-shaped model does not describe the structure of all forest types. The urban landscape is a complex mixture of planted and conserved self-established trees of native species origin. Besides, due to the different levels of exposure to stress (e.g., pollution), it is unlikely that there is equal mortality among diameter classes.

Similarly, both the species richness and Shannon diversity index were left skewed, with peaks at DBH = 25 and 30 cm, respectively. Species richness ranged between 60 species in DBH = 25 cm and 19 species in DBH > 130 cm (Figure 4). Likewise, the Shannon index was 3.47 in DBH < 25 cm and 2.45 in the DBH > 130 cm.
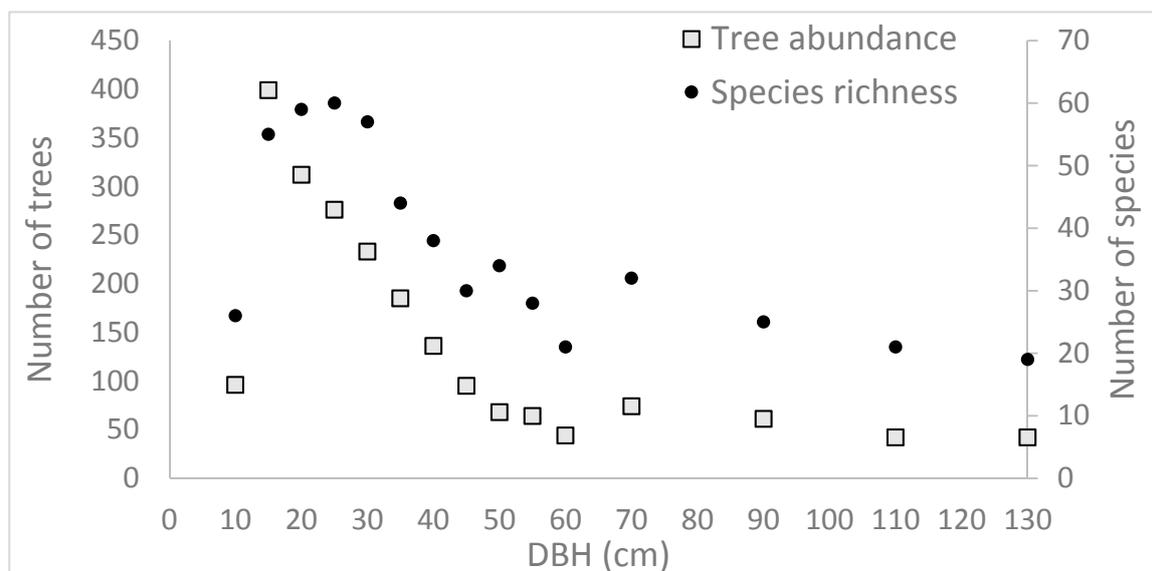

