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"Structural Assessment of Beirut's Urban Forest: Bridging Ecology and Urban Planning"

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Abstract:

Urban forests serve as a nature-based approach to promoting urban sustainability through the provision of diverse ecosystem services, notably temperature regulation, air pollution mitigation, carbon sequestration and broader environmental benefits. To enhance these ecosystem services, efficient management is imperative, necessitating an in-depth understanding of the determinants of arboreal growth and the constraints imposed by densely urbanized settings. In this study, we assessed the urban forest structure of Beirut using the I-Tree Eco model, establishing 200 sampling plots and conducting extensive field surveys to estimate leaf area and its spatial variability across the city. This study aimed not only to quantify the city's leaf area but also to elucidate the key drivers of foliar development across street trees and remnant forest stands, while formulating management strategies to foster a more resilient and sustainable urban canopy. Findings indicate that impervious surface cover is the dominant driver shaping Beirut's urban forest structure, acting as a social-mediated factor that governs biophysical conditions such as soil quality and microclimate, which in turn affect tree growth. Recommendations emphasize species selection, adequate planting spaces, and long-term sustainable management practices as key measures to enhance canopy cover and ensure the continued delivery of ecosystem services in Beirut's rapidly urbanizing landscape.

Key words: Urban forests, Ecosystem service, Impervious surfaces, Leaf area, Sustainable management.

Introduction:

Historically, ecological research primarily concentrated on "natural" systems located outside urban areas. However, with the rapid urbanization of the global population, scientists have increasingly recognized cities as significant ecosystems in their own right. Early investigations often regarded urban areas as disturbances, focusing on discrete natural elements within cities, such as parks, street trees, or rivers, while treating them as isolated from their surrounding urban context. Over time, the perspective shifted to conceptualize the entire city as an ecosystem, emphasizing the dynamic interactions between biophysical components e.g. vegetation, soils, water, and air and social processes e.g. human behavior, urban planning, economic activity, and governance (Fan et al., 2019). Rather than viewing humans as external agents disrupting ecological systems, this approach incorporates human activities and decision-making as integral elements of urban ecological structure and function.

Street trees, parks, woodlands, within urban areas, collectively define the "urban forest." Urban forests are intricate socio-ecological systems arising from the interaction between human activities and natural processes (D. J. Nowak, 1994). They provide services to urban dwellers. Optimizing the management of these ecosystems necessitates a detailed knowledge of urban forest structure and its linkage to its services. Urban forest structure describes the spatial distribution and organization of vegetation in relation to urban infrastructure, such as buildings and roads (Rowntree, 1984). It has been examined across a spectrum of scales, from broad evaluations of tree canopy and land-use patterns to detailed studies of individual trees. Research suggests that the quantity, quality, and composition of urban forests are strongly shaped by socio-economic factors, which act as primary determinants of species distribution and structural characteristics (Watkins et al., 2017). Moreover, numerous studies have further documented significant correlations between canopy cover and neighborhood socio-economic attributes (Landry & Chakraborty, 2009). This underscores the pivotal role of human management. Such management must prioritize specific ecosystem services provided by green infrastructure, for instance, air pollution mitigation (Escobedo et al., 2011).

Given Beirut's elevated air pollution levels (Farah et al., 2018), this study aims to quantify the urban forest structure to estimate the total leaf area and its spatial distribution across the city. Leaf area serves as a key indicator of tree growth and canopy cover and is an important arboreal attribute necessary to be determined when we want to evaluate the pollution removal by trees. Nevertheless, assessing leaf area alone is insufficient; identifying the driving factors behind leaf area development is crucial for understanding its spatial variability and determining is it predominantly influenced by socio-economic or biophysical factors? Thereby informing more effective urban planning strategies for Beirut.

Sampling designs have been widely employed to assess and quantify urban forest structure. This includes simple random sampling (SRS), systematic sampling (SS), and stratified random sampling (STR), which are the principal methods for quantifying forest attributes (Jin & Yang, 2020). Stratified sampling is generally providing more accurate estimates of population means or totals than non-stratified methods (Jin & Yang, 2020). However, this assumption may not always be valid due to the high heterogeneity often observed in urban forests. I-Tree Eco surveys represent a statistically robust sampling approach (D. J. Nowak et al., 2008) that includes trees on both public and private properties. Research indicates that using 200 circular plots of one-tenth acre (0.04 ha) can achieve a relative standard error of 12% for the total trees population (D. J. Nowak et al., 2008). As a result, these surveys offer a comprehensive and reliable evaluation of urban tree populations, providing greater insight for assessing urban forest sustainability than inventories that consider only public trees. Although widely applied in North America and Europe, the I-Tree Eco model has seen limited use in the Middle East.

In this study, we applied the I-Tree Eco model in Beirut to analyze the structural characteristics of the urban forest in the Methodology section. The Results section, we present the findings about the structure of Beirut urban forest, the spatial distribution of leaf area and the efficiency of this leaf area in removing air pollutants. In the Discussion, we interpret these results, discuss the driving factors of Lead area development across the city and propose policy recommendations to enhance the sustainability of Beirut's urban forest, thereby maximizing the ecosystem services it provides particularly its role in mitigating air pollution.

Methodology

2.1. Study Area

This research was conducted in Beirut, Lebanon, located along the eastern Mediterranean coast (35.58°88'54''E, 33.7°961'40''N). The city extends over approximately 1,980 hectares and hosts a population of about 2.379 million inhabitants (Beirut population review, 2025). Beirut is characterized by a Mediterranean climate and exhibits a dense urban fabric with limited green areas. Existing vegetation is largely confined to small parks, fragmented patches, and street trees. Officially protected wooded areas cover only 49 hectares, concentrated primarily within two sites: the historic pine forest and the campus of the American University of Beirut.

