Ann. For. Res. 66(1): 139-153, 2023
https://doi.org/10.15287/afr.2023.3011

ANNALS OF FOREST RESEARCH
www.afrjournal.org

Structure and diversity in a periurban forest of Bucharest, Romania

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Leca Ș., Popa I., Chivulescu Ș., Popa A., Pitar D., Dobre A.-C., Pascu I.-S., Apostol B., Badea O., 2023. Structure and diversity in a periurban forest of Bucharest, Romania. Ann. For. Res. 66(1): 139-153, 2023.

Abstract: Mitigating the adverse effects of climate change and worldwide urbanization is one of the main tasks of local authorities and city managers. As a long-term solution, urban and periurban forests have the potential to mitigate the impacts of climate change by providing ecosystem services such as removing air pollutants, mitigating the urban heat islands, storing carbon, regulating local climate, limiting the risk of flooding, reducing noise levels, and improving the physical and mental health of citizens and their welfare. To promote, conserve, and enhance the benefits offered by the periurban forests, it is needed to adequately describe the forest ecosystems state, and understand well their structure and functionality. The objective of this study was to investigate the structure, diversity, and health status of one of the main periurban forest in Bucharest. In 2015 and 2020, biophysical measurements (diameter at breast height, total height, wood quality, cenotic class) and assessments of forest health status were conducted in a permanent sample monitoring network (PSMN). This PSMN consists of 46 sample plots located in the periurban Stefănești forest near Bucharest, Romania. The calculation included tree characteristics and stand volumes, while the tree species diversity was characterized using the Shannon (H) and Gini (G) indexes. Our study confirmed that higher diversity indexes of tree species and variability amongst the biometric characteristics at forest stand level sustain ecosystem resilience and adaptability to climate change, simultaneously bolstering their capacity to provide various ecosystem services. The gained insights are critical in helping forest managers, policymakers, and any stakeholders in the effort to evaluate and model the ecosystem services.

Keywords: forest health; urbanization; Shannon index; Gini index; species composition

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Manuscript: received June 06, 2023; revised June 28, 2023; accepted June 29, 2023.

Introduction

Some of the major problems resulting from rapid urbanization include poor air quality and higher air temperatures in urban environments (e.g., urban heat islands, UHI) worsening air pollution and affecting human health and citizens well-being (Cohen et al. 2017). An effective strategy in developing and designing urban green spaces (parks, and urban and periurban forests) is to mitigate the negative effects (Marando et al. 2016, 2022, Chiruță et al. 2023). The concept of urban forestry has been introduced in Europe during the 1980s (Konijnendijk 2003), and multiple definitions, concepts and management plans were developed (Helms 2002, Randrup et al. 2005). Despite all, there is still no standard definition at the European level for periurban forests, which are currently seen as a strategic area providing communities with multiple socio-economic, climatic, and aesthetic benefits (Ostoić & van den Bosch 2015, Nita et al. 2018).

The new European Forest Strategy aims to overcome these challenges and unlock the potential of forests for our future. Moreover, European Union (EU) regulations, such as the Green Deal and EU 2030 Biodiversity Strategy (European Commission 2020), recognize the central and multi-functional role of forests and their contribution for reaching the EU's target for greenhouse gas emission reduction of at least 55% by 2030 and neutrality by 2050, as set out in the European Climate Law. Current concerns regarding this issue focus on how the anthropogenic environment influences urban and periurban forests (Blood et al. 2016). Thus, the rapid urbanization and change in land-use lead to changes in the structure and composition of the forest stand (Wear 2013). Climate change strongly influences trees' capacity for regeneration and growth by affecting their biochemical and physiological processes, including their air-cleaning capacity (Cheng et al. 2018).

Urban and periurban forests have the potential to mitigate the impacts of urbanization and climate change by removing air pollutants, storing carbon, mitigating the UHI, limiting the risk of flooding by slowing down the water flow and buffering precipitation in forest soil, reducing noise levels, and improving the physical and mental health of citizens (e.g., Tzoulas et al. 2007, Escobedo & Chacalo 2008, Byrne et al. 2016, Sarre 2018, Nowak et al. 2018, Pace et al. 2021, Ren et al. 2022, Sicard et al. 2018). Previous studies showed that urban vegetation has a considerable cooling effect and that increasing vegetation-covered area and density is an effective strategy to reduce the impact of urban warming (e.g., Zhao et al. 2019 Ren et al. 2022). Recent studies (Andree 2020, Cole et al. 2020) have suggested that air pollution contributes to COVID-19 mortality by increasing the risk of infection due to (i) aerosols containing the virus being more easily spread in more polluted areas, or (ii) the negative impact of air pollution on the immune system.

The Romanian forests are also suffering from a rapid urbanization process, mainly around large cities (Tóthmérész et al. 2011, Geacu et al. 2018). At the local scale, several studies have focused on periurban forests in Romania (Badiu et al. 2016, Grigorescu & Geacu 2017, Nita et al. 2018), but few of them analyzed the structural diversity of these types of ecosystems, their species composition succession and resilience capacity.

