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Structural features of Peleș Park Forest: managing for ecosystem services provision

Șerban Chivulescu[1], Diana Pitar[1], Ștefan Petrea[1,2]✉, Bogdan Apostol[1], Ovidiu Badea[1, 2]

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Abstract The Peleș Park Forest (PPF), a semi-natural peri-urban forest near Sinaia, Romania, is essential in providing ecological benefits and improving human well-being through recreation. As the urban population grows and stress-related health problems increase, green spaces are increasingly recognised for their restorative functions, including air purification, temperature regulation and mental health improvement. This study aims to develop a sustainable management framework that reconciles forest conservation with recreational value use by assessing forest structure, evaluating tourism-related stressors, and proposing adaptive management strategies. We assessed forest structure through tree diameter, height, volume, and crown health measurements, applying principal component analysis (PCA) to identify the main structural drivers. The results revealed a strong correlation between tree diameter and height, modulated by species composition and site conditions. They showed pronounced crown defoliation in the upper canopy layers, particularly among trees of lower wood quality. The findings suggest that uneven-aged stand structures, which support biodiversity and ecological resilience, are subject to tourism-related pressures such as soil compaction and vegetation damage.

Keywords: Forest Park, ecological functions, recreational value, forest structure, sustainable management.

Addresses: [1]National Institute for Research and Development in Forestry ”Marin Drăcea” (INCDS), Voluntari, Ilfov, Romania. | [2]Faculty of Silviculture and Forest Engineering, Transilvania University of Brașov, Brașov, Romania.

✉ **Corresponding Author:** Ștefan Petrea (stefan.petrea@icas.ro).

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Introduction

Urban areas are becoming increasingly crowded (Wen et al. 2020, El-Didy et al. 2023), which exacerbates pollution levels (Sicard et al. 2018, 2023) and intensifies stress due to daily challenges such as heavy traffic and the pressures of modern life (Seiler et al. 2020, Javaid et al. 2021). As a result, there is a growing demand for relaxation and an escape from urban routines (Zhang & Zhang 2022), making nature therapy - such as spending time in forests and parks - an increasingly vital remedy for stress reduction and well-being (Lee et al. 2012, Corazon et al. 2019, Kotera et al. 2022).

Studies worldwide emphasise the multifaceted benefits of park forests, which not only enhance physical and mental health by providing spaces for exercise, relaxation, and nature immersion (Sicard et al. 2018, Martínez Pastur et al. 2020, Carrari et al. 2022) but also strengthen community ties through shared green spaces (Salbitano et al. 2016).

As urbanisation expands, the importance of these forested areas grows, serving not only as ecological buffers but also as critical retreats for urban residents seeking recreation (Bonilla et al. 2021). Mounting scientific evidence highlights the profound physiological and psychological benefits of spending time in forest environments, a practice often called forest bathing (shinrin-yoku).

Studies have demonstrated that exposure to forest settings can enhance human immune function (Li 2010, Park et al. 2010), reduce stress biomarkers (Farkic et al. 2021), and improve overall mental well-being (Tsunetsugu et al. 2010). Notably, large-scale research conducted across 24 forests in Japan (Tsunetsugu et al. 2010) has empirically validated these therapeutic effects, linking them to biogenic volatile organic compounds (BVOCs) emitted by trees and the restorative influence of natural landscapes. These findings underscore the critical role of forests as ecological assets and public health resources - particularly in peri-urban areas where recreational demand intersects with conservation priorities. Forests, especially those in urban settings or close to cities, provide a vital sanctuary for people to unwind and reconnect with nature (Leca et al. 2023).

At the same time, forest parks are essential for nature conservation (Baycan-Levent & Nijkamp 2009, Niemelä 2014, Carrari et al. 2022, Vargas-Hernández et al. 2023), providing recreational spaces and ecological benefits (Van Oijstaeijen et al. 2020, Gradinaru et al. 2023, Mullenbach & Wilhelm Stanis 2024) that improve the quality of life of people living in urban and suburban areas. These green spaces serve as vital refuges within cities, providing essential regulating services such as absorbing carbon dioxide, cleaning air and water and cooling urban temperatures (Susca et al. 2023). Their importance has become even more apparent as cities expand and the need to tackle climate change grows in influence. Also, they can help combat climate change by acting as carbon sinks, which means they absorb and store carbon dioxide in the air, reducing the greenhouse effect (Zhao et al. 2023). They also help cool cities by providing shade and through the process of transpiration, which can reduce temperatures (Chivulescu et al. 2023). In addition, they support a variety of plants and animals, which helps maintain biodiversity and strengthens ecological networks in and around cities (Chivulescu et al. 2023, Leca et al. 2023, Braga et al. 2024, Mullenbach & Wilhelm Stanis 2024).

Despite these benefits, park forests face many challenges, especially with the rise in tourism and recreational activities (Huang 2014). Visitors can cause soil compaction, damage to vegetation, and disturbances to wildlife, which can disrupt their natural balance (Saminpanya et al. 2009). Additionally, climate change poses significant threats, with rising temperatures, changing rainfall patterns, and extreme weather events putting extra stress on these ecosystems (Grimm et al. 2013, Weiskopf et al. 2020).

Uneven-aged stands, characterised by a mix of trees of different ages and sizes, play a crucial role in sustaining biodiversity and enhancing ecological resilience. These forests, often resulting from natural processes or specific management practices, support a wide array of plant and animal species by providing a variety of habitats and resources (Pilli & Pase 2018, Tiemann & Ring 2022).

