Urban forests baseline and ecosystem benefits of a tropical metropolis: case of Dhaka, Bangladesh

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Abstract

Dhaka, one of the world's most crowded megacities, is undergoing rapid urban development that has led to an alarming and fast decline of urban forests and trees. Urban trees provide critical services to city landscapes, including the provision of shade, reducing air pollution through absorption of air pollutants, managing wastewater runoff and surface water, and absorbing carbon dioxide from the atmosphere. There is very little information on the extent, characteristics, and ecological value of Dhaka's urban trees, which limits policymakers in designing sustainable measures that protect urban trees for the future. To address this information gap, we conducted Dhaka's first-ever urban tree inventory that provides robust baseline data to set and monitor goals for improving urban tree cover and access to urban tree benefits. We used the i-Tree Eco modeling tool to estimate the economic value of selected ecosystem services urban trees provide. We found that the tree cover in Dhaka is currently below 11%, which is much lower than its potential as a tropical city. There are 1.3 million trees, or about one tree per 7 people. The inventory identified 110 tree species belonging to 33 families in Dhaka, and more than 60% of the tree species are exotic. Overall, urban trees provide an estimated USD 6.74 million per year in ecosystem benefits and store an additional estimated USD 3.19 million worth of carbon. The overall tree diversity is considered moderate to high based on several diversity indices. The three most dominant species of Dhaka are *Mangifera indica*, *Swietenia mahogani*, and *Cocos nucifera*. This new baseline information equips policymakers to guide urban greening strategies and monitor progress towards city-level tree cover goals.

Keywords: Tree Inventory; Ecosystem Services; i-Tree Eco; Economics Value; Urban Forestry

1. Introduction

Urban green spaces provide essential ecosystem services that connect the human population with the environment, improve the quality of urban life, and promote overall human well-being. These ecosystem services include clean air, waste assimilation, regulation of the urban heat island (UHI) effect, water filtration, noise reduction, pollination facilitation, and climate moderation, among others [1,2]. Access to green spaces promotes physical activity, reduces stress, and improves the mental well-being of urban people. Trees, an integral part of the urban green spaces, act as natural air purifiers, absorbing carbon dioxide and releasing oxygen, thereby improving air quality[3–5]. Urban trees lower air temperature as much as 1.5 °C in heat-prone areas by providing shade and evapotranspiration [6]. It produces localized cooling that biodiversity experiences at ground level and improves thermal comfort for humans[7,8]. . Assessment performed in all US urban areas larger than 500 km^2 suggests that extended urban tree canopies can help reduce heat-related discomforts and offer life-saving potential[9,10]. Urban forests are also widely recognized as a nature-based solution that contributes to climate resilience and ecological health[9,11,12].

As urbanization intensifies globally, the need for accurate data to manage and monitor urban forests has become increasingly critical. Urban tree inventories offer essential information related to tree resources and help stakeholders understand the value of the ecosystem services they provide. Regular forest cover inventories are critical to track the periodic changes in ecosystem services and support data-driven city planning[13]. Notably, however, nearly 80% of published urban forest research focuses on the United States and Europe. On the other hand, fast-growing cities in the Global South, like Dhaka, remain understudied[14]. Recent global assessments indicate that urban canopy cover varies widely across regions due to differences in climate, planning, and investment in green infrastructure[7,12,13]. Cities in the Global North often report substantially higher canopy levels. For example, Washington, DC has an estimated 28.6% tree canopy, and national assessments in Canada show many urban areas sustaining canopy in the 20–30% range, supported by long-standing urban forestry programs and canopy targets[17–19]. Sales et al. (2023) demonstrated this variation within the United Kingdom, where urban tree canopy cover ranged from 11.8% in Northern Ireland to 18.1% in Wales[20]. Broader synthesis further revealed that access to canopy and associated tree benefits remained consistently higher and more stable in the Global North, while similar access declined in many Global South cities over the past two decades[21]. In contrast, rapidly urbanizing regions of South America reported canopy level below 20% in more than half of its cities due to climate, geographic factors, and mounting development pressure[22], Similar patterns were documented across Southeast Asia, where cities such as Kuala Lumpur in Malaysia, Jakarta in Indonesia, and Metro Manila in the Philippines experienced reductions in greenspace from 45% to 20% over the 25 years period[23]. Taken together, these studies show that Global South cities, in comparison with Global North, generally maintain much lower canopy cover, experience uneven access to green space, limited institutional and financial resources, and intense anthropogenic pressures.[24] Against this global backdrop, establishing Dhaka's first urban tree inventory, provides critical baseline data which is a much-needed effort to align local efforts with international best-practice trends for sustainable urban development and to fill a critical data gap.

According to publicly available data, vegetated areas, hereafter defined as green spaces, of Dhaka primarily consist of 54 parks and one botanical garden, rooftop gardens, and roadside vegetation[25,26]. The city features 61.45 km of primary roads and 108.2 km of secondary roads, with significant roadside vegetation citywide[27]. However, tree cover and green spaces in Dhaka are declining, primarily due to an increasing population and relentless demands on infrastructure, often followed by unplanned urbanization[28]. According to the Population and Housing Census, Dhaka's population increased by nearly five million between 2022 and 2021[29]. The unprecedented population growth in recent decades is mainly fueled by increasing rural-to-urban migration, with nearly half a million people moving to Dhaka each year[30,31]. The migration influx has strained available land, creating an urgent need for housing, infrastructure, and commercial establishments[28,32]. Although the greater Dhaka area occupies just 1% of the national territory with an area of 1,528 km^2, the city and its suburbs are home to over 10% of the country's total population and 36% of the total urban population[33,34]. Rampant tree felling, prioritizing brick works and infrastructure over greeneries, encroachments on parks and open areas, and inadequate efforts to maintain greenery have left Dhaka in an unhealthy and unbalanced urban environmental condition[35]. One study estimated that land cover changes from 2000 to 2020 in Dhaka, included a 5% decrease in vegetative cover and a 14% increase in built-up areas, resulting in a subsequent 7.24°C increase in Land Surface Temperature over the same period[36].

Prior to the current study, there was no urban tree inventory in Dhaka, making it challenging to accurately assess the overall extent, condition, and value of trees in the city. As such, researchers have relied on global datasets and remote sensing techniques. For example, using remote sensing, Endreny et al.[37] estimated that Dhaka had between 18% and 23% tree cover. For vegetation cover, which is somewhat different than tree cover, Nawar et al.[35] estimated that "healthy" vegetation cover decreased from 17% in 1989 to only 2% in 2020. Shammi et al.[38] estimated 16% vegetation cover for Dhaka North City Corporation, the result of a 65.9% decrease in vegetation cover and a 95% increase in urban areas from 1992 to 2022. Collectively, these studies have helped to highlight the impact of declining tree cover and green spaces. Yet, the variability of tree cover estimates that rely primarily on satellite imagery makes it difficult to establish a baseline for monitoring. This complicates what decision makers can do with the information. They also fall short in capturing detailed information on urban tree resources, such as vegetation structure, species composition, diversity, and associated ecosystem services.

In contrast, a field-based urban tree inventory, supplemented with tree valuation tools such as i-Tree and mapping initiatives, offers a reliable alternative to accurately represent the resources and economic value provided by urban trees. The i-Tree Eco model has emerged as a de facto standard for quantifying the benefits of urban trees, and its adoption now spans multiple continents[39,40]. Co-developed by the United States Department of Agriculture Forest Service (USFS) and Davey Institute, i-Tree Eco integrates field inventory data with local environmental variables and land uses to estimate the economic value of services including air pollution removal, carbon sequestration potentials, surface runoff reduction, oxygen production, and more. Its rigorous, peer-reviewed, and scientifically validated methodology has encouraged researchers in North America, Europe, Asia, and beyond to apply i-Tree Eco to estimate their urban tree benefits[13,41–43]. Researchers have also extended the capabilities of i-Tree Eco by coupling its outputs with Geographic Information System (GIS) and statistical programming tools to gain finer insights[39].