In the last decade, multiple studies revealed the role of mixed forests in improving trees resistance to the climatic extreme phenomenon (drought, heat waves, wind, ice, flood, fire, etc.) and their capacity to recover (Lebourgeois et al. 2013, Bielak et al. 2014). Mixed forests are considered as one of the main options for mitigating and adapting to climate change. However, this hypothesis cannot be generalized to all forest types and tree species, as species identity can be more important than their number and structural diversity in the mixture (Jourdan et al. 2019, Pretzsch 2019, Steckel et al. 2020). Higher tree species diversity provides a higher resilience to drought and other climatic extremes, productivity, temporal stability, and a more diverse portfolio of ecosystem services (Gamfeldt et al. 2013, Jactel et al. 2017, Pardos et al. 2021). However, knowledge of mixed forests ecology has increased over the last few decades, and information about how to design and manage them to achieve these potential benefits is still lacking.

Conversely, contemporary research has a keen interest in linking the forest stand characteristics and biophysical parameters to the ecosystem's capacity to provide various services. To that end, indicators were developed to assess the ecosystem functions and to determine how their provision varied (Dobbs et al. 2011). As anticipated, most frequently addressed were services within the provisioning function, through the mean of the key biometric characteristic (diameter; height) (Dobre et al. 2021). The forest structure among biodiversity served as support for determining productivity (Bohn & Huth 2017, Fischer et al. 2019) and assessing regulating services (Escobedo et al. 2015, Hui et al. 2019). Furthermore, information derived from biodiversity and forest structure was used to model the recreational functions of the forest (Giergiczny et al. 2015, Tudoran et al. 2022). This was accomplished by using indicators such as the leaf area index, angle index, and nearest neighbor index (Edwards et al. 2012, Gundersen & Frivold 2008).

The current study investigated the structure, diversity, and health status of one of the main periurban forest in Bucharest, and emphasizes its importance of providing specific ecosystem services (ES) to the urban agglomeration. At the same time, it provides relevant information to support the decisional process and the sustainable management of urban and periurban forests.

Materials and Methods

Study area

Located in the southern part of the country, Bucharest is surrounded by several managed periurban forests, such as Snagov, Căldărușani, Pasărea, Cernica, Ștefănești, and Băneasa. These forests are remnants of the old widely spread Vlăsia forests ('the forests of Wallachia'), massively deforested during the 19th and 20th centuries due to the expansion of Bucharest, industrialization process and increasing agricultural land (Giurescu & Farca 1980). The climate is temperate continental with an annual mean temperature of 10.6°C, July being the warmest month (23°C) and January the coldest (-3°C). The mean annual amount of precipitation is 600 mm, with a maximum in June (85 mm) and a minimum in March (15 mm). The study area is represented by the Stefănești forest, a mixed mesophytic-xerothermic forest (Doniță et al. 2005) located in the north-eastern part of Bucharest at the biogeographic limit between mesophyllous deciduous forests and the sylvo-steppe (Fig. 1). With an area of 404.3 ha, managed by the Romanian National Institute for Research and Development in Forestry (INCDS 'Marin Drăcea'), the Ștefănești forest accommodates species, such as the pedunculate oak (*Quercus robur* L.), European hornbeam (*Carpinus betulus* L.), small-leaved lime (*Tilia cordata* Mill.), Turkey oak (*Quercus cerris* L.), Norway maple (*Acer platanoides* L.), and black locust (*Robinia pseudoacacia* L.). The dominant soil type is the preluvosol developed on Mesozoic deposits overlying a crystalline bedrock (Florea et al. 2000). Forest management activities mainly include thinning, sanitary silvicultural works. The intensity of these silvicultural works was very low, due to their protective role and functionality classification and had no impact on stand structure. At the same time, in 2007, 0.56 ha were planted with species such as white poplar (*Populus alba* L.), honey locust (*Gleditsia triacanthos* L.), and red oak (*Quercus rubra* L.).

Network design and data sampling

In order to better understand the effects of anthropogenic climate change, air pollution, and other stress factors on the periurban forest ecosystems, a permanent sampling monitoring network (PSMN) was designed and set-up in 2015. The PSMN is characterized by 46 permanent sample plots (PSP), distributed systematically on a 300 x 300 m grid, covering the entire Ştefăneşti forest area (Fig. 1). The design of each PSP comprises two circular subplots of 500 m^2 (r = 12.62 m) located 30 m from the centre of the PSP (eastward and westward). In the PSMN, until now two measurement campaigns were conducted in 2015 and 2020. During the field campaigns, all trees with a diameter at breast height (*dbh*) above 8 cm, located within the subplots, were measured. For each sampled tree, the following data were recorded: species, azimuth (angular direction relative to the north), distance to the centre of the subplot (m), circumference at breast height (mm), total height (h, in m), quality class, cenotic class according to the Kraft classification (Badea 1998, Badea 2008) and crown defoliation percentage (%) according to the European ICP protocol (UN/ECE 2020).