The structural diversity inherent in uneven-aged stands promotes the development of multiple layers of vegetation, which can host diverse flora and fauna and create microhabitats beneficial for species with varying ecological needs (Bončina et al. 2019, Chivulescu et al. 2022, 2024). Furthermore, this variability in stand structure contributes to the forest's resilience against disturbances such as pests, diseases, and climate change, ensuring the continuity of ecosystem functions and services (Chivulescu et al. 2024). By preserving or emulating these natural conditions in forest management practices, we can enhance the stability and adaptability of forest ecosystems in the face of environmental changes (Chivulescu et al. 2021, García-Duro et al. 2021). In this context, the pressures from recreational use make it necessary to understand the forest's structure better.

This research aims to develop a management approach that balances conservation with recreational use while also contributing to creating a practical guide for establishing and managing park forests to ensure sustainable practices and multifunctional benefits. By studying the forest's structure and evaluating the effects of tourism, we aim to (1) assess and analyse the structure of the uneven-aged forest stand within the Peleș Park Forest (PPF), (2) assess the relationship between the structure of PPF and touristic stress and (3) create (or develop) sustainable and balanced management practices for PPF that could also serve as a model for other park forests. The proposed strategies will better protect the forest's ecological functions while allowing sustainable tourism.

Materials and Methods

Study area

The Peleș Park Forest is situated in the Southern Carpathians mountains, relatively in the centre of Romania, near Sinaia city (Figure 1), at 1000 m altitude. The climate is characterised by a temperate climate, with a minimum average annual temperature of -3.9° C and a maximum average annual temperature of 15.7° C. Annually, the number of frost-free days is 148 (Sandu et al. 2008, Cheval et al. 2014).

PPF is owned by the Romanian Royal Family and administrated by Sinaia Forest District (OS Sinaia), covering 21.5 ha of forest vegetation. Post-1989, PPF was classified under special conservation measures and forestry activities were prohibited.

PPF is a significant recreational site that attracts numerous visitors annually due to its scenic beauty and proximity to Peleș Castle.

Field measurements

In 2022, a 1-hectare study plot was placed in PPF when the site inventory was performed. Previous studies have indicated that a 1-hectare plot, when located within a representative area, is a suitable scale for accurately describing stand structure (Leca 2014). The study plot encompasses a mixed montane forest with high productivity, situated on an east-facing slope with a 25-degree gradient. This terrain enhances the site's overall productivity.

The characteristics of the study plot are similar to those of the whole forest area because it is located in the same management unit. The homogeneity of the structural and ecological characteristics of the forest in this area further supports the representativeness of the plot for broader assessments of forest dynamics. The forest stand exhibits a varied

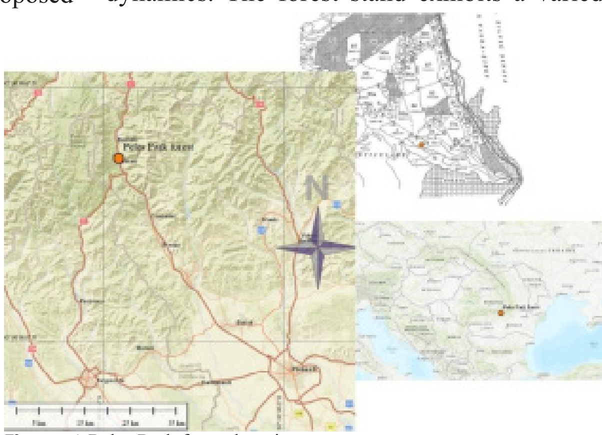

Figure 1 Peleș Park forest location.

structure that supports its high productivity levels. It comprises 50% beech, 41% silver fir, and 9% other hardwoods and spruce. The soil is classified as *eutricambosol molic*. The . presence of *Asperula dentaria* as an indicator species highlights the natural richness and productivity of the forest.

An inventory of all trees was conducted, involving measuring the breast height diameter (DBH), assessing stem quality (where class 1 represents the highest wood quality and class 4 the lowest quality) according to the method proposed by Dobbertin et al. (2020), determining the tree positional class specific for uneven-aged forests (cenotic class: 1-predominant, 2- dominant, 3- co-dominant), and evaluating the health status of the trees (0% defoliation - healthy tree to 100% defoliation - dead) by estimating their level of defoliation (Badea 2008).

Simultaneously, 3-4 tree heights were measured for each diameter category to apply the regression equation (eq.1), which is used to determine the height (h). This equation is frequently used in Romanian forestry practice, being precisely enough to determine the tree heights in natural stands.

$$h=1.3+d^2/(a_0+a_1d+a_2d^2+a_3\,d^3) \quad \text{(eq. 1)}$$

where: d represents the DBH; h - tree height and a_0, a_1, a_2, a_3 - determined regression coefficients (fir a_0=5.687868, a_1=-0.75788, a_2=0.053157, a_3=-0.00023; beech a_0=-34.10094649, a_1=4.59016, a_2=-0.11055, a_3=0.001257).

To calculate the volume of individual trees, we used the following regression equation (eq. 2), with different coefficients for each species:

$$\log v=a_0+a_1 \log d+a_2 \log d^2 +a_3 \log h+a_4 \log h^2 \quad \text{(eq. 2)}$$

where v represents the volume; d - DBH, h – height, a_0, a_1, a_2, a_3 and a_4 - species regression coefficients (fir a_0=-4.46414, a_1=2.19478, a_2=-0.12498, a_3=1.04645, a_4=-0.016848; beech a_0=-4.11122, a_1=1.30216, a_2=0.23636, a_3=1.26562, a_4=-0.079661) (Giurgiu et al. 2004).

The total volume of the plot was calculated by summing the volumes of individual trees.

Statistical analysis (descriptives, correlations)

The statistical parameters computed for all quantitative variables (DBH, h, volume) were average, standard deviation, and coefficient of variation, which were calculated using the *R PASTECS* package, a specialised tool within the R software environment (Grosjean & Ibanez 2002). This package, widely used in forestry research, facilitates comprehensive statistical analysis and data management, providing robust tools for handling and interpreting complex forestry datasets (Grosjean & Ibanez 2002). The *R PASTECS* package was chosen for its proven efficacy in previous studies related to forest science, ensuring reliable and accurate analysis of the collected data (Atkins et al. 2022). We also used Pearson/ Spearman correlation coefficients to assess the relationship between different structural variables.