This study, based on stratified random field measurements, established Dhaka's first comprehensive baseline information for tree resources, including species composition, vegetation structure, and the ecosystem services provided by the urban trees. Specifically, we address three interrelated research questions: (1) What is the current urban canopy cover of Dhaka? (2) What is the taxonomic composition, structural characteristics, and origin (native versus exotic) of the city's urban tree population? (3) What is the approximate economic value of major ecosystem services provided by these trees? We used i-Tree Eco, spatial datasets, and R programming to enrich our urban tree inventory analyses and enhance the scientific foundation of the overall assessment. We collaborated with the Bangladesh Forest Department, Green Savers, Davey Institute, and the USFS, through their implementation of the USAID-funded Community Partnerships to Strengthen Sustainable Development (Compass) program, to customize i-

Tree Eco for Dhaka's local context. The findings provide crucial data for informed decision-making, enabling authorities to set tree cover goals, execute robust monitoring of tree cover change, and identify areas with the greatest potential for urban greening. Inventory-derived metrics may also justify investments for enhancing urban greenery, support funding proposals, and integrate green infrastructure into development plans[44,45]. Having a tree inventory reflects progress along the continuum from initial urban forestry efforts towards a fully developed and institutionalized urban forestry program[45]. Ultimately, this study lays the groundwork for evidence-based strategies to protect existing urban tree resources, enhance urban resilience, and promote environmental equity across Dhaka.

2. Methods

2.1. Study area

The research area is Dhaka, Bangladesh, the world's most densely populous megacity[46]. Dhaka spans from 23.58° N to 23.90° N latitude and 90.33° E to 90.50°E longitude[47]. It is subdivided into two administrative units - Dhaka North City Corporation (DNCC) and Dhaka South City Corporation (DSCC), covering an area of 194.2 km^2 and 109.24 km^2, respectively. Both the DNCC and the DSCC are overseen by political units and were established under the Local Government (City Corporation) of Bangladesh Act 2009, Amendment 2011, and governed by elected mayors. Over the last several decades, urban areas have expanded by 17%, which altered the city's land uses and landscapes at the cost of its green spaces and wetlands[48]. Such expansions resulted in reduced canopy cover, increased UHI effect, air pollution, and seasonal flooding, to name a few. A large part of both city corporations such as Mirpur, Tejgaon, and old Dhaka are the worst victims of UHI[49,50]. Poor air quality is a persistent concern for Dhaka and frequently measures particulate matter ($PM_{2.5}$) at about 112.49 $\mu g/m^3$ which exceeds both the national and global standards[51]. The city experiences a humid subtropical monsoon climate, which is characterized by high temperatures, humidity, and rainfall. The monsoon, from June to September, contributes nearly 80% of the country's annual rainfall, which often causes flooding in large parts of the city[52,53]. On the other hand, dry winter months witness accumulated air pollution levels since low seasonal rainfall is insufficient to disperse airborne pollutants effectively.

2.2. Preparations and Fieldwork

2.2.1. Establishing Experimental Land Use Zoning

Dhaka's land cover is heterogeneous, which largely influences ecosystem services[54], and it is helpful to stratify the areas into homogeneous zones before applying a sampling strategy[55]. Therefore, we created land cover zones based on high-resolution worldview satellite imagery (0.5m spatial resolution) using the Support Vector Machine (SVM) algorithm, a commonly used non-parametric imagery classifier[56–58]. Considering the tree occurrence and homogeneity of the urban areas, the land cover classes were categorized into three zones (what we considered as strata): Trees, Scatter, and Others. Tree patches greater than an area of 400 m^2 were included in the Tree zone, which covered 1,636 ha in DNCC and 1,201ha in DSCC. The Scatter zone, characterized by tree patches ranging from 200 m^2 to 400 m^2, occupied 11,445 ha in DNCC and 1,304ha in DSCC. The remaining areas were included in Others zone, which occupied 5,209 ha in DNCC and 6,974ha in DSCC (details in the supplementary material S1). In addition to improving sampling efficiency, our zoning system, considering tree occurrence, also offers operational and planning advantages. Such as Trees zone typically consists of parks or fenced areas, mostly managed by government authorities, where protection and maintenance are prominent than re-greening needs. The Scatter zone is often located within institutional compounds or residential neighborhoods, where community engagement is central to sustaining Dhaka's urban forests. The Others category captures areas with the greatest potential for future government-led greening interventions.

Thus, these zones constitute broader categories defined by the presence and spatial configuration of trees, rather than conventional land-cover classes, and were used as strata in the sampling design of this study.

2.2.2. Sampling Design

We used i-Tree Eco to conduct this urban tree inventory in the metropolis of Dhaka. The i-Tree Eco is a freely accessible tool that adequately estimates and quantifies the multifarious benefits trees confer upon communities[41,59]. Given that stratified random sampling increases the accuracy in heterogeneous areas[60–62], i-Tree Eco was configured to a stratified random sampling where Trees, Scatter, and Others were the three strata. After delineating strata on the map, random points were generated within each zone using ArcGIS Pro for locating the sample plots (Figure 1). The sample plots were circular with 11.35 m radius (0.04047 ha or 0.1 acre) as per recommendation in the i-Tree Eco guidelines[63–65].