Data analysis

The diameter at breast height (*dbh*) for each tree was calculated based on the measured circumference at 1.3 m assuming a regular circular stem shape. The structural relationship between *dbh* and *h* was modelled for each species or group of species (in case of low number of trees) using an exponential equation (Giurgiu et al. 2004):

$$\ln h_i = a_1 + a_2 \cdot dbh_i^{a_3} \quad (1)$$

where: dbh_i represents the breast height diameter of the (i) tree;

h_i represents the height of the (i) tree; and

a_i represents the regression equation coefficients.

The regression equation was calibrated on the measurements carried out in 2020 on 1643 measurements. Based on this model, the height of each tree in both campaigns (2015 and 2020) was estimated. Based on the tree *dbh* and *h*, the

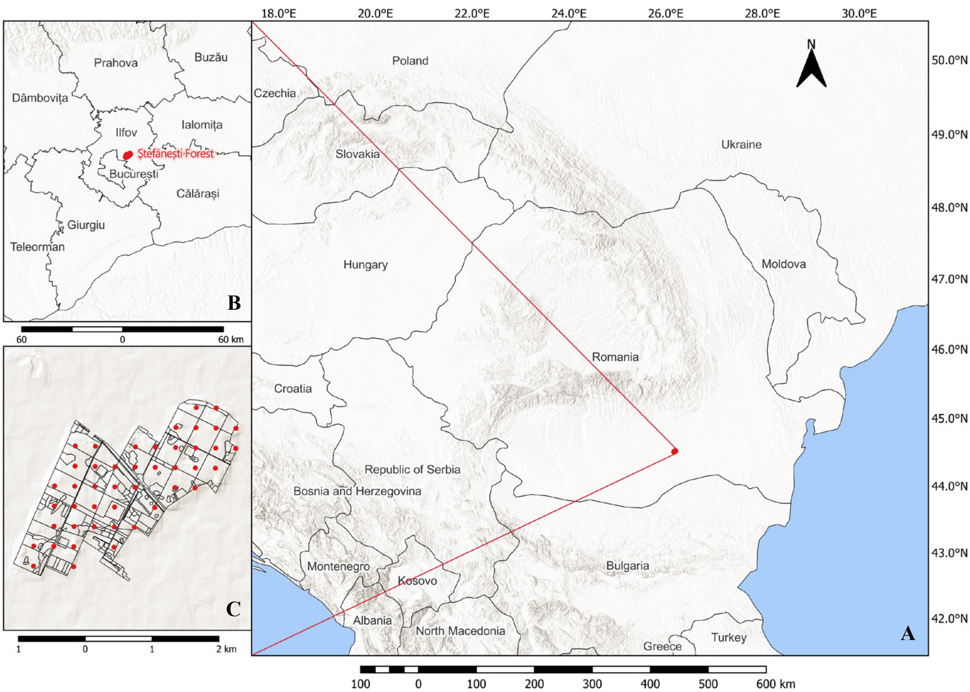

Figure 1 Location of the study area and spatial distribution of the permanent sample plots within the permanent sample monitoring network (PSMN). (C) Elementary management units of the Ştefăneşti forest (black borders) and PSPs (red dots).

basal area and volume values were calculated at the tree level. Basal area was calculated with the following equation:

$$g_i = \frac{\pi \cdot d^2}{4} \qquad (2)$$

where: g_i is the basal area of the (i) tree; and
d_i is the diameter of the (i) tree.

Tree volume was calculated using a double logarithmic equation (Giurgiu et al. 2004):

$$v_i = a_1 + a_2 \cdot log(dbh_i) + a_3 \cdot log^2(dbh_i) + a_4 \cdot log(h_i) + a_5 \cdot log^2(h_i) \quad (3)$$

where: v_i represents the volume of the (i) tree;
dbh_i represents the diameter at breast height of the (i) tree;
h_i represents the height of the (i) tree; and
a_i represents the regression equation coefficients (specific to each species).

Based on individual values and PSP areas (m²), values were extended to hectare level: basal area (G, $m^2 \cdot ha^{-1}$) and volume (V, $m^3 \cdot ha^{-1}$). The Shannon (H) and Gini (G) indexes were used to characterize the species diversity of the Stefanești forest. The Shannon index was calculated based on the number of species and diameters stratified into classes. The Shannon index based on species (H_s) was calculated at the plot level using the following equation:

$$H_s = -\sum_{i=1}^{k} \frac{n_i}{N} \cdot ln\left(\frac{n_i}{N}\right) \qquad (4)$$

where: n_i - represents the number of individuals of the ith species;
N represents the total number of individuals in a plot; and
k represents the number of species in a plot.

The Shannon index based on diameter (H_d) was calculated at the plot level using the following equation:

$$H_d = -\sum_{i=1}^{k} \frac{n_i}{N} \cdot ln\left(\frac{n_i}{N}\right) \qquad (5)$$

where: n_i - represents the number of individuals of the ith diameter category;
N represents the total number of individuals in a plot; and
k represents the number of diameter categories in a plot.