Principal Component Analysis (PCA)

To effectively reduce the dimensionality of the datasets and enhance the granularity of visualisation, we employed the Principal Component Analysis (PCA) method (Greenacre et al. 2022). This analysis was conducted using several R packages within the R studio environment (R Core Team 2021). Specifically, we utilised the following packages:

(1) *corrr* (Kuhn et al. 2022) - used to explore and analyse correlations among variables;

(2) *ggcorrplot* (Kassambara 2016) - facilitated the visualisation of correlation matrices through aesthetically pleasing and informative correlation plots;

(3) *FactoMineR* (Lê et al. 2008) - package used to perform the core PCA and factor analysis, providing essential tools for dimension reduction and data interpretation, and

(4) *factoextra* (Kassambara & Mundt 2020) - package employed to extract and visualise multivariate analysis results, making PCA

outputs more accessible and informative.

The PCA analysis incorporated the following variables: species, DBH, wood quality, cenotic class, height, health status (defoliation), and volume, each tree representing a row. By analysing these variables, we aimed to uncover underlying patterns and structures within the data, facilitating a more nuanced understanding of the relationships between different factors.

Ecosystem Services and Recreational Value of a Park Forest

This study assessed the ecosystem services of PPF and similar urban or peri-urban forests through a comprehensive literature review and data analysis. The literature review focused on the microclimatic effects of forests (Almeida et al. 2018, Doli et al. 2021), their role in improving air quality (del Pilar Arroyave-Maya et al. 2020), noise reduction (Nowak et al. 2006, Almeida et al. 2018, Kim & Coseo 2018, Vieira et al. 2018), and psychological benefits (Almeida et al. 2018, Vieira et al. 2018). Additionally, visitor data and the economic impact of tourism to the Peleș Park area were obtained from National Peleș Museum activity reports (https://peles.ro/transparenta/rapoarte-de-activitate/).

The analysis focused on assessing the recreational and economic value of the ecosystem services provided by the forest by correlating visitor numbers with generated income (travel-cost method), which allowed us to determine its recreational value (Cazacu et al. 2020). The analysis assessing the influence of tourists on forest ecosystems in PPF was conducted using data from 2017 to 2022, as earlier records were unavailable.

Establishment and Management of Park Forests

For the Establishment and Management of Park Forests, existing research was combined with expert opinion and draft guidelines to analyse key management practices that affect the provision of ecosystem services. Particular focus was placed on critical factors such as strategic site selection, species diversity and sustainable resource management, all of which are essential for maintaining the ecological integrity of park forests. In addition, the study analysed best practices in ecological conservation, recreation facility design, and community engagement to understand their role in supporting the long-term functionality and sustainability of park forests. Similarly, for "Establishing and Managing Park Forests", guidelines and methodologies were used to guide the analysis (DiCicco 2014, Perry et al. 2020, Ferretti-Gallon et al. 2021).

Results

Descriptive statistics

Descriptive statistics revealed a highly variable forest structure with a wide range of tree diameters, heights, and volumes (Table 1). This heterogeneity is evident in both broadleaved and coniferous trees. The dataset has information on 298 trees, of which 240 were broadleaves (mainly *Fagus sylvatica*) and 58 coniferous (mainly *Abies alba*).

Table 1 Descriptive statistics of main dendrometric variables.

Variable	Tree group	N	Mean	s	s (%)
DBH (cm)	Broadleaves	240	34.1	18.6	54.4
DBH (cm)	Coniferous	58	57.1	28.2	49.3
DBH (cm)	Total	298	38.6	22.6	58.7
Height (m)	Broadleaves	240	26.2	9.5	36.3
Height (m)	Coniferous	58	34.7	11.2	32.2
Height (m)	Total	298	27.8	10.4	37.3
Volume (m^3)	Broadleaves	240	2.0	2.2	111.6
Volume (m^3)	Coniferous	58	5.2	3.9	76.2
Volume (m^3)	Total	298	2.6	2.9	111.9

Note: Tree group - type of forest, N – number of trees, Mean - average, s - standard deviation, s% - coefficient of variance

The overall mean diameter at breast height (DBH) is 38.6 cm, with a standard deviation of 22.6 cm and a coefficient of variation of 58.7%. The DBH distribution follows a downward trend, with a high frequency in the lower DBH classes. This pattern is characteristic of uneven-aged stands, in which interspecific competition leads to a dominance of smaller trees (Figure 2). This substantial variability reflects a stand with trees in diverse growth stages. For broadleaved trees, the mean DBH is 34.1 cm, with an SD of 18.6 cm and a CV of 54.4%. This relatively high CV indicates a diverse range of broadleaf tree sizes, including younger, smaller individuals and older, larger ones. In contrast, the coniferous trees have a significantly larger mean DBH of 57.1 cm, with an SD of 28.2 cm and a CV of 49.3%. The coniferous group shows slightly less relative variability compared to the broadleaves. Overall, the forest stand exhibits a highly heterogeneous structure, with a broad range of tree diameters, including smaller broadleaved trees and larger coniferous trees.

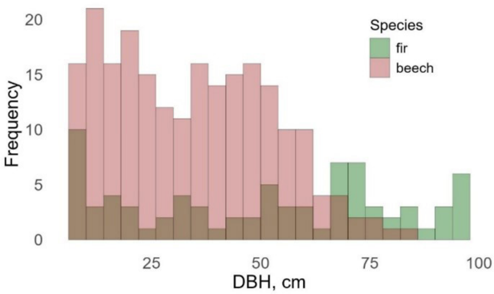

Figure 2 DBH frequencies in PPF.