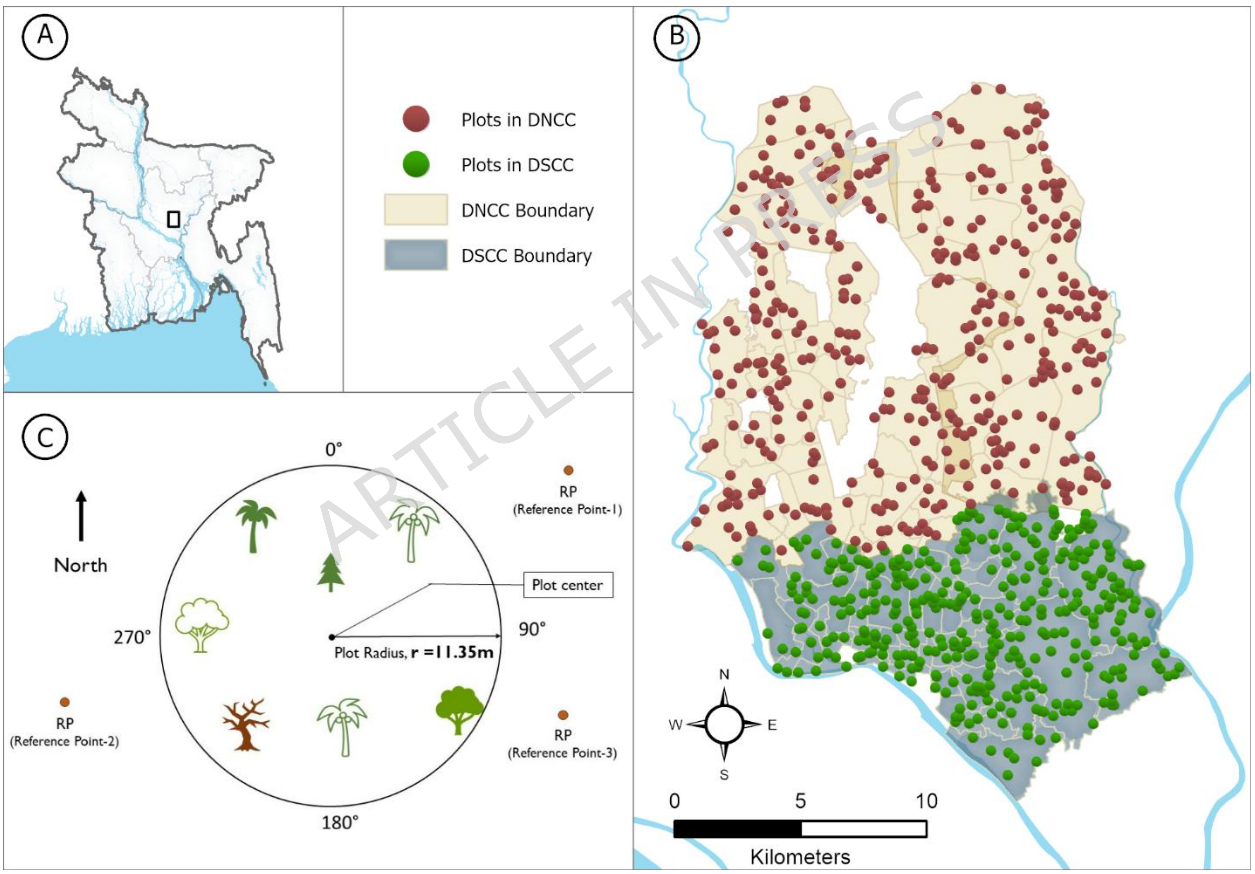

Figure 1: Study area (A) location in Bangladesh, (B) plot distribution in DNCC and DSCC and (C) schematics of sample circular plot with a radius of 11.35m, reference points are permanent landmarks used to triangulate the location of the plot center using the GPS coordinates of the points.

To determine the sample size within each strata, we used Cochran's formula[66,67] as shown in Equation 1,

$$\text{Sample size} = \frac{z^2 \times \mathrm{p}(1-p)}{e^2} \quad \text{-----------------------Equation 1}$$

N = population size
e = margin of error (5%)
z = z-score (derived z-score for 95% confidence level was 1.96)
p = proportion (0.5)

As per the sampling design, we aimed to visit and measure a total of 756 plots for Dhaka (386 for DNCC and 370 for DSCC). Due to access limitations, we were able to collect data from 697 plots, of which 344 from DNCC and 353 from DSCC (details in supplement table S2). The access limitations were either from security restrictions for critical government infrastructure or because of limited access to private property. Despite this limitation, the achieved sample size remains robust and suitable for Dhaka's inventory. The USDA Forest Service Forest Inventory and Analysis (FIA) program recommends at least 200 plots for urban forest assessment in a city[68]. With the archived 697 plots for data collection, we calculated the overall standard error for this study using Equation 2 suggested by i-Tree developers[69], which is 6.48%.

$$SE_{des} = SE_{exp} \cdot \sqrt{\frac{N_{exp}}{N_{opt}}} \quad \text{-----------------------Equation 2}$$

SE_{des}= desired standard error (%)
SE_{exp} = expected standard error (%), as found by Nowak et al[64]., which is 12.1
N_{exp} = number of plots used to determine SE_{exp}, which is 200
N_{opt} = achieved sample size of the study area

2.2.3. Plot and tree data collection

We collected the sample plot inventory data during the period spanning September 2021- February 2023. A team of 40 graduate students with academic backgrounds in Forestry, Environmental Science, Geography, and Botany was recruited to support our fieldwork. They were trained for 4 days on theoretical and practical aspects of tree attributes, definition, and instrument usage for inventory data collection. We used diameter tape for tree diameter at breast height (DBH) measurement, laser range finder for height measurement, measuring tape, and distance measurement equipment (DME) for laying the plots and distance measurements. See Figure S3 in the supplement materials for a complete list of instruments and associated usage. Tree attributes collected from sample plots include the tree species name, horizontal bearing from the plot center, DBH (up to six stems in case of trees with multiple stems emerging below 1.3m height), tree total height, crown base height, crown width, canopy missing, canopy dieback, and crown light exposure. Additional attributes included information about tree ownership, roadside presence, and the nature of ground cover under the trees. The data collection form is available in S4. Two taxonomists consistently supported field team to identify the right floral species in the plots. Beyond individual tree details, we collected plot-specific information, such as actual land use, ground cover, reference objects, and coordinates using GPS. Land-use and ground cover categories and definitions are listed on S5. To ensure the accuracy of collected data, a separate Quality Assurance and Quality Control (QA/QC) team from BFD conducted hot checks of 10% of the plots, and cold checks of 6% of the plots, and updated the plot data respectively where needed. Hot Checks are in-field quality assessments conducted during data collection that allow QA/QC experts to provide real-time feedback. Cold Checks happen later through a subsequent visit to a plot, when QA/QC team revisits a plot and independently verifies the original recorded data.

2.3. Analytical framework

2.3.1. Forest Structure, Diversity, and Attributes

We used the R (version 4.0.2) to estimate key tree inventory derivatives like vegetation structure metrics, phytosociological attributes, and diversity indices (Table 1). Structural attributes, such as tree density, basal area, growing stock, above and belowground biomass, were analyzed to provide insights into urban tree stand dynamics, biomass productivity, and carbon stock potentials. Phytosociological attributes, such as density, relative density, frequency, relative frequency, abundance, relative abundance, and importance value index, were estimated to understand the composition, dominance, and spatial distribution of the tree species. In addition, an Importance Value (IV) was calculated as the sum of the percent population and percent leaf area. As indicators of ecological stability and species richness, we computed diversity indices like Shannon-Wiener Diversity Index, Margalef's Richness Index, Simpson's Dominance Index, and Pilou's Evenness Index. The exotic and native trees were identified based on the existing literature and records indicating their history of occurrence, as well as by consulting with national experts and taxonomists.

Table 1: Analytics, attribute, and methodological details related to the measurement of urban trees of Dhaka, adopted from Bangladesh Forest Inventory[70]