Tree heterogeneity was evaluated using the Gini index, which ranges between 0 and 1 (Gini 1921, Lexerød & Eid 2006, Duduman 2011). The Gini index was calculated at the plot level using the equation:

$$G = 1 - \sum_{i=1}^{k} [(ba_{i-1} + ba_i)(n_i - n_{i-1})] \qquad (6)$$

where: k represents the number of diameter classes;
ba_i represents the cumulative fraction of the basal area of trees from all diameter classes smaller or equal to ith diameter class, in the case of $i = 1$, $ba_{i-1} = 0$; and
n_i represents the cumulative fraction of the tree number from all diameter classes smaller or equal to the ith diameter class, in the case of $i = 1$, $n_{i-1} = 0$.

Results

Forest composition and structure

From a compositional standpoint, the main tree species identified within the PSMN were *Quercus robur*, *Tilia cordata*, *Carpinus betulus*, *Acer campestre,* and *Robinia pseudoacacia*. In 2020, *T. cordata* represented 42% and 41% of the total number of trees and tree volumes, respectively, whilst *Q. robur* represented 23% and 40% (Table 1, Fig. 2). The total number of trees per hectare decreased by 4.78% from 2015 to 2020, contrasting the increasing values of the other biometric indicators: volume (+ 5.17%) and basal area (+ 3.97%).

Quercus spp. displayed the highest mean diameter (37.1 cm) and height (30.0 m) and the minimum was recorded for *R. pseudoacacia*. The coefficient of variation for height (30%) was lower than for the diameter (45%), indicating a relatively uniform canopy profile. Generally, the forest vertical structure comprises a tree layer and a shrub layer of 2–3 m high.

Table 1 Synthetic structure parameters for main species (*dbh – diameter at breast height; h – tree height; G – basal area at stand level; V – volume at stand level; coef. var. – coefficient of variation*).

Species	No. of trees/ ha	Mean dbh (cm) coef. var. (%)	Mean h (m) coef. var. (%)	G (m²)/ ha	V (m³)/ ha
		2015			
Tilia cordata	229	26.4 (39.7)	26.8 (23.1)	14.5	203
Quercus sp	130	35.0 (25.3)	29.1 (14.7)	13.4	202
Other species	81	22.8 (61.5)	21.9 (50.6)	4.6	67
Carpinus betulus	49	19.9 (33.0)	21.3 (24.3)	1.7	21
Acer campestre	30	18.3 (36.8)	17.3 (29.9)	0.9	9
R. pseudoacacia	23	10.3 (36.9)	12.9 (21.6)	0.2	2
Total	**543**	**26.2 (45.1)**	**25.2 (30.0)**	**35.2**	**502**
		2020			
Tilia cordata	219	27.9 (38.3)	27.8 (25.7)	15.3	216
Quercus sp.	120	37.1 (24.5)	30.0 (15)	13.7	209
Other species	77	23.7 (61.9)	23.5 (45.8)	4.7	70
Carpinus betulus	46	20.6 (33.1)	22.0 (24.9)	1.7	21
Acer campestre	30	18.3 (40.7)	16.9 (32.6)	0.9	9
R. pseudoacacia	26	12.7 (34.5)	15.5 (24.7)	0.4	3
Total	**517**	**27.4 (44.8)**	**26.2 (30.3)**	**36.6**	**528**

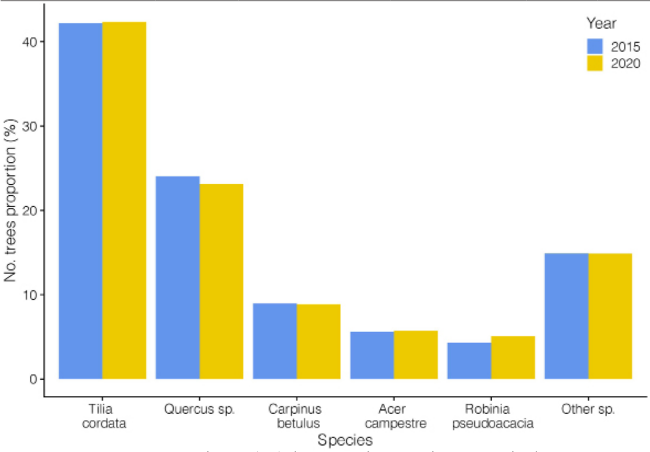

Figure 2 Tree proportions (%) by species, as inventoried in 2015 and 2020 within the Ștefănești periurban forest PSMN.

The spatial distribution of each species proportion, based on the number of trees, highlighted the dominance of oak and linden in most PSPs. The proportion of linden was generally higher than oak, whilst pure linden PSPs were also identified. The other species (*C. betulus*, *A. campestre*, or *F. excelsior*) were evenly distributed within the PSMN, although in a much lower percentage (below 10–15%). Two pure stands of *R. pseudoacacia* were identified. The forest composition remained relatively constant between 2015 and 2020. A slight decrease in *Quercus* spp. population has been observed due to tree death mainly along the main road that passes by the forest (Fig. 2). The increase in the *R. pseudoacacia* ratio, based on the number of trees, can be explained by the high number of young trees (ingrowth), characterized by a rapid growth rate, thus overpassing the defined diameter threshold (8 cm) by 2020.