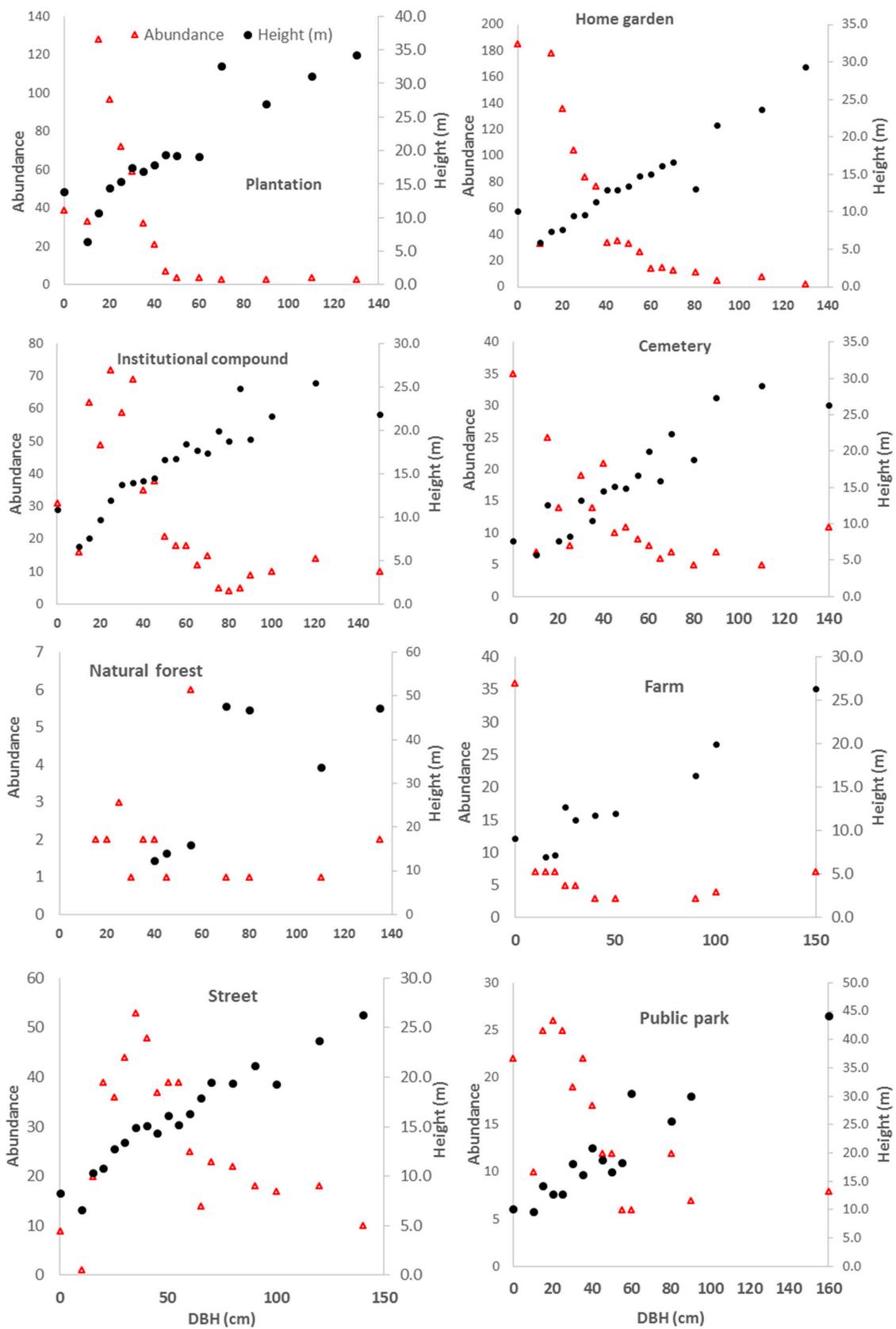**Figure 4.** A unimodal distribution of the number of trees and number of species within Kumasi, Ghana.

Figure 5. The abundance and mean total height of trees in different diameter at breast height (DBH) classes among green spaces of Kumasi, Ghana.

3.3. The Structure and Composition of the Urban Zones

The species richness and diversity of the HDUZ, LDUZ, and natural forest were significantly different. Species richness and diversity of the HDUZ was less than the LDUZ ($p < 0.0001$, $n = 1$, $X^2 = 15.70$). Species richness and Shannon's diversity index were 109 and 3.5 for the HDUZ, 141 and 3.7 for the LDUZ, and 96 and 3.8 for the natural forest, respectively.

Overall, there were more species per unit area in the HDUZ (0.25 ha^{-1}) compared to the LDUZ (0.18 ha^{-1}) and the neighboring natural forest (0.11 ha^{-1}). The native tree species composition was less than 50% in the HDUZ, slightly above 50% in the LDUZ, and about 95% in the natural forest (Figure 6). As a result, the HDUZ and LDUZ are more similar in composition, with high adjusted Jaccard's and Sørenson's indices, while the HDUZ and natural forest are the most dissimilar, with low indices and number of shared species (Table 4).

The tree density was higher in the HDUZ (366 trees ha^{-1}) than the LDUZ (351 trees ha^{-1}), while the sizes of trees in the LDUZ (DBH = 45.6 cm) were significantly larger ($p = 0.0144$) in girth and height compared to those of the HDUZ (DBH = 40.8 cm).

Table 4. Similarity (Jaccard and Sørenson indices) in species composition among urban zones in Kumasi. Values close to one indicate high similarity and close to zero indicate high dissimilarity. Bootstrap 95% confidence intervals are also shown.