2.2. Application of a I-Tree Model

The I-Tree model, originally developed in the American United States (USA), was first applied within the American states but has since been extensively adopted across various European, American, and Asian countries (Nowak et al., 2013, Selmi et al., 2016 ,Bottalico et al., 2017, Wu et al., 2019, Andrew & Slater, 2014). Implementing this model necessitates significant adaptation, including the preparation of multiple databases encompassing meteorological, pollution, and geographical data. Initially, an American state with a climate zone analogous to that of Beirut was selected—California—due to its comparable climate. To compensate for absent vegetation species, a comparative assessment was performed between the model's existing vegetation database and the recorded flora of Beirut, after which the missing species were incorporated.

2.3. Sampling Approach and Field Survey Methods

A stratified random plot-based inventory was implemented across Beirut, consisting of 200 plots of 0.04 ha each (Figure 1). Two strata were delineated: forested area and urban areas. Given the homogeneity of Beirut's built environment, highly urbanized land uses were aggregated into a single "urban stratum." The number of plots (200) was selected by the modeler to achieve an optimal reduction of approximately 12% in the standard error of the total tree population (D. J. Nowak et al., 2008).

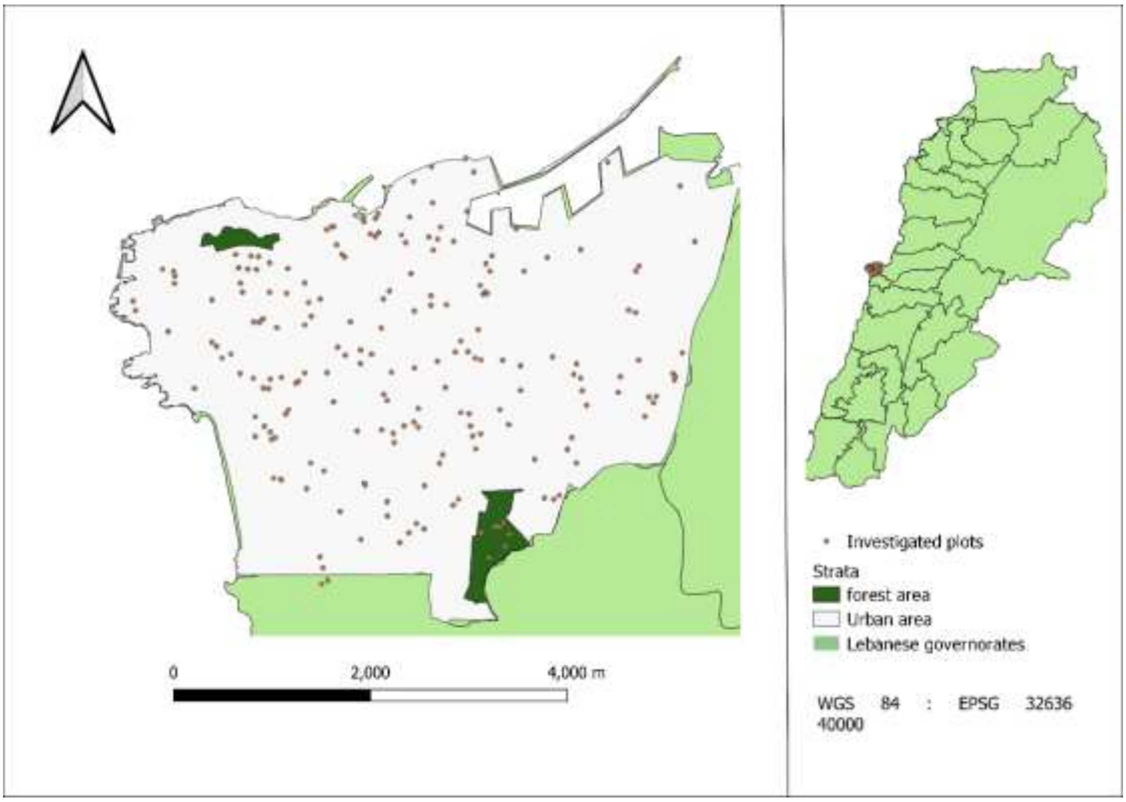

Figure 1. Map showing Beirut City and the distribution of the 200 analyzed plots.

Field surveys were conducted between April 4 and June 10, 2022, coinciding with the period when both deciduous and broadleaf species are fully foliated. Seasonal variability in leaf area is an important factor to consider: in Beirut, leaf emergence begins in March, when foliage area is minimal, and reaches its peak in September or October.

Plots were generated in two strata using a Q-GIS software by following the pre-stratified sampling guidelines provided by (I Tree guide, 2016), with ESRI shapefiles provided by the university's cartography department. In the field, the Q-Field application enabled accurate geolocation of the sampling plots. Data recorded per plot included geographic coordinates, site address, reference point, ground cover, and estimated percentage of tree cover per plot, which was assessed using Google Earth imagery closest in date to the field survey, in accordance with the prescribed methodology (Duhl et al., 2012). In total, 462 trees were inventoried, with measurements taken for species identification, diameter at breast height (DBH; up to six readings at 1.4 m), total tree height, crown base and crown top height, crown width, and percentage of missing canopy (Forest Service, 2021).