The stand density, expressed as the number of trees per hectare in the Ștefănești periurban forest, was on average 517 trees·ha^{-1}, ranging from 210 trees·ha^{-1} to 1060 trees·ha^{-1} (Fig. 3). Concerning the tree species, a higher density of oak was recorded in the western sector than in the eastern part of the periurban forest. Also, the linden reached higher densities in the peripheral areas and lower in the central part of the forest. A high density of trees per hectare has been observed for black locust (410–560 trees·ha^{-1}) and Turkey oak (320–600 trees·ha^{-1}), making for practically pure

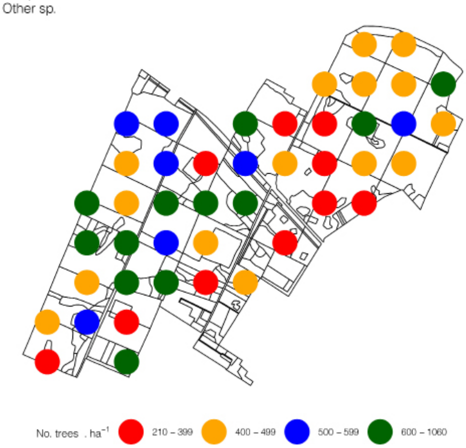

Figure 3 Spatial distribution of tree numbers by plot, as inventoried in 2020 within the Ștefănești periurban forest PSMN.

stands. The other species showed density below 150–200 trees·ha^{-1}. The coefficient of variation of the number of trees per hectare recorded in the surveys was 31.1%.

The composition of the periurban Ștefănești forest, according to the tree volume ratios (in 2020), was predominantly represented by linden (41%) and oak species (40%), followed by hornbeam (4%) (Fig. 4). The ratio between species remained similar when considering the basal area: 42%, 38% and 5% for linden, oak species, and hornbeam, respectively. Compared to these results, the proportion of species established by the management plan was relatively similar, with 40% of oak, 35% of linden and 8% of hornbeam, the rest being other deciduous and coniferous species. Between 2015 and 2020, a slight increase in linden volume and a decrease in oak species volume were observed.

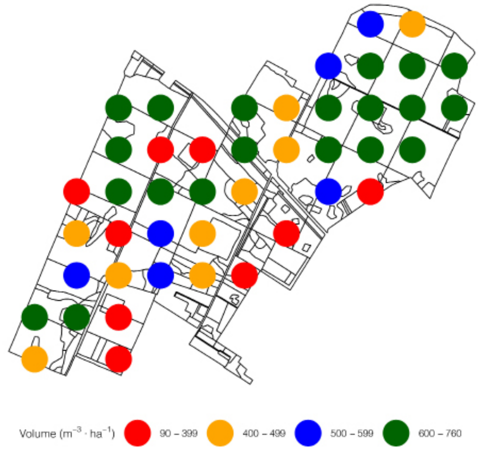

Figure 5 Spatial distribution of tree volumes by plot, as inventoried in 2020 within the Ștefănești periurban forest PSMN.

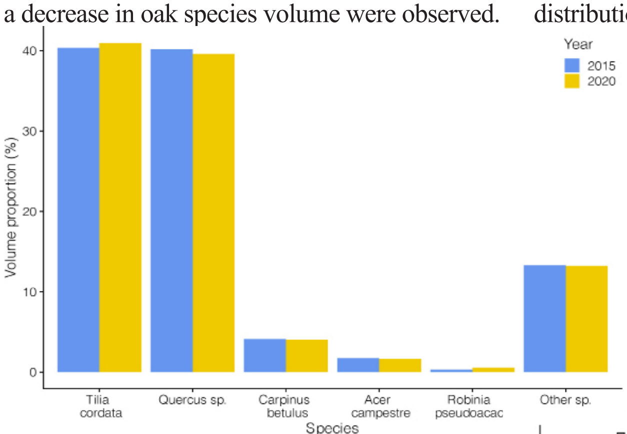

Figure 4 Volume distribution by species as inventoried in 2020 within the Ștefănești periurban forest PSMN.

The average volume per hectare in the permanent survey network in the periurban Ștefănești forest was 528m^3·ha^{-1}, ranging from 95.6 m^3·ha^{-1} to 759.8 m^3·ha^{-1} (Fig. 5). The coefficient of variation of the average volume recorded at the survey level was 30.4%. The higher volume has been observed in the eastern part of the periurban forest, and the lowest volume was associated with young stands with a high number of trees per ha.

The distribution of the number of trees related to diameter classes highlighted a quasi-normal distribution of oak species, and a unimodal distribution with left asymmetry for linden and hornbeam (Fig. 6). For other species, the distribution of the number of trees by diameter classes was a negative exponential due to the high number of small acacia trees.

The *dbh* and *h* regression models were calibrated for the main species of the Ștefănești periurban forest. The similar shape of the regression models have indicated a high homogeneity in

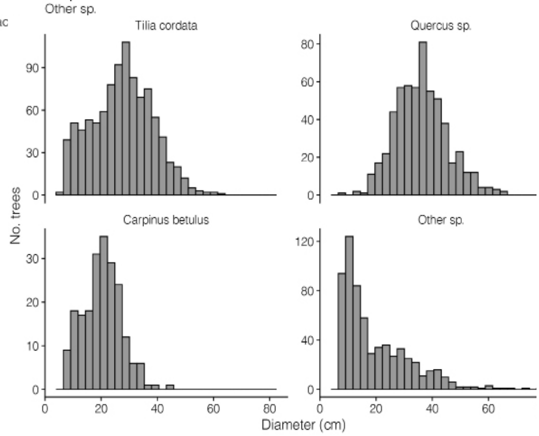

Figure 6 Distribution of the number of trees related to diameter classes, as inventoried in 2020 within the Ștefănești periurban forest PSMN.