Analytics	Attribute	Methodological details
(a) Vegetation structure	Tree Density [trees ha^{-1}], D_{TPH}	$D_{TPH} = \frac{N_k}{A_k}$, where N_k is the number of trees in plot k *and* A_k is an area of plot k in ha.
	Basal Area [m^2], BA	$BA = \pi \times \frac{D^2}{4}$, *where* D is the diameter at breast height in m.
	Growing Stock [m^3], V_g	$V_g = \frac{D^2}{4} \times \pi \times H_{tot} \times f_{gross}$, where D_{bh} is tree diameter at breast height (m) and greater than 10 cm, π is 3.1416, H_{tot} is tree total height (m), and f_{gross} is average form factor of trees 0.693
	Aboveground Biomass [kg], Y_{agb}	$Y_{agb} = 0.0673 \times (\rho D^2 H)^{0.976}$, where ρ is average wood density 0.6133782 g cm^{-3} adopted from BFI[70]. D is diameter at breast height in cm, and H is total height in m
	Belowground Biomass [kg], Y_{bgb}	$Y_{bgb} = exp[-1.0587 + 0.8836\, ln(Y_{agb})]$, where $Y_{agb})$ is aboveground biomass
	Zonal mean, $\bar{y}_h$	$\bar{y}_h = \frac{\sum_{i=1}^{n_h} y_{hi}}{n_h}$, where y_{hi} is value of i-th unit and n_h is sampled units in zone h
	Stratified mean, $\bar{y}$	$\bar{y} = \sum_{h=1}^{k} W_h \bar{y}_h$, where W_h is weight of zone h, k is total zones, and $\bar{y}_h$ is mean of zone h
	Zonal variance, s_h^2	$s_h^2 = \frac{1}{n_h - 1} \sum_{i=1}^{n_h} (y_{hi} - \bar{y}_h)^2$, where y_{hi} is observation i in zone h, and $\bar{y}_h$ is zonal mean
	Stratified variance, $Var(\bar{y})$	$Var(\bar{y}) = \sum_{h=1}^{k} W_h^2 \left(1 - \frac{n_h}{N_h}\right) \frac{S_h^2}{n_h}$, where n_h is sample size and N_h is population size in zone h and S_h^2 is zonal variance
(b) Phytosociological attributes	Density, D	$D = \frac{a}{b}$, *where a is the number of individuals of the i[th] species and b is total number of quadrats*
	Relative density, RD	$RD = \frac{a}{M} \times 100$, where *M is total number of individuals of all the species in the area of interest*
	Frequency, F	$F = \frac{c}{b}$, where *c is the total number of quadrats in which the species occurred*
	Relative frequency, RF	$RF = \frac{F_i}{\sum_{i=1}^{S}(F_i)}$, where F_i *is frequency of i-th species and S is number of species.*
	Abundance, A	$A = \frac{a}{c}$, *where a is the number of individuals of the i[th] species and c is the total number of quadrats*
	Relative abundance, RA	$RA = \frac{A_i}{\sum_{i=1}^{S}(A_i)}$, where A is abundance
	Importance Value Index, IVI	$IVI = RD + RF + RA$
(c) Diversity indices	Shannon-Wiener Diversity Index, H	$H = -\sum_{i=1}^{S} P_i(\ln P_i)$, where Pi is proportional occurrence of i-th species and S is total number of species
	Margalef's Richness Index, R	$R = \frac{(S-1)}{\ln(M)}$, where S is total number of species and M is total number of individuals of all species
	Simpson's Dominance Index, S_D	$S_D = \left(1 - \frac{\sum_{i=1}^{S} a_i(a_i - 1)}{M(M-1)}\right)$, where a_i is number of individuals of i-th species and M is total number of individuals of all the species
	Pilou's Evenness Index, E	$E = \frac{H}{\ln(S)}$, where H is Shannon-Wiener Diversity Index, and S is total number of species

2.3.7. Ecosystem services and benefit estimates

Ecosystem services and benefits were quantified using the i-Tree Eco (version 6.0.32) tool, which has been extensively used for similar applications globally[39]. The model integrates inventory field data, city information, local air pollution, and local rainfall data to estimate the environmental benefits of a given urban forest area[41]. In this study, estimated ecosystem services were air pollution removal, avoided runoff, and carbon sequestration. Also, supply of oxygen production was estimated but this ecosystem service was not valued in monetary terms[59]. i-Tree Eco uses peer-reviewed model equations based on long term ecological research to quantify ecosystem services. Core inputs required for the models are species information and stem DBH from the sample plots. Additional tree attributes of condition, structure, and spatial context increase model accuracy. Graphics S5 in the supplement provides an overview of i-Tree-Eco attributes and associated relations, adopted from the US Forest Service i-Tree documentation by Nowak[59]. For localized estimates, it is crucial to use local air quality and precipitation data. Hence, we used air quality data from the Department of Environment (DoE) for the period of 2012 to 2019. This dataset contained hourly pollutant measures of Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), Ozone (O_3), PM_{10}, $PM_{2.5}$, Sulfur Dioxide (SO_2). Rainfall data were obtained from the Bangladesh Meteorological Department (BMD) for 2015 to 2020, and the most recent data were used for this analysis. These datasets were processed and integrated into the i-Tree database, following the template as required to enable localized ecosystem modeling and analysis.

All ecosystem services were quantified using field inventory data and ancillary information specific to Dhaka. During the monetary valuation process, the best available local economic data were applied first, and the remaining parameters were taken from the i-Tree Eco default values for tropical regions. For example, the electricity price was based on the average local rate of USD 0.07 per kWh, and the carbon price was set at USD 15.78 per metric ton of carbon[71,72]. This approach aligns with global practice, as researchers using i-Tree Eco typically combine local prices with model default values when local data are unavailable[73,74]. In our case, unit value of removing one metric ton of each pollutant was calculated as follows: CO at USD 1,607.61 per metric ton, O_3 at USD 11,319.63 per metric ton, NO_2 at USD 11,319.63 per metric ton, SO_2 at USD 2,771.00 per metric ton, $PM_{2.5}$ and PM_{10} at USD 7,555.06 per metric ton. For avoided stormwater runoff, the valuation was based on USD 2.36 per m^3. While these figures provide a basis for estimating the economic benefits of ecosystem services, they rely on model assumptions. Therefore, the resulting monetary valuations represent indicative economic benefits rather than exact financial savings.

3. Results

3.1. Urban tree baseline of Dhaka

3.1.1. Species richness and structural composition

This inventory finds the urban forest of DNCC has an estimated 682,810 ± 66,181 trees with a tree cover of 10.5%. The three most common occurring species are *Mangifera indica* (17.2%), *Swietenia mahagoni* (16.9%), and *Cocos nucifera* (8.2%). On the other hand, DSCC has an estimated 616,947 ± 48,446 trees with a slightly higher tree cover of 10.8%. The three most common species are *Mangifera indica* (33.3%), *Cocos nucifera* (10.2%), and *Swietenia mahagoni* (9.3%). A total of 110 species belonging to 33 families were found, of which 73 species (under 30 families) were found in DNCC and 82 species (under 32 families) in DSCC (S7 and S8). Species occurrence varied significantly among zones, indicating spatial variations in diversity across the city. A higher number of both native and exotic tree species were found in the residential areas (S9), likely due to individual houseowners' preference for plant species selection. Many households prefer to plant exotic fruiting and ornamental species in their house premise and rooftop gardens. While higher tree diversity can minimize the risk of widespread damage from species-specific pests or diseases, the presence of exotic species, especially invasives, can potentially out-compete and displace native species. Tree species of only approximately 38% in DNCC and 36% in DSCC are native to Bangladesh. This highlights the need for careful species selection and urban forestry planning to balance diversity with ecological integrity. In terms of forest structure and maturity, tree DBH in Dhaka ranges from 10 to over 121.9 cm. The largest proportion of trees falls within three DBH classes: 15.2-30.5 cm, followed by 10-15.7 cm and 30.5-45.7 cm, indicating a predominance of mid-aged tree stands in the city.

3.1.2. Leaf area, tree density, and basal areas

Among the different zones across both city corporations, the Tree zone exhibited the highest leaf area, followed by Scatter and Others zones. In DNCC, the most dominant species in terms of total leaf area are *Swietenia mahogani*, *Mangifera indica*, and *Swietenia macrophylla*. In DSCC, the dominant species contributing to leaf area are *Mangifera indica*, *Swietenia mahogani*, and *Albizia procera*. Tree density and basal area varied significantly across zones, and land uses within Dhaka. Most trees were concentrated in Tree zones for both DNCC (235 ± 32.70 stems/ha) and DSCC (254.95 ± 27.15 stems/ha). In DNCC, the tree density is almost six times higher in Tree zone than that's of whole city corporation area (Table 2). On the other side, in DSCC, the Tree zone has almost four times the average density of the city corporation as a whole. In contrast, Scatter zone primarily consisted of built-up areas, exhibited significantly lower tree densities. For example, DNCC's Scatter zone has a sparse distribution of 16 ± 2.63 stems/ha, reflecting fragmentation of the urban green space in these areas. Similarly, Tree zones have the highest basal areas, particularly in DSCC, where the average basal area reached 17.70 ± 2.68 m^2/ha. This suggests the presence of larger and more mature trees in these areas. Combining all zones, we found DSCC exhibited higher overall tree density (64.34 ± 6.51 stems/ha) and basal area (3.88 ± 0.48 m^2/ha) than DNCC, indicating a relatively better-developed urban forest structure in the southern part of the city. In terms of land-use, Parks had the highest tree density and basal area within DNCC, whereas graveyards showed the highest values for both parameters in DSCC (Figure 2). In addition to dominant species, other trees with high Importance values (IV) in Dhaka include *Artocarpus heterophyllus, Albizia lebbeck, Peltophorum pterocarpum, Syzygium cumini, and Moringa oleifera*. These species contribute significantly to the structure and function of urban green spaces across Dhaka (a list of ten species with the highest IVs is provided in S10).