The canopy cover of the city was estimated using two independent approaches. The I-Tree Canopy tool was first employed to quantify urban land cover and tree canopy by classifying 1,500 randomly distributed points using high-resolution Google Earth imagery (Nowak, 2006). Subsequently, the I-Tree Eco model re-estimated citywide canopy cover based on plot-level canopy values derived following the prescribed methodology of (Duhl et al., 2012), as mentioned previously. The results of both approaches were later compared to evaluate consistency.

3-Results

3.1- Landcover of Beirut

The results of "I tree canopy" indicate that the city comprises 10.07% soil surfaces (including herbaceous cover and bare ground), 12.68% tree canopy cover, and 77.12% impervious surfaces, encompassing buildings, roads, activity zones, and undeveloped areas (Table 1).

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Table 1. Classification of land cover with their areas and percentage cover from the total surface of the city.

Land cover	Classes	Area (ha) ±SE	Percentage cover ± SE (%)
Impervious	Highways and roads	481.63 ±23.3	22.62 ±1.08
	Buildings	903.9 ±28.48	42.82 ± 1.28
	Activity zone / Unbuilt area	248.63 ±18.12	11.68 ± 0.83
Soil	Herbaceous	124.31 ±12.94	5.84 ± 0.61
	Bare ground including coastal area	90.64 ±10.35	4.23 ±0.52
Canopy	Forested area and street trees	269.35 ±18.12	12.68 ±0.86
Total	Beirut City	21.18	100

From plots measurements, the “I-Tree eco” model extrapolated a canopy cover of 16.3% for Beirut, which is closely comparable to the earlier estimate of 12.68% (Table 1). As field-based assessments involve direct observation and verification of trees, the 16.3% estimate is considered more robust. Despite the inherent difficulties of quantifying canopy cover in a highly urbanized setting, the close alignment of the two estimates strengthens their validity and indicates that both values fall within an acceptable range. Notably, a study advocates for a minimum of 30% tree canopy cover in every neighborhood to enhance health and well-being (Van den Bosch, 2021). In this context, Beirut’s urban forest structure, with canopy cover estimated between 12.68% and 16.3%, remains below internationally recommended thresholds. This shortfall highlights a deficit in vegetative infrastructure, potentially constraining the city’s capacity to deliver essential ecosystem services and to enhance climate resilience. When compared with other global urban centers, the gap becomes more pronounced. For example, according to the U.S. Forest Service’s National Land Cover Database, urban areas in the United States maintain an average tree canopy cover of approximately 35%. (Nlcd, 2021) thereby exceeding the WHO guideline and illustrating a relatively well-developed urban green infrastructure. European cities present varied patterns: Strasbourg has achieved 27.8% (Selmi et al., 2016), reflecting active urban greening initiatives, while Florence lags behind at 10.4%, (Pace et al., 2018), possibly due to historical urban morphology and limited planting space. The Basque Country in Spain stands out with an exceptionally high canopy cover of around 49% (García de Jalón et al., 2019), suggesting a robust integration of urban forestry into regional land-use policy. This comparative assessment underscores a substantial deficit in Beirut’s green infrastructure. The findings point to a need for comprehensive urban forestry strategies that prioritize species diversification, long-term management, and integration into broader spatial planning frameworks. Addressing this canopy shortfall constitutes not only an ecological necessity but also a critical public health priority.

3.2- Trees’ structure of the urban forest of the city

The I-Tree model estimated Beirut’s total tree population at approximately 110,500 trees with a margin of error of ±8,667. Within this total, the urban stratum is estimated to contain around 95,595 trees (±7,558), while the forest stratum comprises approximately 14,933 trees (±2,084). Specifically, the Pine Forest accounts for an estimated 8,790 trees (±1,109), closely aligning with Al-balad (2016) who reported approximately 8,000 trees in the same area. The overall tree density across the city is 56 trees per hectare, with the urban stratum at 50 trees/ha, and the Pine Forest at 293 trees/ha. Nowak & Crane (2002) have reported that urban forest densities in various U.S. cities range from 50 to 300 trees per hectare, situating Beirut among cities with relatively low tree density. However, the structure of an urban forest is influenced by more than just the total tree count; factors such as species diversity, tree size, spatial distribution, and overall tree health are equally important. Urban forests that incorporate a broad range of species, including numerous small-diameter trees alongside healthy, mature individuals, demonstrate greater resilience to pests and environmental fluctuations while delivering a more comprehensive array of ecosystem services (Rogers et al., 2023).

3.2.2- Tree-size classification based on Diameter Breast Height (DBH)

A healthy forest shows a mix of different trunk diameters (young, middle-aged, and old trees). Uniform sizes might signal poor regeneration or vulnerability (Morgenroth et al., 2018), (Pretzsch et al., 2023). If most trees are small and there aren’t many old, large ones, the forest’s ability to naturally regenerate and sustain itself will be negatively affected (Lindenmayer, 2017). This is because, large-diameter trees to produce seeds, provide suitable habitats, or create conditions needed for younger trees to thrive. On the other hand, it’s important to encourage young trees to grow and thrive. Without new growth,

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the forest could lose balance as older trees die off, leading to long-term decline. Results show that their a shift in DBH class toward young to middle age trees, with 57% of the tree population having diameters ranging from 15.2 to 30.5 cm (Figure 2).