The tree heights show significant variation, with an overall weighted mean height of 27.8 m and a coefficient of variation of 37.3%. Broadleaved trees have an average height of 26.2 m, while coniferous trees are generally taller, with a mean height of 34.7 m. The lower coefficient of variation among coniferous trees suggests a more uniform height distribution due to a more consistent age within this group. In contrast, broadleaved trees show greater variability in height, likely reflecting the diversity of growth conditions. The observed variation in tree height within the study plot contributes to a heterogeneous light regime, favouring understory vegetation development. This canopy structural diversity is critical in supporting species richness and maintaining essential ecological functions within the forest ecosystem. The research plot exhibits a highly variable structure in tree volume, with an overall mean of 2.6 m³ and an exceptionally high coefficient of variation of 111.9%. Broadleaved trees have a mean volume of 2.0 m³ with a similarly high CV of 111.6%, indicating a wide distribution of volumes, likely due to a mix of young and mature trees. Coniferous trees, on the other hand, have a higher average volume of 5.2 m³, also showing significant variability, with a CV of 76.2%.

Correlation matrix

The strong positive correlation (r = 0.895) between DBH and height (Figure 3) reflects an intrinsic growth pattern observed in trees, driven by their biological and structural development. This relationship is fundamental in forest ecology and has been widely used in predictive models to estimate tree height from easily measurable parameters such as DBH. In the context of Peleș Park Forest, this strong correlation further validates the applicability of using DBH measurements as a reliable proxy for estimating tree height, which is essential for assessing the forest's ecosystem services and structural attributes. Understanding this correlation helps estimate the forest's overall biomass and structural complexity, which are essential factors for evaluating the health and productivity of the ecosystem.

Species moderately correlate with DBH (0.416) and height (0.341). This suggests that while the species of trees have some influence

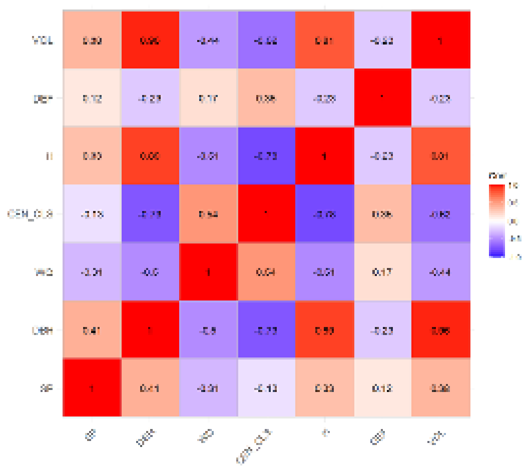

Figure 3 Correlation matrix of the main dendrometric variables from PPF. SP- species, DBH - diameter at breast height, WQ - wood quality, CEN_CLS - cenotic class, H - height, DEF - defoliation and VOL – volume.

on these growth parameters, other factors such as environmental conditions, soil quality, and competition also play significant roles. The moderate correlation implies that particular species may generally grow larger and taller, but this is not a strict rule. This insight is essential for forest biodiversity conservation, highlighting the need to consider species-specific growth patterns when planning reforestation and conservation efforts.

PCA Analysis

The PCA (Figure 4) revealed a clear pattern in the distribution of variance across different dimensions by identifying underlying patterns and reducing data dimensionality while preserving the main characteristics of our dataset. The first principal component (PC1) was the dominant factor, accounting for 57.383% of the total variance in the dataset. This was followed by the second principal component (PC2), which explained 16.840% of the variance. The remaining dimensions contributed incrementally to our understanding of the overall variability within the data.

After projecting the individual data points onto the principal components, we identified distinct clusters and trends within the data. The positioning of each data point revealed its distinct relationship with the overall structure of the dataset. This analysis was further informed by examining the variable loadings and their contributions to defining the principal components, highlighting the key variables that significantly shaped the reduced representation of the data. Our analysis shows that the most important variables in PC1 were DBH, height and wood quality, the first two positively influencing PC1 and the latter negatively. The second PC is positively correlated with defoliation and species.

From a practical perspective, PCA facilitated informed decisions regarding dimension reduction. This approach streamlined the dataset by emphasising the cumulative variance explained by key components, such as the first four principal components, which collectively accounted for over 90% of the total variance. This, in turn, enabled deeper interpretations of the inter-variable relationships and patterns discernible within the reduced PCA space.

Structure of tree characteristics

The relationship between tree diameter and height for the main species, beech and fir, was examined (Figure 5), indicating a significant variability. The relationship between DBH and volume (Figure 6) also demonstrated an ascending trend: smaller DBH categories corresponded to lower volumes, while larger DBH categories corresponded to higher volumes.

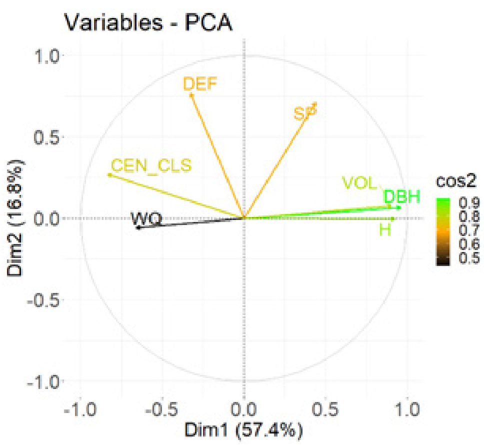

Figure 4 PCA Analysis.