Urban Zone	Shared Species	Jaccard Index			Sørenson [λ] Index		
			95% LL	95% UL		95% LL	95% UL
HDUZ–LDUZ	74	0.897	0.559	2.230	0.946	0.717	1.380
LDUZ–NF [1]	45	0.520	0.218	1.204	0.684	0.358	1.092
HDUZ–NF	27	0.312	0.135	0.605	0.476	0.239	0.754

[1] NF = Natural forest, HDUZ = high density urban zone, LDUZ = low density urban zone. [λ] LL = Lower limit, UL = Upper limit.
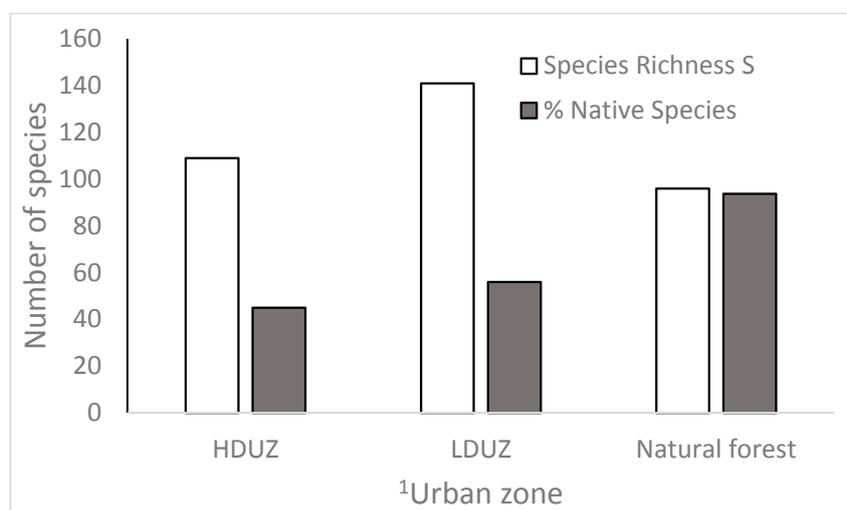

Figure 6. The species richness and proportion of native species in the urban zones in Kumasi. [1] HDUZ—high density urban zone, LDUZ—low density urban zone and natural forest (Owabi sanctuary).

3.4. Carbon Storage among Diameter Classes

Although lower diameter classes had the highest tree densities and species diversity (richness), the amount of carbon sequestered was low compared to trees in the upper diameter classes (Figure 7). The carbon density of the trees in the city increases exponentially with the girth (size) of the trees. It ranges between 11 kg ha^{-1} for plants in the Arecaceae family, who's DBHs were not measured to over 500 kg ha^{-1} for the largest sized trees in the city. Overall, trees with DBH > 60 cm store

over 54% of the total aboveground vegetation carbon (1.2 million t) of Kumasi (Figure 7). However, this diameter class constitutes only 17 and 9% of the total species richness and abundance of trees in the city, respectively. Areas with small-sized trees have a greater potential for carbon sequestration than areas with large-sized trees.
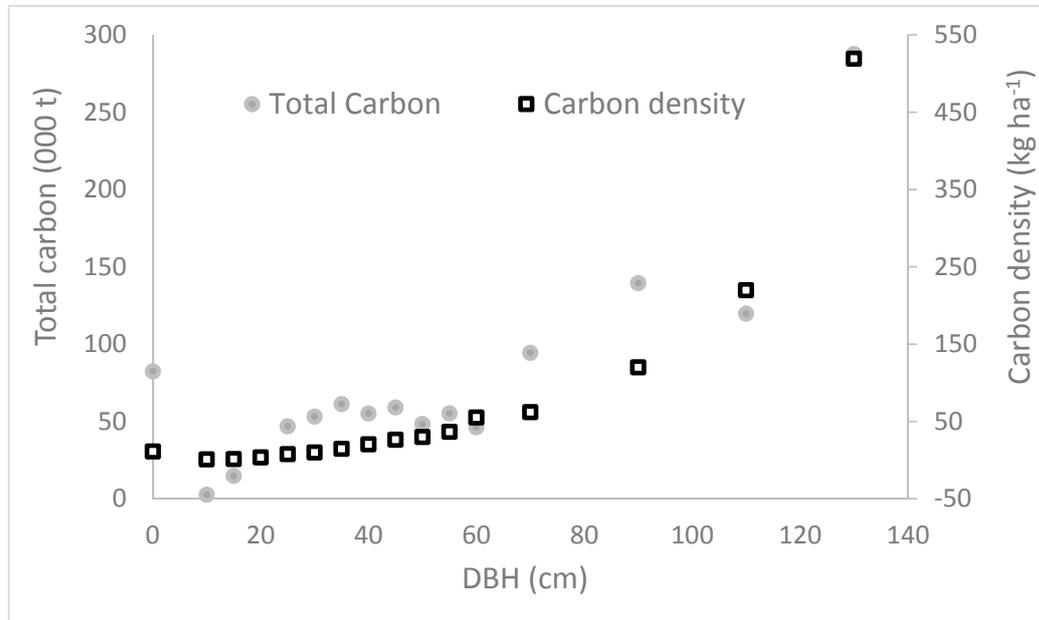