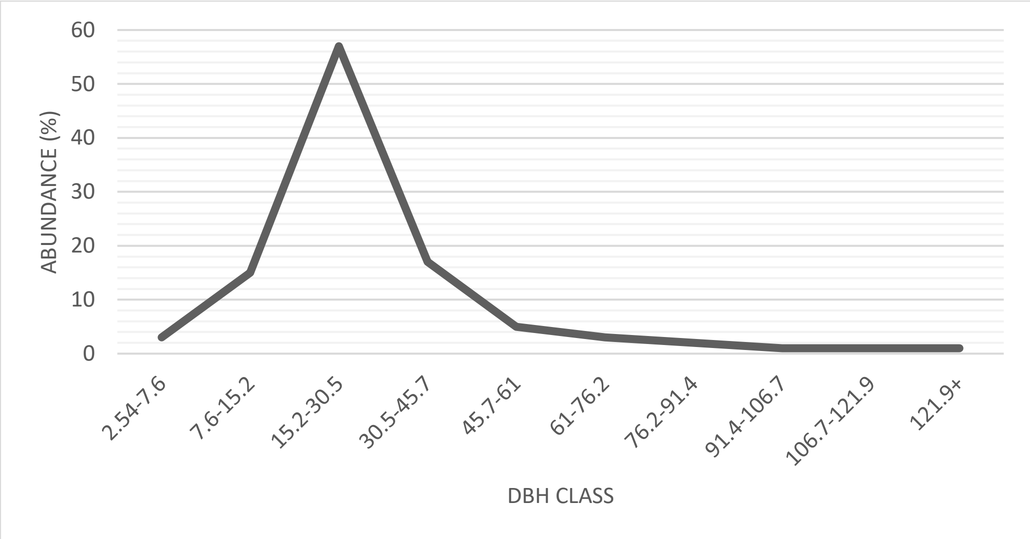

Figure 2. Abundance of DBH classes predicted by the model based on field-collected tree data.

The most common species of small diameter trees are Ficus macrocarpa (15.1%), Pinus halepensis (2.6%), Ficus benjamina (32.6%), Ficus thonningi (5.4%), Brachychiton populneus (25%), Jacaranda mimosifolia (22.2%), Ailanthus Altissima (28.6%), and Ficus elastica (33.3%). The 10 most common species of large diameter trees (greater than 45.7cm) are: Ficus mcacrocarpa (4.7%), Pinus halepensis (1.1%), Ficus benjamina (6.5%), Ficus thonningi (21.6%), Eucalyptus camaldulensis (73.7%), Ailanthus Altissima (7.15%), Ficus elastica (33.3%).

Ficus macrocarpa, Ficus benjamina, Ficus thonning, Ficus elastica, Pinus halepensis and Ailanthus Altissima are among the 10 most common small diameter trees and the 10 most common large diameter trees. Some species have more large trees than small trees, which may lead to reduction of this species in the future as there is minimal planting of regeneration of these species to sustain the species population, unless Ailanthus Altissima. The analysis of tree species composition across size classes reveals important patterns in urban forest dynamics. Several species, including Ficus macrocarpa, Ficus benjamina, Ficus thonningii, Ficus elastica, Pinus halepensis, and Ailanthus altissima, are represented in both small-diameter and large-diameter classes, suggesting sustained planting or successful recruitment over time. However, some species such as Eucalyptus camaldulensis and Ficus thonningii are more prominent among large-diameter trees and appear less frequently in the small-diameter class. This may indicate aging populations with limited recent planting, raising concerns about the long-term viability of these species in the urban landscape.

Conversely, species like Brachychiton populneus, Jacaranda mimosifolia, and Ficus elastica are abundant in smaller size classes, pointing to their recent popularity in urban greening efforts. If these younger trees are successfully maintained, they are likely to shape the future canopy structure. The prevalence of Ailanthus altissima in both size categories is particularly notable, as it may reflect natural regeneration due to its invasive nature and adaptability. While its resilience is advantageous, its spread should be carefully managed to avoid displacement of more ecologically valuable or native species.

Overall, the findings underscore the importance of proactive urban forestry strategies that ensure the regeneration of mature trees. A long-term planting plan that includes underrepresented but ecologically beneficial species is essential to maintain a stable and diverse urban forest.

3.3-Composition of Beirut Urban Forest

Field surveys identified a total of 59 tree species, with the ten most dominant species contributing 76.1% of the city's total leaf area (Figure 3) (Table 2). It is noteworthy that "Horsh Beirut" hosts over 200 shrub species; however, these were excluded from the present study, which focused exclusively on arboreal taxa.

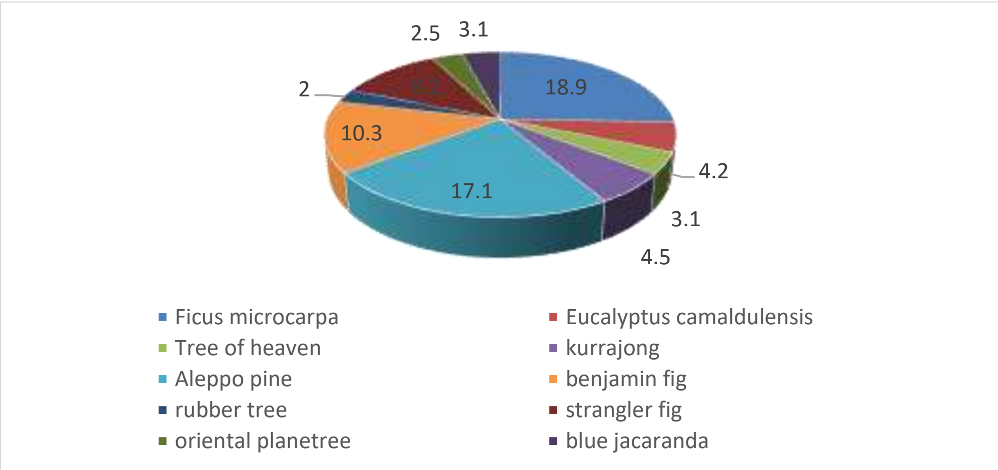

Figure 3. Species composition of Beirut's trees expressed as percentages.