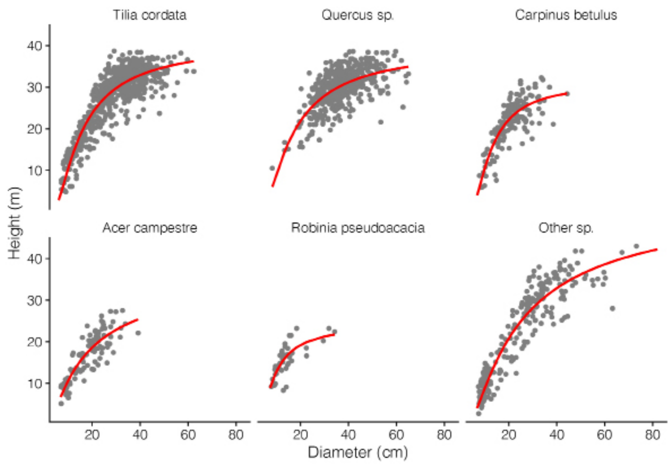

Figure 7 Relationship between tree height and diameter by species.

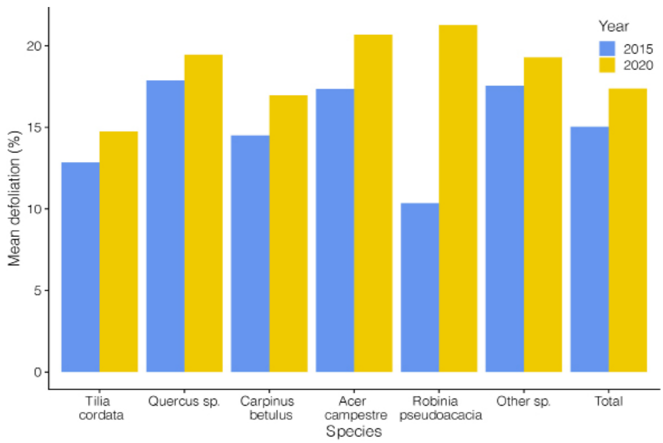

Figure 8 Mean defoliation for the main species.

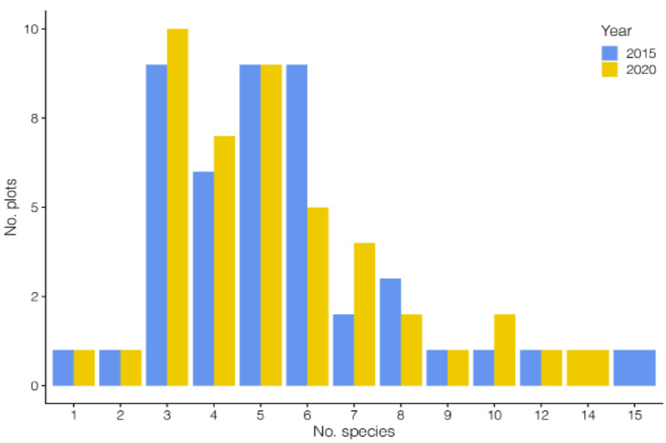

Figure 9 Distribution of the number of plots with a certain number of species.

the relationship between these two dendrometric characteristics for the entire PSMN. Higher variability was observed for oak species (Fig. 7).

The mean crown defoliation is higher in 2020 comparing with 2015 for most species. Overall, the mean crown defoliation increased by 2.4%, and the most affected tree species is *R. pseudoacacia* (Fig. 8). In 2020, the mean defoliation percentage for *R. pseudoacacia* doubled compared to 2015, from 10.3% to 21.3%.

Forest tree diversity

The number of tree species varied between 2 and 15 per PSP, with an average of five species per plot at the level of the entire PSMN (Fig. 9). Between the two inventories, the number of PSPs with 3, 4, 7 and 10 species increased. The trees from 23 species overpassed the defined diameter threshold of 8 cm, resulting in them being included in the 2020 inventory as ingrowth trees. In 2020, an increasing number of tree species has been observed.