Table 2: Tree density and basal area as per zones

Sl	**Zone**	**Tree density in stem/ha (Mean ±SE)**		**Basal area in m²/ha (Mean ±SE)**	
		DNCC	**DSCC**	**DNCC**	**DSCC**
1	Tree	235 ± 32.70	254.95 ± 27.15	13.32 ± 1.82	17.70 ± 2.68
2	Scatter	16 ± 2.63	111.95 ± 19.19	0.73 ± 0.14	4.83 ± 0.90
3	Others	22 ± 4.71	22.62 ± 3.53	1.14 ± 0.29	1.33 ± 0.23
All Zones		37 ± 4.49	64.34 ± 6.51	1.97 ± 0.25	3.88 ± 0.48

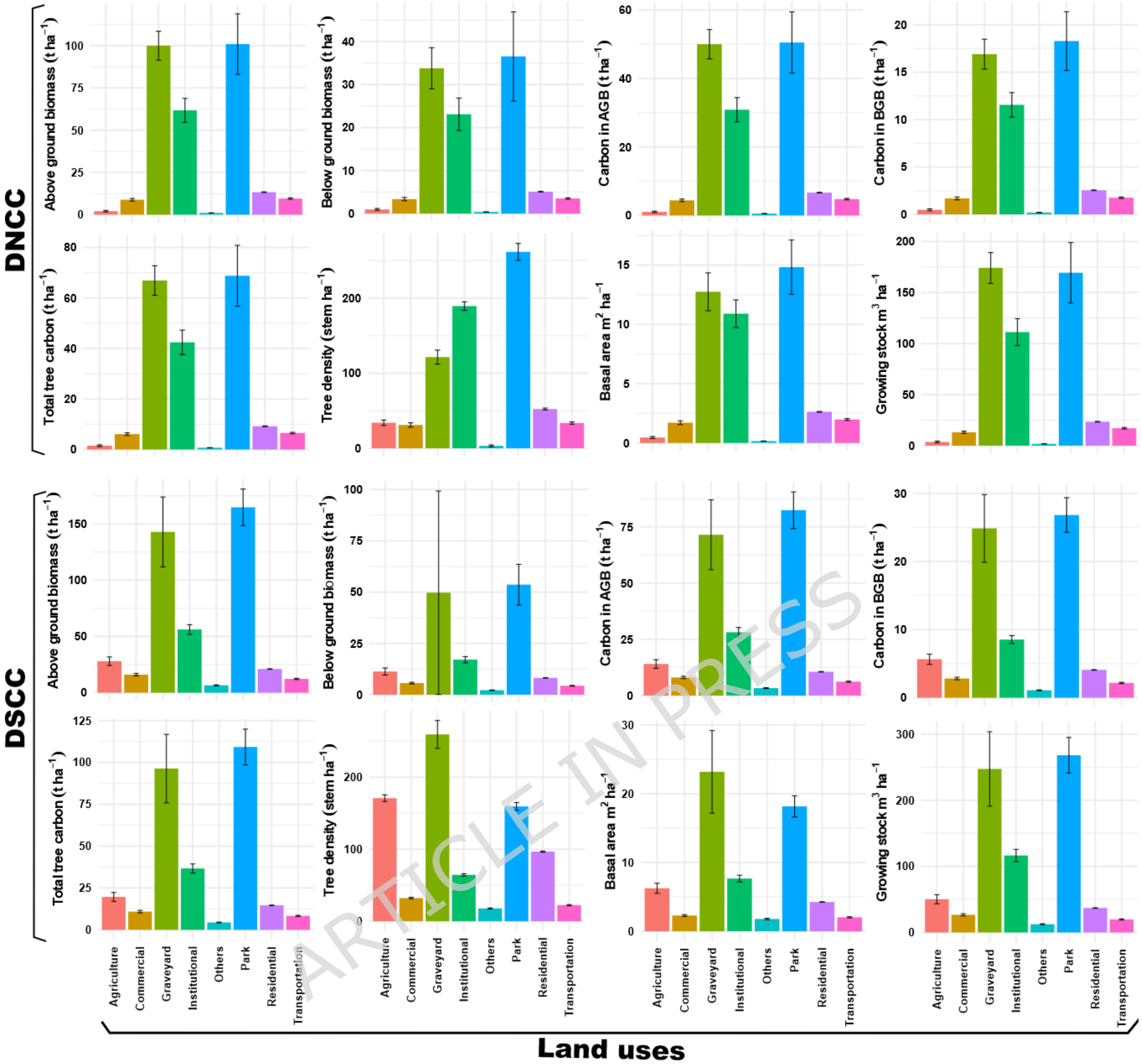

Figure 2: Land use segregated values of aboveground biomass, belowground biomass, Carbon in aboveground biomass, carbon in belowground biomass, total tree carbon, tree density, basal area

3.1.3. Phytosociological attributes

The phytosociological attribute of species indicated that both DNCC and DSCC are dominated by a few key species, with *Mangifera indica* consistently exhibiting the highest relative density, frequency, abundance, and Importance Value Index (IVI) regardless of land use types and zones. In DNCC, *Mangifera indica* and *Swietenia mahogani* were the most frequently occurring species, together contributing over 40% of the relative density, particularly in tree and Scatter zones (Figure 3). Similarly, in DSCC, *Mangifera indica* alone accounted for more than one-third of the total tree population across zones, with peak IVI values reaching 63.88% in the Scatter zone. Other species such as *Cocos nucifera*, *Artocarpus heterophyllus*, and *Swietenia macrophylla* showed moderate dominance. The dominance of a few species, indicated by their high IVI values, suggests a relatively low species evenness that urges for a promotion of the rare species occupying the lower end of the IVI to prevent them from disappearance locally (more on supplemental table S11 and S12). This can potentially enhance the value of Dhaka's urban green spaces in terms of biodiversity and ecological resilience.