In Beirut, 32% of species are species native to Asia (Figure 4). Most of the remaining species have an origin from Europe (20% of the trees). The city's structure provides favorable and heterogeneous environments for stress-adapted native species such as Pinus species and even endangered species. The urban vegetation consists of both native and exotic tree species (Figure 4). Within the forested areas, with a specific focus on the pine forest, the composition is predominantly native species, primarily Aleppo pine (Pinus halepensis) with a smaller presence of Italian stone pine (Pinus pinea). Thus, the urban forest has a tree diversity that is higher than the pine forest, so it can pose a risk to native plants if some of the exotic species are invasive plants that can potentially out-compete and displace native species. One of the most important observations in Beirut is to outline trees distribution in the cities. Regarding the built environment, increasing imperviousness saw not just reduced tree density but a decline in native species abundance. For instance, street with higher impervious cover saw a greater abundance of non-native and hardy naturalized species like Ficus macrocarpa. Pinus halepensis, a species native to the region, was the most abundant tree species in the city. However, much of this population is comprised of trees planted in the residual pine forest. The Tree of Heaven (Ailanthus altissima), a fast-growing deciduous species native to China and Taiwan, is recognized as invasive due to its capacity to thrive in disturbed environments (Pindaru & Nita, 2023). Accounting for 3.1% of the total population, its presence warrants careful management to control its spread or explore potential replacement strategies.

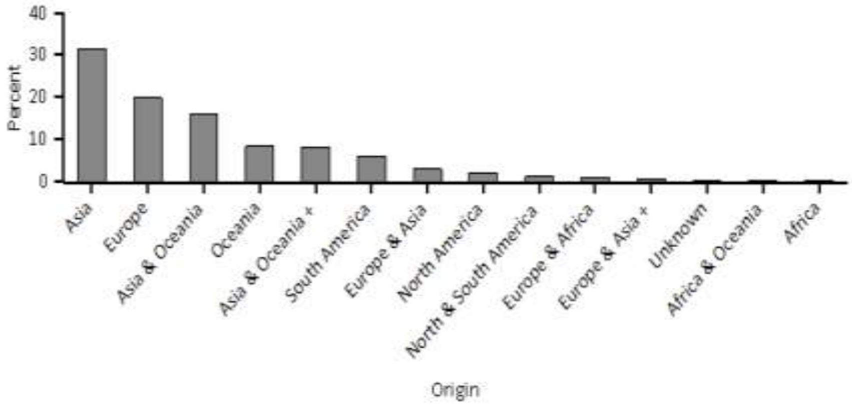

Figure 4. Relative distribution (%) of native and non-native species across Beirut.

3.4-Leaf area

3.4.1- Estimating Leaf area in Beirut

Leaf area is defined as the total surface area of the leaves of all the plants within a given area of ground(Hirabayashi et al., 2015), which is crucial for determining plant growth rates and estimating some ecosystem services such as air pollutants deposition. The total leaf area (LA) in Beirut is estimated at 1,045 hectares (ha), with 960.50 ha contributed by street trees in the urban stratum and 84.26 ha in the forest stratum. Specifically, the pine forest accounts for 45.08 ha. The mean leaf area density (LAD) across the city is 5,276.56 m²/ha, with 4,974.12 m²/ha in the urban stratum, 17,195.26 m²/ha in the forest stratum, and 15,026.58 m²/ha specifically in the pine forest. According to the model, the most ten abundant trees in the city contribute the most in the leaf area.

Table 2.The top ten tree species, estimated by the model, contributing the most to the city's total leaf area.

Species name	**Toral Number of trees**	**Percent population (%)**	**Leaf area (ha)**	**Percent leaf area (%)**
Ficus macrocarpa	20,942	18.9	112.71	10.8
Pinus halepensis	18,875	17.1	112.79	10.8
Ficus thonningi	9,116	8.2	147.2	14.1
Eucalyptus camaldulensis	4,681	4.2	143.21	13.7
Ficus benjamina	11,333	10.3	52.24	5
Platanus orientalis	2,710	2.5	67.02	6.4
Ailanthus altissima	3,449	3.1	56.32	5.4
Ficus elastica	2,217	2		5.5
Jacaranda mimosifolia	4,435	4	32.58	3.1
Brachychiton populneus	4,928	4.5	13.20	1.3

3.4.2-Leaf Area and DBH relationship

Tree size is a critical attribute of urban forest structure, significantly influencing the ecosystem services it provides. Large, healthy trees play a predominant role in delivering environmental benefits, largely due to the strong correlation between leaf area and these benefits. In the urban forest of Beirut City, trees with diameters less than 15.2 cm diameter range represent 17% of the population but account for only 2% of the total leaf area. In contrast, trees with diameters of 15.2–30.5 cm, which make up 57% of the population, contribute 28.68% of the total leaf area. More than 50% of the population of the 10 most abundant species in Beirut falls within this diameter class. However, Trees with diameters 30.5- 106.7 cm represent 60% of the population, likely similar to the pervious DBH classification, but contribute to 52% of the total leaf area, the double of them (Figure 5). These large-diameter trees are a vital component of the urban forest, significantly enhancing its ecological value.