The spatial distribution of species and diameters diversity in the Stefănești forest showed high variability, as highlighted by the Shannon index (Fig. 10). The maximum species diversity wa s observed in the central area of the Ștefănești forest with a simplification of the structure in terms of species number in the western peripheral area. The Shannon index based on the number of

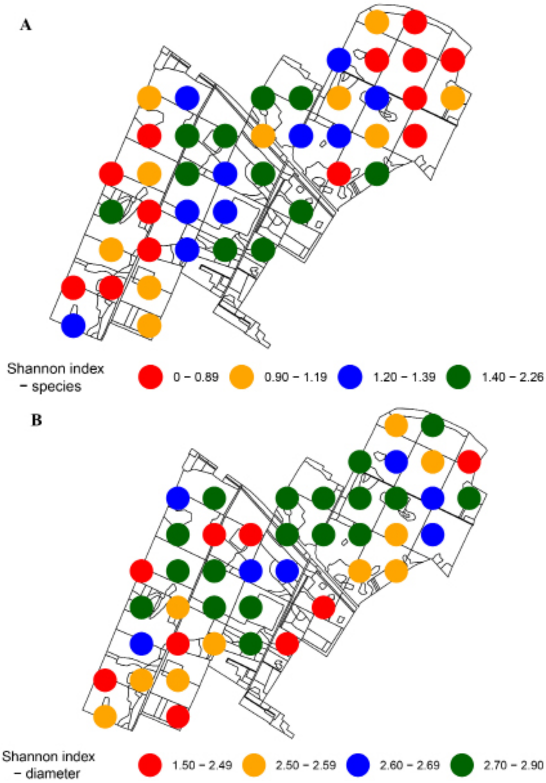

Figure 10 Spatial distribution of the Shannon index based on species (A) and tree diameter (B) by the plot, as inventoried in 2020 within the Ștefănești periurban forest PSMN.

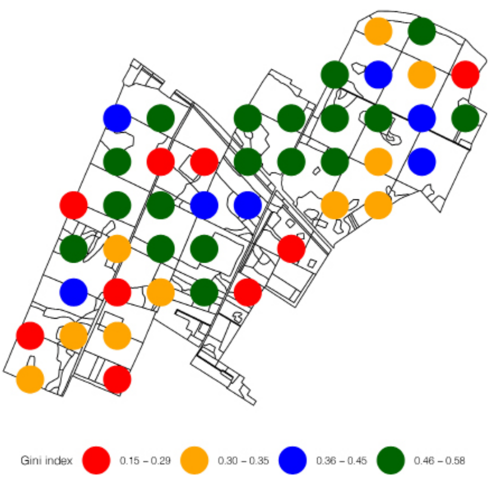

Figure 11 Spatial distribution of the Gini index by the plot, as inventoried in 2020 within the Ștefănești periurban forest PSMN.

species varied from 0 to 2.26. Meanwhile, the Shannon index based on tree diameters ranged from 1.5 to 2.9. The Gini index ranged from 0.15 to 0.58, with most plots exceeding 0.35, indicating moderate structural diversity (Fig. 11). The central part of the periurban forest displayed the highest structural diversity compared to the peripheral areas of the western and eastern regions.

Discussion

Although numerous studies have analyzed the benefits of urban and periurban forests (Manes et al. 2012, Manes et al. 2016, Mariani et al. 2016, Manzini et al. 2023), understanding how tree species diversity and stand structure of these forest ecosystems influence their capacity to face climate extremes, urban pollution, or other anthropogenic interventions remains to be explored. Over the past 100 years, Bucharest's periurban forest areas decreased by 12,500 ha, from 62,581 ha in 1912 to 53,010 ha in 1990 and 50,081 ha in 2014, covering 9.4% of the area, much lower than the national rate of 27% (Grigorescu & Geacu 2017). The main reasons for this reduction were the urbanization process and agricultural development, which decreased the surface of existing forests in the region (Grigorescu & Geacu 2017).

The relatively high groundwater level in the north of Bucharest has favored, in time, the vigorous growth of forest vegetation, especially for *Quercus robur*. The formation of these actual stand structures was possible through the application, over time, of some forest management solutions adopted for these stands and implemented in the last decades of the 20th century. Following societal requirements and considering the production and protection potential of the forest ecosystems in the area, several objectives were assigned, such as biodiversity conservation, ecologically balance protection, extreme climate mitigation or recreational and leisure purposes, the last one being one of the most sustained and promoted (Carcea & Seceleanu 2011).

Urban and periurban forests, characterized by low diversity (i.e., pure stands), are also susceptible to pests and diseases (Richardson & Rejmánek 2011, Subburayalu & Sydnor 2012). During both monitoring years, we did not identify any major pests, fungi or other diseases that could be related to a decrease in stand resilience. Several extreme drought years were recorded during the 2015–2020 period, with 2018 and 2019 being the most extreme in the last decades (Markonis et al. 2021), and no notable changes were observed in the forest structure. Because of the mortality caused by the interspecies relationship, the total number of trees per hectare decreased by ca. 5% from 2015 to 2020, contrasting the increasing values of the other biometric indicators, such as tree volume and basal area. Regarding the health status of the trees, expressed by their crown defoliation (Badea 2008), the tree species most affected by the 2018 and 2019 droughts was the black locust, whose mean defoliation increased from 10% (2015) to 21% (2020). The drought sensibility of *R. pseudoacacia* was noticed by several authors in their studies, also mentioning the capacity of fast recovery of this species after drought events (Moser et al. 2016, Jia et al. 2022, Chen et al. 2023). Overall, the mean defoliation percentage slightly increased by 2.4% for all trees and species. One reasons for crown defoliation increase can be the drought, but to confirm this trend longer time series data are needed.