Figure 7. The total carbon stored and carbon stock densities for the different diameter classes in the urban forest of Kumasi.

4. Discussion

In this paper, spatially extensive data were used to identify variations in the structure, floristic, and functional composition of forest patches in Kumasi. These variations among green space types imply prominent differences in the population and ecosystem functions and call for different management and conservation strategies.

4.1. Species Diversity and Composition among Green Space Types

Inventory of the woody vegetation in Kumasi revealed a degree of species diversity among green spaces. Global urban forest inventory data is scarce because of the difficulty in operationalizing the concept [36]. The findings of this study represent perhaps the first comprehensive urban tree inventory in Ghana at a citywide scale. The species richness of 176 in Kumasi is numerically comparable or divergent to the species richness, diversity, and composition of other traditional land uses and national parks in Ghana. It is greater than the tree species richness of 73 in Kakum National Park [37] and 70 in the Boabeng-Fiama monkey sanctuary [38], and similar to the 171 species in the Tano Offin globally significant biodiversity area (GBSA) [39], as well as the 126 and 133 species found in the natural forest and fallow lands, respectively, within the high forest zone of Ghana [40]. Urban areas are comprised of modified abiotic and biotic environments which create room for species of native and exotic origins, as well as species of different guild compositions, to thrive [41,42]. This explains why the species richness and diversity of Kumasi is comparatively higher than other habitat types.

The overall species richness and Shannon index of 176 and 3.70, respectively, compare favorably well with tree diversity data of other cities in the region. In Abuja, Nigeria, the species richness and Shannon index of 69 and 3.56, respectively, were recently reported [43], while in Lome, Togo, 297 tree species in 141 genera and 48 families were recorded, with 69% of the species being alien [44]. Similarly, within the campus of the Valley View University, near Accra, 108 plant species in 51 families were

recorded, of which 89% were native to the thickets of the Accra plains [45]. The high diversity and richness values in Kumasi conform with recent findings that cities in Africa support an extremely high diversity, even when compared to neighboring natural forest [43,44]. The relatively high presence of non-native species may be linked to the city's culture and history of development. Historically, when Kumasi was designated the "Garden city" of West Africa, several parks and green belts were created for agricultural production, entertainment (sports) for the British imperialists, and the enhancement of environmental quality [46]. In these green belts and parks, exotic vegetable and ornamental species were cultivated to beautify the residential areas and provide fresh food for the European settlers [47]. The inter-city differences in the diversity and composition of woody species may, however, be attributed to the morphology and age of the city, the natural ecological factors, and the building and population densities.

Among green spaces, there were significant differences in species diversity and composition in Kumasi. These differences reflect human management and stratified ecological conditions within the urban landscape. On farmlands and cemeteries, certain species may be selectively preserved because of the desired key services they confer on society. Natural forests and public parks are mostly protected areas, with the latter intended for recreational use. Consequently, these spaces are moderately disturbed and comprise native species such as *Triplichiton scleroxylon*, *Morinda lucida*, and a host of others. Vegetation near residential, institutional, and commercial buildings, as well as on streets, was dominated by a mix of species planted for their aesthetic, amenity, and alimentary values. It is worth noting that the top five most common species in the home gardens are all edible (Table 2). These findings agree with other studies which found that *Terminalia* spp., *Gmelina arborea*, *Tectona grandis*, *Delonix regia*, and *Elaeis guineensis* species were the most common species in urban areas in the tropical rainforest zone of West Africa [7]. The variations in species composition among the different green space types underscore the multidimensional attribute of the urban forest and its potential to provide multiple products and services to satisfy multiple societal and personal needs. These divergent forces underpinning the composition of the urban forest will have cascading effects on the urban forest structure.