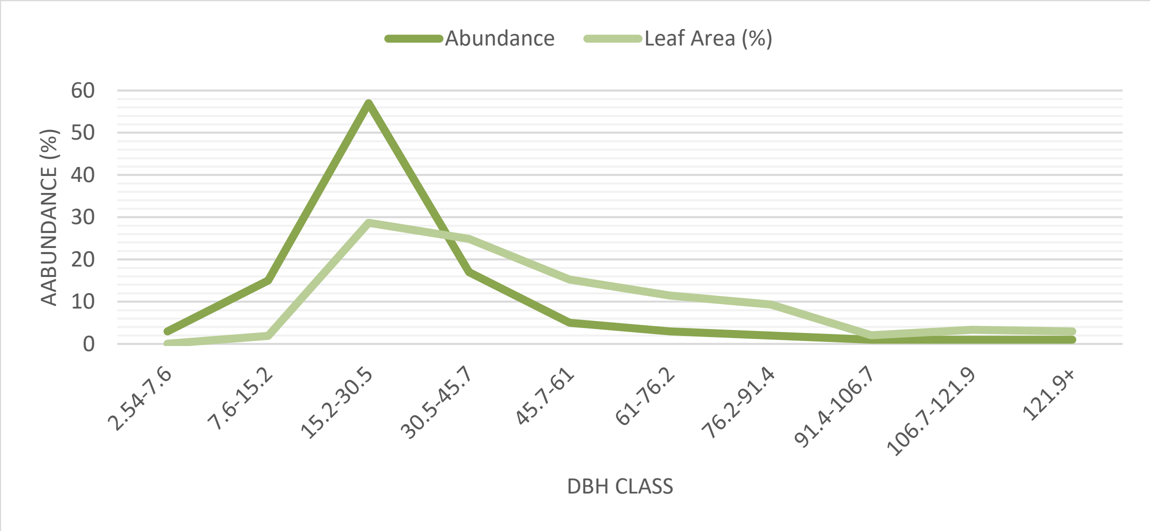

Figure 5. Percentage of total tree population and leaf area by diameter class, Beirut City.

3.4.3- Spatial Variation in Urban Tree Leaf Area in Beirut

Given the substantial variation in leaf area values and the absence of an established classification among plots, we applied quartile calculations to categorize the plots into four groups and to assess the factors influencing increases or reductions in leaf area across the city. Results show that Q_1 (LA) = 126.3 m^2, Q_2 (LA) = 221.6 m^2, Q_3 (LA) = 551.1 m^2, and Q_4 (LA) = 1581.6 m^2, represents the highest LA value (Figure 6).

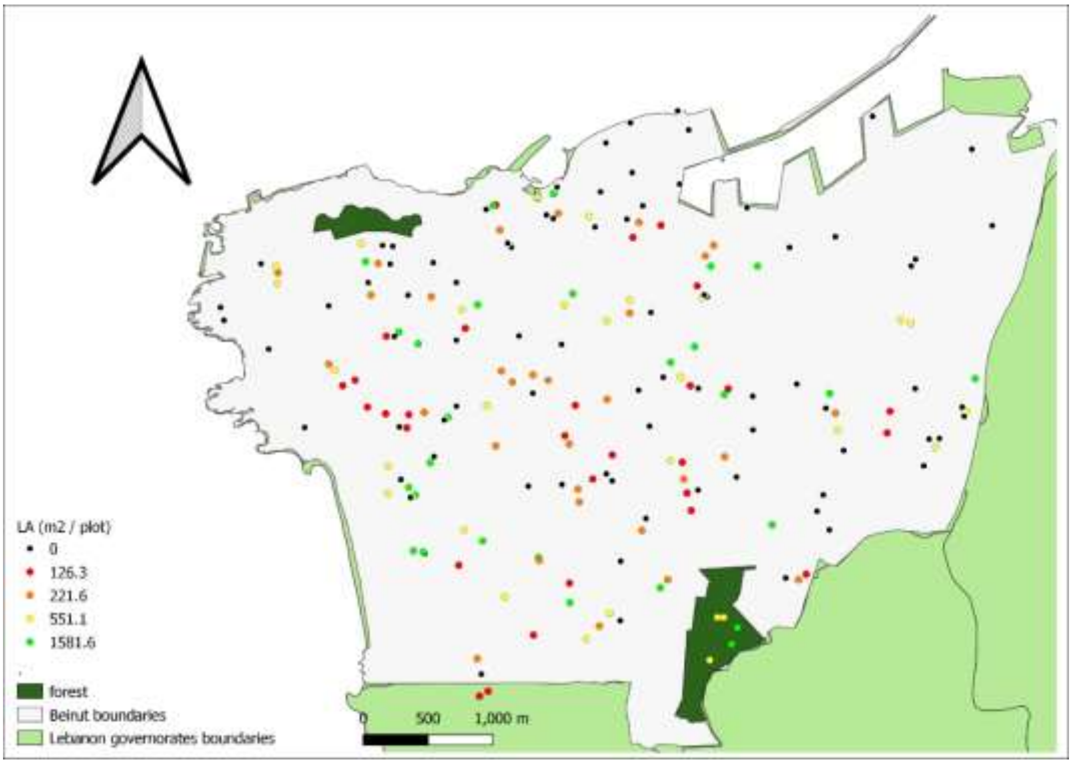

Figure 6. Map illustrating the spatial distribution of computed leaf area (LA) quartiles across Beirut.