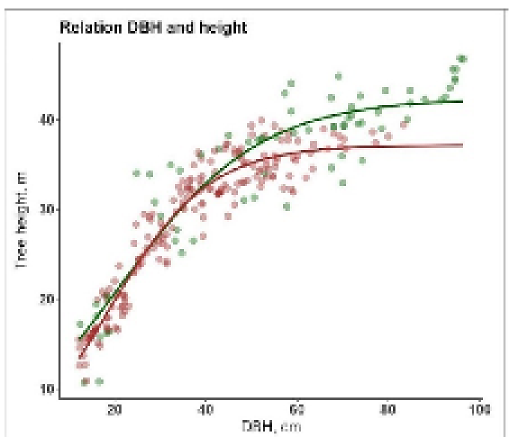

Figure 5 Relation between diameter and height.

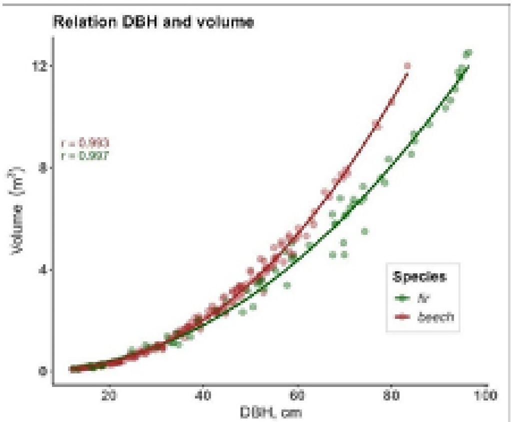

Figure 6 Relation between diameter and volume.

Relation between health status and cenotic class

Our analysis revealed a relationship between tree health status and cenotic class. It was observed (Figure 7a) that trees with a high percentage of defoliation were more prevalent in the higher cenotic classes (cenotic class 1 represents the highest trees and class 3 the lowest trees). For cenotic class 1, the median defoliation level was relatively low, around 15%, with the interquartile range (IQR) spanning from approximately 10% to 20%. This suggests moderate variability in defoliation within this class. However, some outliers exceeded 40%, indicating that certain trees within class 1 experienced significantly higher defoliation levels.

In contrast, cenotic class 2 demonstrates a higher median defoliation rate of approximately 20%. IQR for this class ranges from around 15% to 30%, indicating greater defoliation level variability than class 1. Furthermore, several outliers exceed 40%, with some reaching as high as 60%, suggesting substantial foliage loss of certain trees within this cenotic class.

Cenotic class 3 exhibits the highest median

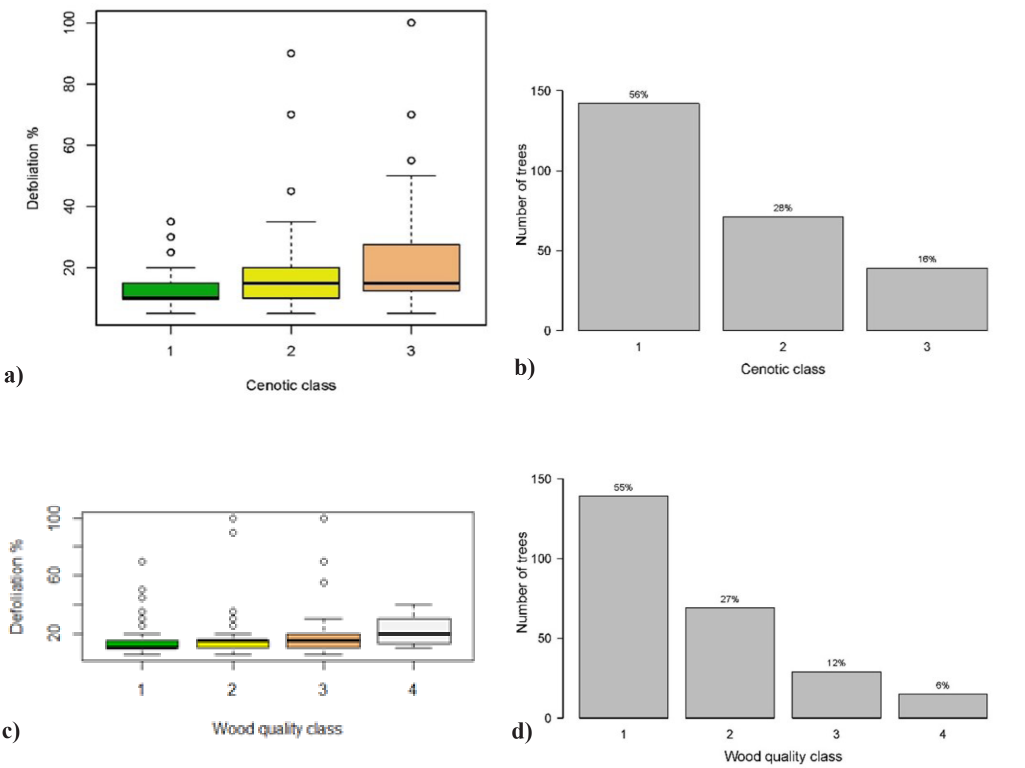

Figure 7 a) Relation between cenotic class and defoliation; b) Distribution of cenotic class; c) Relation between cenotic class and defoliation; d) Distribution of wood quality.

defoliation rate, reaching approximately 30%. IQR spans from 15% to 40%, reflecting the most significant variability among the three cenotic classes. Furthermore, numerous trees exceed the 40% defoliation, with some cases approaching 90%, suggesting the presence of extreme defoliation. Moreover, it can be observed (Figure 7 b) that the majority of trees in Peles Park forest are located in Cenotic class 1.

Relation between health status and wood quality

When analysing the relation between defoliation and wood quality (Figure 7 c,d), the median defoliation for wood quality class 1 is about 15%, with most trees losing between 10% and 20% of their leaves. Also, outliers above 40% were observed in wood quality class 2; the median defoliation remains around 15%, with most trees losing between 10% and 20% of their leaves and outliers exceeding 40%. For wood quality class 3, the median defoliation increases to around 20%, with most trees losing between 10% and 30% of their leaves. Outliers in this class go beyond 40%, reaching up to 60%. Wood quality class 4 has the highest median defoliation at about 30%, with most trees losing between 10% and 40% of their leaves and several outliers exceeding 40%. Defoliation increases with lower wood quality classes, with class 4 showing the most extreme defoliation.