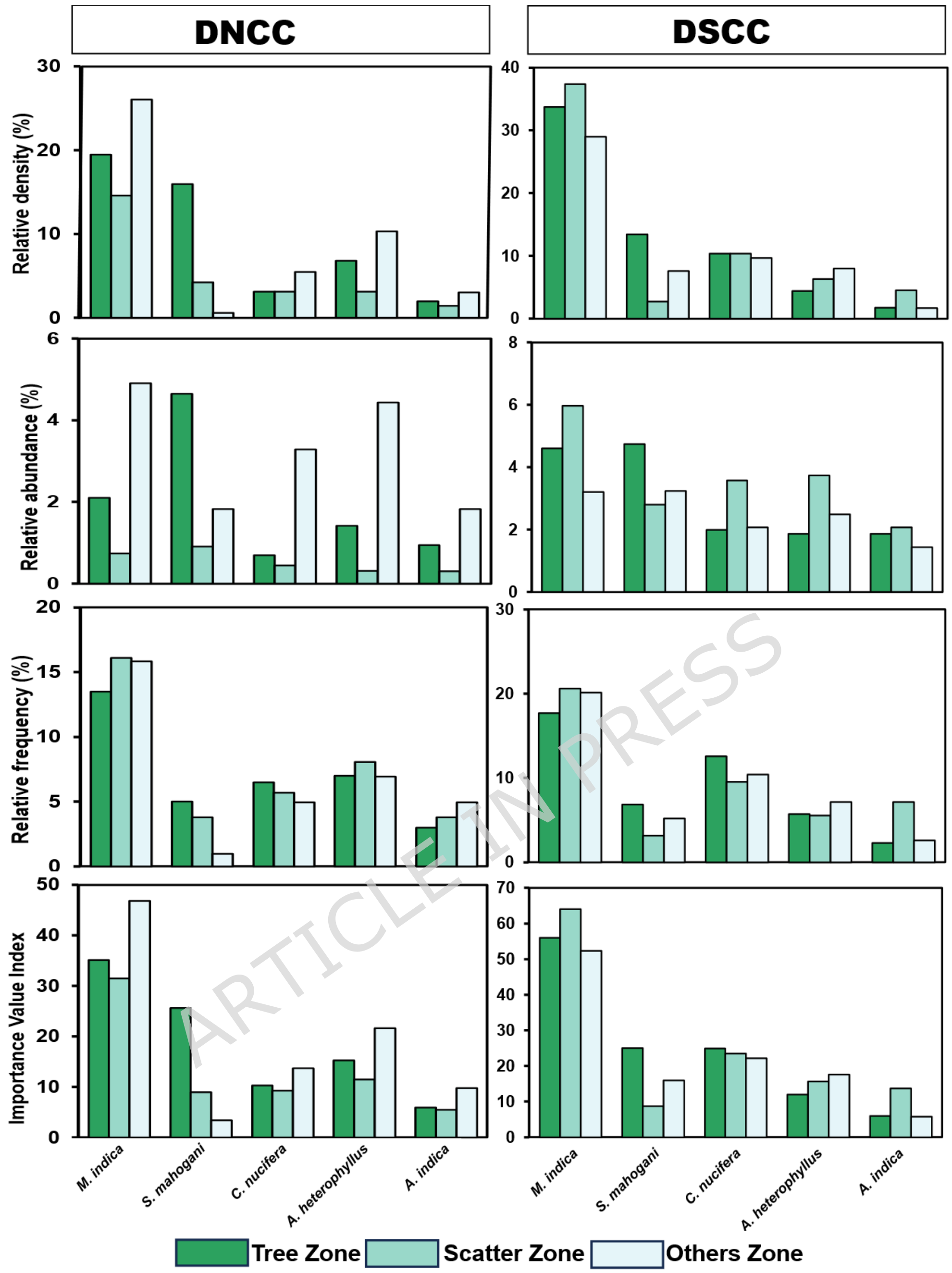

Figure 3: Phytosociological attributes namely relative density, relative frequency, relative abundance, and importance value index of DNCC (left) and DSCC (right)

3.1.4. Biomass and Carbon

In both administrative regions of Dhaka, the spatial distribution of biomass and carbon pools exhibited distinct but complementary patterns across land use types. Parks recorded the highest levels of aboveground biomass (AGB), belowground biomass (BGB), aboveground carbon, belowground carbon and total tree carbon per ha (70 metric tons in DNCC and 110 metric tons in DSCC), followed by graveyards and institutional premises (Figure 2). These findings highlight the positive influence of enhanced protection, reduced anthropogenic disturbance, and active maintenance practices typically associated with fenced or managed green spaces. The dominance of these land-use types in carbon storage suggests that the most mature and long-standing trees in Dhaka are concentrated within those areas. The second tier of carbon stock contributors included agricultural, commercial, residential, and transportation-related land uses, with total tree carbon ranging from 2 - 8 metric tons per ha in DNCC and 8 - 18 metric tons per ha in DSCC. While biomass and carbon value in residential premises remained relatively consistent between two city corporations, the key differentiating factor was the substantially higher carbon reserves in parks and graveyards in DSCC compared to DNCC, likely due to more established vegetation and greater canopy continuity. Looking at the zonal statistics, Tree zones held the highest carbon, averaging 54.88 ± 8.73 metric tons per ha in DNCC and 74.02 ± 10.96 metric tons per ha in DSCC (S13). Similar patterns were observed for the aboveground carbon pool, which was nearly double in DSCC compared to that of DNCC. In contrast, the Scatter zone which was largely characterized by built-up areas, stored considerably lower tree carbon stocks, ranging from 2.27 – 16.78 metric tons per ha in both cities. Overall, DSCC demonstrates a higher potential for biomass-based carbon sequestration, reflecting the presence of older, denser, and well-maintained urban green spaces.

3.1.5. Growing stock

Growing stock distribution across Dhaka's urban forests showed clear spatial variation, with DSCC consistently recording higher timber volumes than DNCC, across land use types and vegetation zones. At the zone level, Tree zones accounted for the largest share of growing stock, amounting to 227,743 m^3 in DNCC and 236,890 m^3 in DSCC. Despite occupying a smaller spatial extent, the Scattered zone exhibited timber volume of 43.72 m^3/ha in DSCC which is much higher compared to DNCC with 5.70 m^3/ha growth stock, indicating relatively better urban greening in fragmented built-up areas of DSCC. Land uses categorized as Others, A zone also contributed modest growing stock in both city areas (DNCC: 10.32 m^3/ha, DSCC: 12.11 m^3/ha). Among the land uses, parks and institutional premises emerged as the dominant contributors to growing stock in both city corporations. Interestingly, graveyards in DSCC also held high growing stock, contrasting with lower growing stock in DNCC. The total growing stock was estimated at 346,686 m^3 in DNCC and 378,354 m^3 in DSCC, with Tree zones accounting for nearly two-thirds of the total in each city corporation.

3.1.6. Diversity indices of the tree species per zone of Dhaka

Tree species diversity across Dhaka was assessed using four standard ecological indices, revealing clear spatial variation between the two city corporations and across different zones (Table S14). The Shannon-Wiener Diversity Index was highest in the Scatter zone of DNCC (3.15), which indicates relatively greater species diversity, though it mainly consisted of fragmented built-up areas. In DSCC, Tree zone showed greater species richness, though with slightly lower Shannon value (3.01). Previous research on species diversity in Dhaka often categorizes a Shannon value above 3 as high diversity and values ranging from 2.1 to 3.0 as moderate diversity[75–77]. Margalef's species richness index highlighted differences in total number of species present, peaking in the Tree zone of DSCC (9.32) and the Scatter zone of DNCC (8.9). At city corporation-wide scale, DSCC supported slightly larger species pool than DNCC. Simpson's Dominance Index ranged from 0.84 to 0.93, with the highest value in DNCC's Scatter zone, reflecting a lower probability of the tree community being dominated by few species and a greater compositional balance. Pielou's Evenness index indicated relatively balanced species distribution across most zones, with the highest evenness recorded in the Tree zone of DSCC (0.89). Interestingly, while DSCC exhibited higher overall species richness (Margalef's index: 12.17 vs. 11.99), DNCC had higher evenness (Pielou's index: 0.76 vs. 0.67) and a marginally higher Simpson's index (0.92 vs. 0.86). Researchers using Simpson's value note that values close to 1 indicate higher diversity, while Pielou's index 0 stands for low and 1 for greater evenness[78]. Collectively, this pattern indicates that although DSCC harbors more species, the distribution is more uneven, possibly due to dominance by few species. Conversely, DNCC, despite harboring fewer species, maintains a more balanced structural composition - likely influenced by differences in land-use history, management practices, and urban development trajectories between the two city corporations.