3.4.3-Pollution removal

According to the model, the estimated total leaf area (LA) in Beirut, 1,045 hectares (ha), estimated to remove 27.95 ton annually of Ozone (O_3), Nitrogen dioxide (NO_2), sulfur dioxide (SO_2), Particulate matter ($PM_{2.5}$ & PM_{10}) and Carbon monoxide (CO). I-Tree model's output show that 28 plots with leaf area values ranging from 551.1 to 1581.6 m² account for over half of the pollutant mass removal (54.4%) from the total mass of pollutants. 29 plots, with leaf area values between 221.6 and 551.1 m², account for 29.7% of the total mass removal. The remaining 15.6% is removed by 62 plots with smaller leaf area values (Table 3).

In summary, 25% of the total leaf area (28 plots) accounts for over half of the total pollutant mass removal, whereas 50% of the leaf area (62 plots) contributes to only 15.6% of the overall pollutant reduction. This indicates substantial variability in tree removal efficiency, underscoring the need for further investigation to identify the factors that enhance this performance.

Table 3. shows the contribution of each quartile in pollutant mass removing from the atmosphere and their corresponding number of plots.

Quartile of LA	Air Pollutants mass removal (g/yr)	Percent of removal mass (%)	Number of plots
Q_1= 126.3	6,864.7	6.1	35
Q_2= 221.6	10,722	9.5	27
Q_3= 551.1	33,301.8	29.7	29
Q_4= 1581.6	60,965.8	54.4	28

***Note: this air pollutants mass was added from the total mass removal from the 200 plots. their total is different from the total estimation across the city.**

4-Discussion

4.1- Driver factors of Urban Forest framework of Beirut

Results show that high leaf area (LA) values, ranging from 551.1 to 1581.6 m² per plot, were primarily observed within the Pine Forest and in specific areas of the urban landscape, particularly in parks. In these wooded environments, both forested and park settings, the elevated tree densities, supported by favorable soil conditions and surface characteristics, contribute to the increased leaf area where mean tree density in these plots (12 trees/plot) (Figure 7), compared to trees density in the urban stratum (3 trees/ plot).

Figure 7. Photograph taken in "Horsh Beirut" or "Pine Forest", illustrating the stand density of Pinus species.

As previously noted, Beirut was stratified into two categories: urban and forested areas. The urban stratum encompasses all impervious zones, including residential, commercial, educational, vacant, and park areas. Within these impervious regions, plots exhibiting low leaf area (LA) values are primarily associated with either low tree density or small diameters at breast height (DBH). Trees with small to medium DBH were observed in lower socioeconomic residential streets, while the smallest, recently planted trees with low DBH were more common in higher socioeconomic neighborhoods. These urban zones are typically characterized by street trees and, to a lesser extent, small planted patches. Although socioeconomic factors do not appear to directly affect LA, they influence overall tree health: trees in lower-income streets often appeared stressed or unhealthy, whereas vigorous, healthy trees were frequently observed in the city center, commercial districts, and affluent areas (Figure 9). Across the urban landscape, impervious surfaces limit soil availability for planting, reducing tree density. Additionally, compacted and nutrient-poor soils prevalent in developed zones restrict root growth, which in turn diminishes canopy biomass and LA values. (Muhammad Asif et al., 2023).

Certain impervious zones display comparatively high leaf area values, particularly around older buildings and vacant areas such as parking lots, where both building and tree densities are low. In these settings, open-grown trees develop under minimal competition for light, space, or nutrients, leading to broad, expansive crowns and short, thick trunks with relatively large diameters at breast height (DBH) (T. green, 2010) (Figure 8). These trees make a significant contribution to overall leaf area and play a critical role in promoting urban environmental sustainability. They are also frequently located near historic structures or older buildings, where soils tend to be less degraded or disturbed than in more intensively developed urban areas.

Tree growth in urban environments clearly depends on the availability, quality, and condition of soil surfaces, as well as broader environmental factors. Only 10.07% of Beirut's surface area consists of herbaceous zones and bare ground (Table 1), which can still be considered usable soil surfaces. Several key factors influence tree growth under these conditions:
– Building age: Older buildings and sites tend to preserve surrounding soil surfaces more effectively than newer developments, particularly in schools, universities, and historic residences.
– Building configuration: Dense structures that create street canyons modify local microclimates by elevating temperatures and reducing light penetration, while this phenomenon warrants further study, trees in such environments often require greater adaptation to withstand urban stresses.
– Economic factors: Socioeconomic status indirectly affects leaf area by influencing tree health. Healthy trees are essential for maintaining robust canopy cover, which improves the resilience of urban forests to climate change and anthropogenic

pressures and ensures continued ecosystem services (Maco & McPherson, 2002). Proper management of wide-canopied trees and nurturing newly planted trees to maturity are particularly important. Existing literature highlights a consistent positive correlation between income and canopy cover across cities (Schwarz et al., 2015). However, this study suggests that housing attributes and their associated effects on biophysical conditions exert greater influence on species distribution, both within remnant forests and across the broader urban landscape, than income alone. Collectively, these findings indicate that impervious surfaces are the primary determinant of Beirut's urban tree distribution, primarily through their effects on soil availability and microclimate, whereas economic factors act as secondary, indirect influences on canopy development and growth.

Figure 8. Open-grown Ficus microcarpa tree located in the parking area of Saint Joseph University, Huvelin Street.

Figure 9. Comparison between unhealthy Ficus trees in a densely populated, low-income residential street in Beirut and a healthy silk oak tree located on a high-income street in the city center.