The results show that the majority of trees in the study were classified as having the highest wood quality, comprising 55% of the total. The subsequent wood quality classes were represented as Class 2 at 27%, Class 3 at 12%, and Class 4 with the smallest proportion at 6%.

The analysis reveals that the majority of trees in the study are classified as having the highest wood quality and exhibit lower levels of defoliation. In contrast, the lower wood quality classes contain fewer trees but exhibit higher and more variable defoliation rates. This observed relationship suggests that the vulnerability of tree wood quality may be influenced by defoliation, which is an important issue for effective forest management and conservation strategies.

Ecosystem Services and Recreational Value of a Park Forest

Our research focused on a brief literature review of relevant studies on the ecosystem services provided by park forests, particularly their microclimatic influence, air quality improvement, pollution mitigation and recreational value. These findings provide essential information for the next section, Establishment and Management of Park Forests, which serves as a guide for designing and managing these forests to maximise their ecological, social and economic benefits.

Regarding the regulation of the local microclimate, previous research has emphasized the significant role of forests, especially during the summer months. Studies indicate that forested areas generally maintain temperatures 1°C to 3°C cooler than surrounding open spaces (Scripcaru et al. 1987, Nowak & Heisler 2010), providing a natural cooling effect that increases visitor comfort and reduces heat stress (Negruțiu 1980, Lin et al. 2013). In addition, research conducted in Romanian forests near Sărata Monteoru and Bușteni shows that humidity levels inside forests can be 16% to 23% higher than in adjacent open areas (Tinel 2011). Another key microclimatic function of forests is their ability to act as wind barriers, with tree canopies reducing wind speed by up to 20 times the height of the trees (Tinel 2011). These combined effects create a stable and pleasant microclimate for the benefit of visitors and local biodiversity. Understanding these mechanisms is essential for planning park forests' spatial distribution and species composition to optimize their cooling and wind regulation capacities.

At the same time, forests are essential in air purification and pollution control. They absorb carbon dioxide and filter pollutants from the air, with studies showing that urban forests can reduce concentrations of particulate matter by 3 to 6 times compared to non-forested areas (Nowak et al. 2006, Escobedo & Nowak 2009, Tinel 2011). Dense canopy cover and understory vegetation act as natural air filters, trapping harmful pollutants and improving overall air quality. In addition, forests contribute to noise reduction (Nowak et al. 2006, Almeida et al. 2018, Kim & Coseo 2018), with research estimating that tree belts can reduce noise levels by about 1.8 dB per row of trees, especially when strategically arranged (Tinel 2011). The presence of natural sounds, such as the rustle of leaves and birdsong, further enhances the visitor experience, providing a calming alternative to urban noise pollution (Almeida et al. 2018, Vieira et al. 2018).

The forest park is an important tourist and recreational destination, attracting many visitors yearly. According to data from the Peles National Museum, visitor numbers have fluctuated in recent years, with a dip in 2020 due to the COVID-19 pandemic, followed by a steady recovery. In 2022, more than 274,000 visitors were recorded, generating an estimated economic impact of €2.4 million (Figure 7) and highlighting the dual role of forests, both ecological and as a major contributor to local tourism and economic development.

Nevertheless, it can be considered that the results obtained from this literature review provide essential data for the effective planning and management of park forests. All these contribute to the development of guidance on the Establishment and management of park forests by identifying key principles and strategies for the design and maintenance of these forests in order to maximise their ecological, recreational and economic benefits.

Discussion

Descriptive statistics

Since silvicultural interventions in the PPF have been minimal over time, the arboretum's structure can be considered semi-natural due to the relatively low intensity of human activities. This minimal intervention has allowed the forest to grow and develop primarily on its own, preserving its natural characteristics and biodiversity.

The statistical data highlights the semi-natural character of the Peleș Park Forest, suggesting limited human interference and a well-preserved natural structure. Other studies have reported similar findings (Cristea et al. 2019). The diverse habitat composition, including hardwood and coniferous tree species, has contributed to the Peleș forest's rich biodiversity and ecological resilience (Pravalie et al. 2014, Cristea et al. 2019).

The high variability observed in DBH, tree height, and wood volume underscores the forest's ecological vitality and capacity to provide essential ecosystem services (Cicșa et al. 2021). Maintaining the diverse structural composition of the Peleș Park forest is crucial for supporting key ecosystem services, such as carbon sequestration, water regulation, and biodiversity conservation (Brockerhoff et al. 2017, Glushkova et al. 2020, Pache et al. 2020).

The presence of old-growth elements, as evidenced by the variability in tree sizes, sustains wildlife species and contributes to the overall stability and resilience of the forest ecosystem (Luyssaert et al. 2008). This diversity in tree sizes is likely driven by differences in species composition, age distribution, and growth rates within the forest. Effective forest management should aim to preserve these natural dynamics to ensure the long-term sustainability and ecological integrity of the Peleș Park forest (Stancioiu et al. 2010, Dobre et al. 2017, Cristea et al. 2019).

By understanding the interrelationships among factors like tree diameter, height, species, and leaf health, managers can develop tailored management practices that prioritise the preservation of ecologically important species while selectively harvesting timber resources (Cicșa et al. 2021).

Ongoing monitoring and integration of additional variables, such as wood quality and forest floor composition, will further enhance the comprehensive understanding of forest dynamics and inform more holistic conservation strategies (Lindenmayer et al. 2000, Chaudhary et al. 2016, Parisi et al. 2018).