3.2. Ecosystem Services of Dhaka's Urban Trees

3.2.1. Air pollution removal

Poor air quality is a common problem in densely populated megacities that pose threats to human health, degrade landscape materials, and interrupt ecosystem processes. Urban forests improve air quality by directly reducing air temperature and capturing airborne pollutants on leaf surfaces. This inventory quantified the annual air pollutant removal by trees and shrubs in Dhaka. The existing trees and shrubs were estimated to remove 319.3 metric tons of all pollutants annually in DNCC and 219.2 metric tons in DSCC. Among air pollutants, PM_{10} removal was highest in both city corporations, followed by $PM_{2.5}$, NO_2, O_3, SO_2, and CO. The economic value of the pollutant removal is estimated as USD 2.43 million in DNCC and USD 1.67 million in DSCC.

3.2.2. Carbon Sequestration

Trees in DNCC were estimated to store 98,700 ± 12,758 metric tons of carbon, valued at USD 1.56 million, while DSCC estimated carbon storage is slightly higher at 103,000 ± 11,413 metric tons of carbon, valued at USD 1.63 million. Among the inventoried species, *Swietenia mahogani* stored and sequestered the most carbon, approximately 21.4% of the total carbon stored and 19.6% of annual sequestration. In DSCC, *Mangifera indica* was the dominant contributor, accounting for approximately 22.2% of total carbon storage and 20.4% annual sequestration. Previous research by Jaman et al.[79] reported aboveground carbon stocks range from 45.47 to 193.50 Mg ha^{-1} in urban green spaces like parks, playground edges, botanical gardens, and roadside plantations of Dhaka, respectively. As a tree grows, the amount of carbon annually sequestered increases with the size and health of the tree. Gross carbon sequestration by trees in DNCC was estimated at 11,120 ± 1,230 metric tons of carbon per year, with an associated monetary value of USD 0.18 million. Similarly, gross annual sequestration of DSCC trees is about 10,800 ± 1,040 metric tons of carbon, with an associated value of USD 0.17 million.

3.2.3. Oxygen production

Oxygen production is one of the most cited ecosystem services provided by urban trees. A tree's net annual oxygen production is directly proportional to the amount of carbon it sequesters, which is closely linked to biomass accumulation. This study estimated that trees in Dhaka produced approximately 53,550 metric tons of oxygen annually, 26,420 metric tons from DNCC and 27,130 metric tons from DSCC. Among all species, *Swietenia mahogani*, *Mangifera indica*, and *Cocos nucifera* were the top three contributors to total oxygen production.

3.2.4. Avoided runoff

Surface runoff is a growing concern for Dhaka, as it transports pollutants into nearby streams, wetlands, lakes, and rivers. During rainfall, a portion of raindrops are intercepted by trees and shrubs, slowing them down, while the remainder reaches the ground. In densely built environments, impervious surfaces prevent water infiltration, thereby increasing the volume of surface runoff. Urban vegetation is critical in minimizing the problem by intercepting rainfall by aboveground parts, while the tree root system increases soil water infiltration and water retention. We estimated that the trees of DNCC reduce surface runoff by approximately 604,000 m^3 a year with an associated value of USD 1.39 million. On the other hand, trees and shrubs of DSCC help to reduce runoff by an estimated 378,000 m^3 per annum, valued at USD 0.90 million. We provided a consolidated comparison of key results for DNCC and DSCC of this study in Table 3.

Table 3: Summary comparison of key urban forest structure metrics and ecosystem service estimates between DNCC and DSCC

Key issues	**DNCC**	**DSCC**
Tree coverage	10.5 %	10.8 %
No of trees	682,810	616,947
Tree density	37 trees/hectare	65 trees/hectare
Dominating species	1. *Mangifera indica* 2. *Swietenia mahagoni* 3. *Cocos nucifera*	1. *Mangifera indica* 2. *Cocos nucifera* 3. *Swietenia mahagoni*
Carbon sequestration	11,120 metric tons (USD 0.18 million)	10800 metric tons (USD 0.17 million)
Carbon storage	98,700 metric tons (USD 1.56 million)	103,000 metric tons (USD 1.63 million)
Oxygen production	26,420 metric tons/year	27,130 metric tons/year
Pollution removal	319.3 metric tons/year (USD 2.43 million/year)	219.2 metric tons/year (USD 1.67 million/year)
Avoided runoff	604,000 m^3/year (USD 1.39 million /year)	378,000 m^3/year (USD 0.90 million/year)
Exotic vs Native	38% native	36% native

4. Discussion

This study represents Dhaka's first comprehensive urban tree inventory, establishing a much-needed baseline for understanding the structure, composition, and ecosystem services of the city's urban forests. The findings reveal that Dhaka's overall canopy cover is approximately 11%, half of the national average of 24%. The Bangladesh government[80] has a target of 25% national tree cover by 2030. The tree cover found in this study varies substantially from that reported by other studies. For example, Endreny, Sica, and Nowak found tree cover of Dhaka was 22.9% based on Google Earth photo interpretation, and 10.5% with moderate resolution (250m) based on NASA MOD44B imagery[37]. This study findings show similarity with neighboring countries like India, having slightly better urban tree cover in New Delhi (11.87%) according to the India State of Forest Report 2023[81]. Our estimate in Dhaka is within the lower range of tree cover among other cities that conducted field-based inventories like Dhaka's. For example, Washington DC, USA (28.6%) and Toronto, Canada (26.6%) were much higher, while San Francisco, USA (11.9%) was similar to Dhaka[18,82]. A widely endorsed urban forestry guideline is the 3-30-300 rule, which Dhaka can adopt to set its tree cover target and improve access to green spaces[83]. This rule recommends that a person should be able to see 3 trees from their residence, live in a neighborhood of

30% tree canopy, and green spaces are available within 300 meters. Similar field-based inventories in the Global North report higher canopy cover than Dhaka, as well as greater per-capita access to tree co-benefits; however, social inequities were also highlighted in the Global North. National and city-scale assessments in the United States and Canada show that tree cover is often lowest in hotter, lower-income neighborhoods, where additional canopy has the greatest potential to reduce heat-related health risks and improve environmental justice. These studies underscore the urgency of expanding tree cover in a dense, heat-vulnerable city such as Dhaka[5,9,40].

Despite the limited canopy, the urban forests of Dhaka showed floral diversity and delivered considerable environmental and economic benefits. Species richness was found to be moderate, with 110 tree species recorded citywide, although a substantial portion were exotic. Other research similarly estimates that 39-56% of Dhaka's urban trees are exotic[76,75,84]. Exotic species pose ecological risk, reduce resilience to pests, and increase vulnerability to climate variability[85]. A few species, particularly *Mangifera indica*, *Swietenia mahogany*, and *Cocos nucifera* were dominant and indicate limited species evenness. Although these species contribute to urban ecosystem services, a study by Pandey and Kumar[86] in Allahabad city, India, suggests that such structural homogeneity may reduce adaptive capacity, increase vulnerability to disturbance, and limit long-term ecological functionality. Promoting a wider variety of native species is crucial for robust ecosystem functions and a prerequisite to avail all ecosystem benefits of urban trees, which reduces pest outbreaks, and climate extremes[87,88]. . The findings of Martin et al. (2025) revealed how structural inequities in the density, size, and diversity of urban forests emerge even in high-income, Global North cities[89]. This suggests that prioritizing species diversification and equitable distribution is not only relevant for tropical megacities like Dhaka, but a broadly recognized need across urban contexts globally. Therefore, to increase native dominance in Dhaka, a comprehensive strategy to gradually replace exotic trees with locally adapted native species is a critical step in phasing out exotics. It will enhance ecological integrity without causing abrupt canopy loss. Complementing this, a mixed-species planting strategy prioritizing native species while allowing socially preferred, non-invasive exotics aligns with best practice in tropical urban forestry and improves both ecological fit and public acceptability[90]

The current study found considerable spatial variation in tree structure and services among different zones and land uses. Tree zones consistently, compared to the Scatter and Other zones, held the highest tree density, basal area, growing stock, biomass, and carbon across both city corporations. Parks and graveyards in DSCC, in particular, exhibited notably higher carbon storage, likely due to the presence of older and less-disturbed trees[79]. Researchers found that similar urban areas, like parks, playground edges, botanical gardens, and roadsides, concentrate the highest amount of carbon in urban areas due to the stand diversity[79,91]. On the other hand, a fragmented canopy or single stand offers less carbon concentration, particularly in soils[92]. These findings emphasize the need for long-term conservation of mature trees and advocate for mixed-species in fragmented-canopy areas like Scatter and Others zones as part of the city's greening strategies.