4.2- For more sustainable urban forest

Several strategies can be implemented to enhance the sustainability of the urban forest, including careful species selection, adequate allocation of planting spaces, and the adoption of appropriate planting practices.

Species selection should prioritize adaptability to site-specific and microclimatic conditions rather than focusing solely on aesthetic qualities. Additionally, the species' susceptibility to pests and diseases, as well as their potential to provide ecosystem services or cause disservices, must be evaluated. For instance, while Eucalyptus camaldulensis is widespread and contributes significantly to leaf area proportion (13.7%), the model identified it along with Eucalyptus globulus as among the highest emitters of volatile organic compounds (VOCs), accounting for 54% of total vegetation-derived VOC emissions. Finally, consideration should be given to whether a species is invasive; for example, Ailanthus altissima has exhibited invasive behavior in Beirut and should therefore be minimized in future planting strategies.

Public spaces in Beirut, including 43 public gardens and Horsh Beirut, offer valuable opportunities for tree planting. Herbaceous areas account for 5.84% of the city's total surface (Table 1), while land adjacent to roads and highways also represents a significant source of plantable space capable of supporting large, healthy trees. These areas should therefore be prioritized for conservation and strategic planning efforts, rather than inside canyon streets.

Planting practices represent a critical component of effective urban forestry management. As Arnold (1993) says 'A single tree that survives for fifty years provides greater value than twenty trees surviving only a decade.' This underscores the importance of reallocating urban reforestation resources to prioritize long-term performance over short-term planting numbers. Establishing a tree capable of thriving for decades in a constrained streetscape requires three essential elements: a specially engineered soil composition, an underdrainage system, and an appropriate surface material (Arnold, 1993). For example, in Singapore, Samanea saman and Peltophorum pterocarpum planted in structural soil and structural cells demonstrated significantly enhanced growth performance compared to traditional methods. These findings confirm that structural soils and cells provide a viable rooting environment under conditions of limited space and soil volume typical of dense urban areas (Ow & Ghosh, 2017). Additionally, tree maintenance is equally critical to long-term urban canopy health. Urban trees should be managed as integral components of infrastructure rather than as isolated specimens. Improperly installed trees that fail within a decade represent a substantial loss of ecological, financial, and planning resources.

Conclusion

Sustainable urban planning increasingly demands the integration of ecological, social, and economic considerations. Within this context, incorporating urban forests is essential, yet superficial greening efforts alone are insufficient. Beirut hosts a diverse but sparsely distributed urban forest canopy, where dense building structures constrain planting spaces and exacerbate urban heat island effects, particularly along canyon-like streets where most trees are located. Canopy cover in Beirut could be significantly improved through strategic planting of appropriately selected species in adequate spaces, coupled with long-term maintenance. Such measures would yield substantial environmental, public health, and economic benefits. Future research should further investigate the impacts of building configurations and elevated temperatures on leaf area development, as well as quantify the economic value of urban trees to better inform evidence-based planning and management strategies.

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الباحث الأساسي: أسماء الطويل

مركز البحوث البيئية, منطقة شرق البحر الأبيض المتوسط, قسم الجغرافيا, جامعة القديس يوسف في بيروت – لبنان

الملخص:

تمثل الغابات الحضرية إحدى الحلول القائمة على الطبيعة لتعزيز الاستدامة الحضرية من خلال توفيرها لخدمات بيئية متعددة، أبرزها تنظيم درجة الحرارة، والحد من تلوث الهواء، واحتجاز الكربون، إلى جانب فوائد بيئية أوسع. ولتعزيز هذه الخدمات البيئية، يُعدّ تحقيق إدارة فعّالة أمراً ضرورياً، ويتطلّب فهماً عميقاً للعوامل المحددة لنمو الأشجار، وللقيود التي تفرضها البيئات الحضرية الكثيفة. في هذه الدراسة، تمّ تقييم بنية الغابات الحضرية في مدينة بيروت باستخدام نموذج I-Tree Eco من خلال إنشاء 200 قطعة عينية وإجراء مسوحات ميدانية شاملة لتقدير المساحة الورقية والتباين المكاني لها على مستوى المدينة. وهدفت الدراسة ليس فقط إلى تحديد المساحة الورقية الإجمالية لمدينة بيروت، بل أيضاً إلى توضيح العوامل الأساسية المؤثرة في تطور الغطاء الورقي للأشجار المزروعة على الأرصفة وفي بقايا الغابات، مع اقتراح استراتيجيات إدارة تهدف إلى تعزيز مظلة حضرية أكثر مرونة واستدامة.. تشير النتائج إلى أن الأسطح غير المنفذة تُعدّ العامل الرئيس الذي يُشكّل بنية الغابات الحضرية في بيروت، إذ تعمل كعامل اجتماعي-بيوفيزيائي يتحكم في ظروف مثل جودة التربة والمناخ المحلي، مما يؤثر بدوره على نمو الأشجار. وتؤكد التوصيات على أهمية اختيار الأنواع النباتية المناسبة، وتوفير المساحات الكافية للزراعة، وتطبيق ممارسات إدارة مستدامة طويلة الأمد بوصفها إجراءات أساسية لتعزيز الغطاء الشجري وضمان استمرار تقديم الخدمات البيئية في المشهد الحضري المتسارع النمو في بيروت.

الكلمات المفتاحية: الغابات الحضرية، خدمات النظم البيئية، الاسطح الغير النفاذة، المساحة الورقية، الإدارة المستدامة.