The data from the management plan indicated an average volume of 285 $m^3 \cdot ha^{-1}$, which is 30% lower than that obtained by our statistical inventory (528 $m^3 \cdot ha^{-1}$). This difference could be due to different evaluation methods, considering that the tree volumes in management plans are calculated for each specific sub-unit and our analysis was related to the entire PSMN.

Periurban forests are also crucial in mitigating air and soil pollution (Muresan et al. 2022) in their surrounding area and different tree species have different capacities (Alahabadi et al. 2017, Manzini et al. 2023). According to the ICP Forests reports (www.icp-forests.net), no critical values of air pollutants were registered in 'Ștefănești-stejar' Level II plots - a research/monitoring plot placed inside the Ștefănești periurban forest. Moreover, an exceedance of critical levels for ozone was reported in 2018 and 2019 in ozone monitoring plot from this forest (Sicard et al. 2020). In Bucharest, as in most European cities, the most critical pollutants in urban and periurban areas are tropospheric ozone (O_3), particulate matter (PMs), and nitrogen dioxide (NO_2) which can have adverse effects on humans, animals, and vegetation health (El-Fadel & Massoud 2000, Wang et al. 2017, Paoletti et al. 2019; Agathokleous et al. 2022, Sicard et al. 2023) in order to define new standards based on stomatal flux, i.e. PODY (Phytotoxic Ozone Dose above a threshold Y of uptake). Recent research has indicated that trees can effectively remove PMs, NO_2 and O_3 from the air, with some species being more effective than others (Ferrini et al. 2020, Manzini et al. 2023). For example, studies have found that evergreen trees, such as pine and fir, are more effective at trapping PMs than deciduous trees like oak and maple (Marando et al. 2016, He et al. 2020). Therefore, evergreen trees in periurban forests can significantly reduce air pollution and improve air quality. In addition to removing PMs, trees in periurban forests can absorb other pollutants, such as carbon dioxide, sulfur dioxide and nitrogen oxide (Jim & Chen 2009, Chen et al. 2022). Tree species can absorb these pollutants differently (Han et al. 2022). For example, oaks and maples are efficient in removing nitrogen oxides (Wickramarathne et al. 2021), while pines and other conifers are efficient in absorbing sulfur dioxide (Liu et al. 2023). Similarly, top O_3-reducing species include common beech, small- and largeleaved lime, London plane, sycamore maple, Norway maple, tulip tree, horse chestnut, and turkey oak (De Marco et al. 2017, Sicard et al. 2022). These ecosystems serve as natural water filters, absorbing and purifying rainfall and runoff before it reaches the city water systems (Vilhar & Simončič 2012, Roeland et al. 2019). The trees in these forests also provide habitats for various wildlife species, and help maintaining the ecological balance of the environment (Felton et al. 2020, Lo Monaco et al. 2020, Chivulescu et al. 2022). Nevertheless, it must be considered the anthropogenic effect exerted in such ecosystems and the appropriate treatments that are applied in a different manner. Therefore, the periurban forests are not characterized by a growth stock specific to lowland forests (Tudoran et al. 2022). Hence, increased focus should be placed on diversity and productivity information and the indices developed to characterize these ecosystems and their capacity to provide services.

Conclusions

Higher structural diversity indexes of tree species and their various biometric characteristics at forest stand level sustain their resilience and capacity to mitigate climate change and to provide multiple ES. The management activities of the last decades have promoted an increase in the number of tree species, their structural diversity, and their efficiency in maintaining the stability and ecosystem function of this periurban forest. Periurban forests are essential to the natural landscape and provide numerous benefits to human and wildlife health and well-being. Therefore, conserving and protecting them for present and future generations is crucial. They can potentially mitigate the adverse effects of urbanization and climate change by removing air pollutants, storing carbon, regulating local climate, mitigating water pollution, and reducing noise. They also provide habitat for different small wildlife species, thus helping to maintain an ecological balance of the environment. Our results highlighted the importance of this type of study whilst emphasizing the fact that this information is critical in helping forest managers, urban and periurban green spaces planers and other interested stakeholders caring for these forests and the ecosystem services they provide.

Compliance with ethical standards

Author Contributions

Conceptualization, ȘL, IP, and OB; Data curation, ȘC and AP; Formal analysis, IP and AP; Funding acquisition, OB; Methodology, ȘL, IP, and OB; Project administration, ȘL; Supervision, ȘL, IP, and OB; Visualization, AP; Writing – original draft, AP; Writing – review & editing, ȘL, IP, ȘC, DP, AD, IP, BA, and OB.

Conflict of interest

The authors declare that they have no conflict of interest.

Funding

This research was funded by the BIOSERV Programme, Project ID PN19070102, FOR-CLIMSOC Programme, Projects ID's PN23090101 and PN23090201, and the CresPerfInst project—"Increasing the institutional capacity and performance of INCDS "Marin Dracea" in the activity of RDI" (Contract No. 34PFE/30.12.2021), financed by the Ministry of Research, Innovation, and Digitization through Program 1—Development of the national research—development system, Subprogram 1.2—Institutional Performance—Projects to finance excellence in RDI.

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