4.2. The Forest Structure and Carbon Storage in Green Spaces of Kumasi

The forest structure is described by its tree density, basal area, and height and DBH class distributions. The mean tree density and basal area of the urban forest of Kumasi somewhat deviated from what is commonly reported for natural and plantation forests around the country. The mean basal area and density of trees in the rain forest of Ghana are 23.8 m^2 ha^{-1} and 487 trees ha^{-1}, respectively [48]. This deviation may be attributed to the assorted conservation or protection of large girthed trees in natural forest relics, cemeteries, public parks, institutional compounds, and farmlands in Kumasi. However, the tree density of Kumasi is similar to the 141 trees acre^{-1} (348 trees ha^{-1}) in Gainesville, Florida, USA [6]. Basal area and tree density differed among green space types (Table 3). These differences reflect the degree of stress, anthropogenic disturbance, and history of urban development. Whereas natural forest and public parks may be maintained as default establishment of tree species with limited stress and human interference, in green spaces such as home gardens, institutional compounds, streets, and plantations, desired species for specified purposes are usually planted to meet individual and community amenity values. The local government in Kumasi recently launched a project to plant over one million trees along streams and major streets in the city. Trees along streets and near residential areas are more susceptible to stress, hence are more dynamic in population and structure [10].

In many studies, the reverse J-shaped model perfectly describes the structure of the tropical forest in Africa [49,50]. Ecologically, the reverse J-shaped model is ascribed to equal mortality among the various diameter classes. In Kumasi, the diameter class distribution of the trees followed a modified reverse J-shaped curve. Furthermore, while in some green spaces, the actual reverse J-shaped curve applied, in some others, it did not. These trends in Kumasi can be attributed to the complex combination

of forest and non-forest tree species in the different green space types, as well as the presence of natural and plantation forest types. The findings in Kumasi are, however, consistent with others which posited that the reverse J-shaped curve is not the only model that describes the forest structure [51].

At a citywide scale, it was found that species richness and diversity decreased with increasing diameter class. This is consistent with the findings in a Madagascar rainforest, which showed that diversity and richness decreased with the increasing girth of trees [52]. The forest structure of Kumasi, to a large extent, is similar to that of neighboring forest, i.e., showing similarities in diameter, height, and basal area distribution. Similarly, the carbon storage in trees increased with increasing diameter class in Kumasi, although large-sized trees were comparatively fewer than small-sized trees. Carbon storage is a function of size (girth), wood density, and height [29,53]. Small-sized trees, therefore, store less carbon compared to large-sized trees. Although evidence from the tropical forest indicates no relationship between diversity and forest carbon storage [54], data in Kumasi seem to show that tree species diversity within diameter classes may be inversely related to carbon storage. The present study did not categorically estimate other climate mitigation services, such as evaporative cooling and shading resulting from urban tree cover, as chronicled in other studies [55–57]. Nonetheless, it can be inferred that, given the wide diversity of these broad-leaf tree species in Kumasi, the urban forest would be contributing massively to mitigating heat island effects. The findings highlight the importance of the urban landscape in biodiversity conservation and enhancing ecosystem function at the city, national, and regional scales.

4.3. Implications for Conservation

Some species listed by the IUCN as vulnerable and endangered are recorded in the forest of Kumasi. These include *Adansonia digitata*, *Afzelia africana*, *Albizia ferruginea*, *Antiaris toxicaria*, *Chlorophora excelsa*, *Entandrophragma* spp., *Hallea* spp., *Hymenostegia aubrevillei*, *Khaya senegalensis*, *Prosopis africana*, *Rauwolfia vomitoria*, *Samanea dinklagei*, and *Terminalia ivorensis* [58]. Eighteen important Ghanaian timber species were also recorded in the city. These include *Chlorophora excelsa*, *Antiaris toxicaria*, *Entandrophragma* spp., *Albizia* spp., *Pycnantus angolensis*, *Ceiba pentandra*, and a host of others. These were mostly in the upper diameter (>60 cm) classes. Only *Albizia zygia*, *Alstonia boonei*, and *Mammea africana* were found in the lower diameter (<20 cm) classes. This is in accordance with studies in cities which concluded that urban green spaces are repositories of biological diversity, of which at least 8% native bird and 25% native plant species are present [59]. Forests in/near urban areas are targeted for conservation because they harbor biodiversity, including IUCN vulnerable and endangered species [60]. Indeed, significant numbers of birds, mammals, reptiles, amphibians and invertebrates have been reported near some urban centers in Ghana [61]. These show that urban green spaces provide habitats for trees and several fauna species.