The diversity indices indicate that DSCC had higher overall species richness (Margalef's Index), but DNCC exhibited greater species evenness and slightly higher Simpson's dominance scores. This suggests that although DSCC hosts a wider variety of species, they were likely less evenly distributed. In contrast, DNCC supports a more balanced tree composition, potentially resulting from different management practices and urban development patterns. Researchers suggest a balance between richness and evenness is critical for ecosystem stability[93–95]. This underscores the importance of not only increasing the number of species planted but also ensuring they are distributed more evenly across Dhaka to support ecological integrity.

We found that trees in Dhaka play a critical role in mitigating urban air pollution by removing 538.5 metric tons of air pollutants annually, with the highest removal for PM_{10}, followed by $PM_{2.5}$. Researchers identified $PM_{2.5}$ and PM_{10} as the air pollutants of greatest concern for Dhaka[96,97]. According to an emission inventory, different anthropogenic sources emit 181,438.8 metric tons of air pollutants annually in Dhaka[98]. Trees are a natural buffer to neutralize atmospheric pollution, along with other government regulations to scale down Dhaka's atmospheric pollution. Previous studies identified native species like *Mangifera indica* among the most suitable tree species in Dhaka due to its air pollutant removal capacity and tolerance[99,100]. Beyond air pollution, Dhaka is a hotspot of urban flooding and waterlogging[53]. We found Dhaka's trees act as the interceptors of rainwater before it reaches the bare surface. They reduce nearly 982,000 m^3 of stormwater runoff per annum, which reduces the flood intensity. Urban vegetation enhances infiltration and provides localized flood mitigation in the urban built-up environment. This is critical, as Dhaka's flooding is leads to livelihood disruptions, climate vulnerability, river pollution, and degrades city living conditions[101,102]. Recent work on global urban-forest governance warns that while urban tree cover targets help, they fail to deliver long-term ecosystem services if tree health, species diversity, structural integrity, and equitable spatial distribution are not included as core considerations[15]. Ecological analyses of street trees in multiple Indian cities suggested that increasing structurally diverse native trees can enhance carbon storage, mediate heat, and support progress towards the Sustainable Development Goals[103]. So, prioritizing the native species, equity, distribution, and expanding the tree cover at least to the national average (24.4%) or a global benchmark of 30% would substantially confront Dhaka's dual challenges- air pollution and urban flooding.

Taken together, current findings highlight both the strengths and shortcomings of Dhaka's urban forest. While some areas, particularly parks, graveyards, and institutional premises, strongly support biomass and ecosystem services, the overall canopy cover and structural diversity remain inadequate for a city of Dhaka's size and climatic context. Expanding canopy cover, increasing the representation of native species, and diversifying plantings, particularly in densely populated neighborhoods to reduce reliance on a few dominant species should be core objectives in future greening strategies. These results provide a data-driven foundation to inform urban forestry planning, guide equitable resource allocation, and build long-term resilience to climate change and urban environmental stressors.

5. Conclusions and Recommendations:

Urban vegetation in Dhaka delivers a multitude of environmental and economic benefits, including air pollutant removal, carbon storage and sequestration, oxygen production, and stormwater management. These ecosystem services underscore the crucial role of urban trees in fostering ecological balance, urban resilience, and the well-being of city residents. This study presents the first comprehensive urban tree inventory for Dhaka, addressing a critical knowledge gap in urban forestry data. The findings reveal a moderate tree cover of 10.5% in DNCC and 10.8% in DSCC, which is considerably low for a tropical metropolis. Yet, despite limited canopy coverage, the estimated annual economic value of ecosystem services provided by Dhaka's urban trees is approximately USD 6.74 million, highlighting the value these green assets offer relative to their spatial footprint. However, the current urban tree population remains inadequate to support a healthy and resilient urban environment. To maximize benefits from urban green spaces in Dhaka, future planting and greening efforts should:

- Use the findings of this urban tree inventory to raise public and institutional understanding and clarity on urban green spaces and their essential role in environmental health, climate adaptation, and quality of life in Dhaka.

- Set tree cover goals for DNCC and DSCC, which will motivate action to create or update policies and engage partners and grass-roots efforts who care about the urban environment. The goals should be ambitious to reverse trends of decreasing tree cover, but also be practical and consider resources needed to sustain trees over their lifetimes.
- Develop plantation guidelines specific to the urban environment to provide a structured approach to urban tree planting, ensuring optimal environmental impact. Site-specific plantation guidelines can be formulated from the data of this urban forest inventory. The urban tree inventory reveals that certain tree species dominate, providing a majority of the city's environmental benefits, such as absorbing atmospheric carbon, neutralizing air pollution, and reducing surface runoff. These species are *Swietenia mahogani, Mangifera indica, Swietenia macrophylla, Albizia lebbeck, Peltophorum pterocarpum, Albizia procera, Syzygium cumini, Moringa oleifera*, and *Cocos nucifera*, which thrive due to their high survival rates, resilience to urban microclimates, and popularity among Dhaka residents. Planners and urban foresters should recognize the preference for these species to promote public interest in addressing environmental concerns through tree planting.
- Given the high prevalence of exotic species compared to native ones in Dhaka, there is a need for more emphasis on native species during urban plantation programs. We recommend a phased replacement of exotic species for Dhaka. This will enhance biodiversity and create habitats that are friendly to local bird species and other urban wildlife. Native plants are also better suited to local ecosystems, contributing to overall urban ecological health.
- The plan should also direct efforts towards specific plantation areas that seem most promising for planting trees, such as cemeteries and institutional premises. This targeted approach will ensure efficient resource allocation and maximize the impact of tree-planting initiatives.

For the sustained improvement of Dhaka's urban tree cover, the formulation of an urban greening master plan is crucial integrating the urban tree goals, guidelines, and inventories. This long-term strategy will outline targets and actions to systematically improve the city's green coverage. This will ensure coordinated efforts among stakeholders engaged in urban greening, maximizing the positive effects on the urban environment, aesthetics, and overall well-being of its residents. This study provides a foundational baseline for the city planners, policymakers, and researchers, facilitating evidence-based decision-making and integration of urban forestry in Dhaka's broader sustainable agenda. Investing in urban green infrastructure is not only ecologically imperative but also a cost-effective strategy for improving public health, climate resilience, and urban livability.

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CRediT author contribution statement

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Data availability statement

Analytical codes and data supporting the findings are available in the GitHub repository, and this paper's Supplementary Information. GitHub link : https://github.com/sahadeb-gis/DhakaUrbanTreeInventory. Should any raw files be needed, they will be made available from the corresponding author after this publication upon reasonable request.

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