Correlation matrix

The study of forest ecosystems needs a deep understanding of the relationships between various tree attributes, which is crucial for effective forest management, conservation, and ecological research. Analysing the interrelationships among multiple factors within Peleș Park's forests provides significant insights for their management and conservation efforts. One notable finding is the robust correlation observed between diameter at breast height and tree height (Dobre et al. 2017). This relationship enables the development of predictive models that estimate tree height based on DBH measurements (Gering & May 1995, Westfall 2010, Hackenberg et al. 2014). Such models are instrumental in forest inventory assessments and in calculating biomass and carbon sequestration potential (Westfall 2010).

Understanding these species-specific effects can inform the development of tailored management practices. For instance, particular species may be prioritised for timber extraction due to their favourable growth characteristics, while others are preserved for their ecological importance (Sist et al. 2003).

Principal Component Analysis

PCA has revealed the patterns and relationships between variables within our dataset, offering a consolidated view that enhances our understanding of the underlying data structure. By transforming the original variables into principal components, PCA enabled us to explore how variables interact and contribute to the overall variability observed in our study (Li et al. 2008, Thers et al. 2019).

The eigenvalues derived from PCA provided a quantitative measure of how much variance each principal component explains. Notably, Dim. 1 emerged as the dominant component, capturing 57.383% of the total variance. This suggests that a significant portion of the dataset's variability can be attributed to a few key dimensions, highlighting their importance in defining the data's structure.

The projection of individual data points onto the principal components offered further insights into the distribution and clustering of our samples in the reduced-dimensional space. We identified distinct groups and outliers by analysing each data point's coordinates, contributions, and squared cosines, revealing inherent patterns and anomalies within our dataset.

The insights gained from PCA hold substantial implications for park forests. By identifying underlying data patterns and reducing dimensionality, PCA facilitates more focused analyses and informed decision-making. For instance, in forestry, understanding the principal components can help optimise the management of these ecosystems by focusing on variables that contribute most significantly to the observed patterns (Li et al. 2008, Goginashvili et al. 2021).

Height and volume structure

Understanding tree height, volume, and DBH interrelationships is crucial for effective forest management. The observed variability in tree height and the strong correlation between DBH and tree volume underscore the complex structure of the forest, which is pivotal in supporting biodiversity and ecosystem functioning (Hackenberg et al. 2014). Recognizing this dynamic enables the formulation of management strategies that maintain a balanced forest structure, foster sustainable growth, and enhance the provision of ecosystem services (Dorren et al. 2004, Carvalho et al. 2020). This understanding facilitates the implementation of interventions that simultaneously support ecological health and resource sustainability.

Relation between health status and cenotic class

There is a clear trend of increasing median defoliation from cenotic class 1 to class 3. The variability in defoliation also rises with the cenotic class, as evidenced by the widening IQRs. Each cenotic class contains outliers, but the magnitude and number of outliers increase with the class number, particularly notable in class 3. These findings suggest that lower cenotic classes are associated with greater and more variable defoliation, possibly due to various ecological factors affecting the different classes differently, such as variations in tree species, age, density, or susceptibility to pests and diseases (He et al. 2008). Understanding these differences can help effectively manage and conserve the park forest.

In addition, the fact that the presence of large trees does not allow the installation of natural regeneration suggests that in the future, the trees in the Peles Park Forest will reach physiological maturity, and only after their death will it be possible to install artificial or natural regeneration, as appropriate. It is also emphasised that, to have a continuity in the efficiency of the park forests, the management must be carried out continuously and constantly to obtain the optimal structure characteristics of these forest ecosystems (Dorren et al. 2004).

Relation between health and wood quality

The analysis of defoliation in relation to cenotic class and wood quality provides valuable insights into the health and resilience of the forest in the studied park area. The data indicate significant differences in defoliation rates across different classes, which have important implications for forest management and conservation strategies (Heidenreich & Seidel 2022).

Recent studies have shown that insect defoliation can significantly impact wood quality. For example, research on fir in Quebec revealed that prolonged defoliation leads to notable declines in wood properties (Iqbal et al. 2012). This finding aligns with our observations that higher wood quality classes, which likely correspond to healthier trees, exhibit lower defoliation percentages. Also, it underscores the importance of monitoring and managing defoliation to maintain forest productivity and ecological balance.

Our results demonstrate that defoliation percentage increases with lower cenotic class, indicating that trees in more competitive environments (lower cenotic class) are more susceptible to defoliation. This trend might be due to the increased stress from competition for resources, making trees more vulnerable to pests and diseases.

Strategies should focus on reducing tree competition and enhancing tree health to mitigate defoliation impacts. For instance, thinning practices could decrease competition, improving tree vigour and resistance to pests.

Regularly monitoring defoliation rates and wood quality can help identify at-risk areas and enable early intervention. Implementing integrated pest management strategies can also effectively control insect populations and minimise defoliation damage.

The structural characteristics of park forests, including DBH, height, volume, wood quality and tree defoliation, play a significant role in providing ecosystem services (Mexia et al. 2018). Understanding these aspects is essential for assessing how effectively a park forest can fulfil critical functions such as carbon sequestration, habitat support and microclimate regulation. Relationships between variables such as diameter and height or volume explored through correlation matrices and PCA analysis, providing insight into the overall health and resilience of the forest. These structural indicators are directly related to the ability of the forest to provide services such as air purification, noise reduction, and enhanced recreational experiences. Therefore, forest structural analysis not only highlights the current state of the forest but also informs management practices to optimise the ecosystem services it provides (Patterson & Coelho 2009, Deal et al. 2012, Felipe-Lucia et al. 2018).

Ecosystem services and recreational value of PPF

The ecosystem services provided by the PPF underscore the multifaceted value of urban forests. By moderating local climate conditions, improving air quality, reducing noise pollution, and offering psychological benefits, the forest is vital in enhancing the quality of life for both residents and visitors (Kim et al. 2021). The economic value derived from tourism further emphasises the importance of maintaining and protecting such areas, particularly in the face of increasing urban development (Rodríguez-Piñeros & Mayett-Moreno 2015).