In Kumasi, the presence of large-sized native tree species in the natural forest, cemeteries, public parks, and farmlands mimics old-growth forests. Old-growth forests are frequently targeted for conservation since they harbor a large proportion of vulnerable species (disturbance sensitive) and species of restricted distribution [49]. In addition, the high abundance of small-sized trees in Kumasi suggest its urban forest, if maintained and managed adequately, can be sustainable. The wide variation in the structural attributes of the urban forest of Kumasi, as well as patch sizes, is fundamental to supporting high biological diversity and hence warrants being conserved. However, considering that urban biodiversity is determined to a large extent by human preferences, high tree diversity may not imply high overall faunal diversity [62]. To enhance the biological diversity of Kumasi and other urban areas further, the following suggestions may be pursued:

1. Deliberate efforts to expand the urban forest in Kumasi and indeed across Ghana and Africa ought to be pushed forward. This requires planting and conserving a wide variety of native species as well as well-adapted economically-beneficial exotic species, especially in the HDUZ (core) areas of the city.

2. Although invasive species are currently not studied within Kumasi, it is worth noting that some exotic species could potentially be invasive. Therefore, practitioners should judiciously select species when implementing urban afforestation programs.

3. Grasslands and farmlands which are commonly found along wetlands in Kumasi could be planted with trees of assorted species mixes and excluded or protected from build-up development. In this regard, a form of urban agroforestry could be practiced, while at the same time helping urbanites adhere to the 100 m no development zones near water bodies in urban areas in Ghana.

4. Biodiversity in public parks and wetlands within Kumasi could be further guided and protected by formidable policies. This will perhaps require bye-laws enacted by the metropolitan authorities in conjunction with the communities.

5. Considering that home gardens support a high wealth of diversity and are at risk of being cleared for further housing development as and when the economic situation of the land owner permits, it is suggested that clear policy directions be enacted, demanding every parcel of land designated for housing to maintain a certain minimum amount of green cover and tree cover.

6. Both in situ and ex situ conservation measures ought to be adopted to conserve indigenous species in these landscapes, especially rare species and/or shade-tolerant species.

7. Stakeholders in urban forest (ry) need to explore better ways of making urban biodiversity profitable in order to generate income and enhance environmental sustainability. Examples are adhering to best management practices within no-development zones along waterbodies and using these riverine corridors for tourism to generate income.

5. Conclusions

Urban forestry is emerging as a means to enhance urban environmental sustainability and resilience, especially in developing countries. This study discusses the structure and diversity in relation to carbon storage of the urban forest of Kumasi. The species richness and diversity of the city is similar and sometimes higher than that of other landscapes and national parks within the same ecoregion in the country. Structurally, a modified reverse J-shaped model described the distribution of trees in the city and varied among green space types. The modification was due to the inclusion of palms and non-traditional timber species that are a rudimentary part of the urban forest. It is concluded that the urban forest structure is unique and different from that of other forest types.

While species richness and diversity decreases with increasing diameter class, carbon storage increases with increasing diameter class. The selective preservation of certain species and natural processes in the urban spaces accounts for these trends. Carbon storage is a function of tree size and not necessarily tree density. Hence, a few large trees stored more carbon than a bunch of small trees. These findings provide baseline information about the forest structure and species composition and should be the basis for urban planning decision making regarding green urbanism in Kumasi and other cities in Ghana and Africa.

Integrated and coordinated efforts by the local government, urban planners, traditional leaders, ecologists, and environmentalists, as well as the general public, ought to be harnessed to facilitate adequate conservation and utilization of urban forest towards coping with environmental hazards, minimizing poverty, and increasing food security. Further research could be tailored towards the structure, diversity, and function of urban forest in relation to poverty reduction, food security, and public health. Further research should also emphasize tree compositional and structural relationships with microclimatic regulation and shade benefits within urban landscapes in cities in Africa.

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