The benefits of urban forests extend far beyond their aesthetic value (Chaudhry 2011, Yuan et al. 2018) are integral to the environmental health of urban areas, contributing to cleaner air, more stable climates, and improved mental well-being for those who frequent them. The preservation of the Peleș Park Forest and similar areas is crucial for sustaining these benefits and ensuring that urban populations have access to natural spaces that offer ecological and recreational value.

Implications for Park Forest Management

The structural complexity and ecosystem service assessments in the Peles Park Forest (PPF) provide valuable insights into how urban and peri-urban forests can be effectively managed to achieve ecological, social and economic objectives. Although the current study did not experimentally test alternative management strategies, the data highlight key forest characteristics (e.g., uneven-aged structure, species composition, visitor impacts) that inform practical recommendations. Based on these findings and supported by existing literature, this section presents basic considerations and strategies for establishing and sustainably managing park forests (see Supplementary Material 1).

Effective park forest management requires a strategic, integrated approach that balances ecological integrity with human use. The ultimate goal is to create multifunctional landscapes that provide biodiversity support, recreational opportunities and economic value. These ecological, social and economic benefits can only be sustained through comprehensive planning and adaptive management. Our analysis and best practices suggest the following key principles:

a) Site selection and habitat diversity

Strategic site selection is fundamental to maximising biodiversity and long-term forest resilience. Forest parks in areas with diverse topography, soil types and microclimatic conditions can support a richer variety of plant and animal species. Developing heterogeneous habitat mosaics - such as a combination of clearings, dense canopy zones and wetlands - enhances ecological resilience and supports a higher species diversity. These strategies align with research emphasising the role of habitat heterogeneity in maintaining ecosystem health.

b) Species composition and ecosystem health

PPF data show that the mix of native beech and fir contributes to forest resilience. Promoting native species in park forests, especially those adapted to local environmental conditions, is essential. Native trees provide better growth and support wider ecological networks by supporting native wildlife. A balance between deciduous and coniferous, deciduous and evergreen species can enhance year-round ecological functions and improve ecosystem stability (Angelstam et al. 2004, Lõhmus et al. 2014).

c) Soil and water management

Maintaining forest structure in PPF reflects minimal soil disturbance, vital for long-term sustainability. Application of sustainable soil and water management techniques - such as mulching, earth terracing and controlled drainage - can prevent erosion, improve nutrient cycling and protect groundwater. These measures are essential for maintaining the health of forest ecosystems and ensuring the continued provision of regulatory services such as water purification and soil retention.

d) Recreational and educational infrastructure

Given the significant visitor pressure on the PPF, recreational planning is critical.

The design of trails, rest areas and signage should minimise ecological disturbance while enhancing the visitor experience. Educational programs integrated into these facilities can raise awareness about forest conservation and encourage responsible behaviour. Evidence shows that such initiatives promote community responsibility and long-term support for park management.

e) Economic and recreational benefits

Tourism data from the Peles National Museum demonstrates the economic importance of peri-urban park forests. In 2022 alone, more than 274,000 visitors generated local economic benefits estimated at €2.4 million (Figure 8). This highlights the value of forest parks as ecotourism assets. Improving recreational infrastructure while protecting ecological integrity can ensure that park forests simultaneously contribute to well-being and local development.

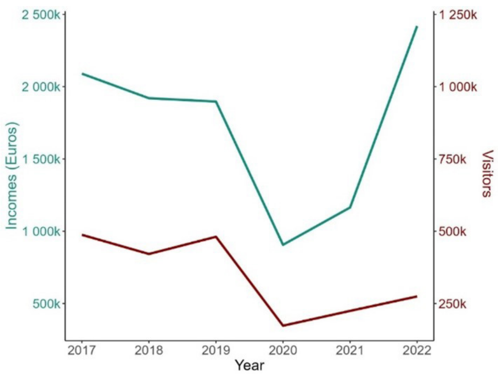

Figure 8 Relationship between visitors' income and number.

f) Community involvement and conservation

A constant theme in successful park forest management is the involvement of local communities. Involvement through volunteering, education and partnerships promotes a culture of stewardship. In the PPF and other similar contexts, community-oriented models help align conservation objectives with local needs, increasing ecological and social resilience.

These implications, supported by this review and the literature (e.g., (Angelstam et al. 2004, Lõhmus et al. 2014, Kumar et al. 2019), emphasise the importance of a holistic approach to park forest management. By combining ecological understanding with participatory governance and adaptive strategies, managers can ensure the continuous provision of ecosystem services and sustainable use of forest landscapes in urban and peri-urban contexts.

Conclusions

PPF provides indispensable ecosystem services that bolster the region's environmental and economic vitality. By moderating the local microclimate, purifying the air, mitigating noise pollution, and providing a serene space for recreational pursuits, the forest represents a pivotal resource for both the local populace and visiting individuals.

The study underscores the need for ongoing monitoring of tree health. Although the current data lacks correlations between structural characteristics and tree health indicators, future investigations should explore these connections to enhance our understanding of forest vitality.

Analysing the relationship between DBH, height, and species is crucial for accurately estimating wood volume. This knowledge is essential for implementing effective forest management strategies and resource planning.

Our results highlight the interconnected nature of forest components. Factors such as wood quality and forest floor composition play important roles in ecosystem function, although their specific correlations were not assessed in this study. Future investigations should integrate these variables to obtain a more comprehensive understanding of forest dynamics and ecosystem processes. At the same time, persistent initiatives to conserve and manage the PPF are essential in sustaining these benefits and ensuring its continued status as a key asset amidst the context of increasing urbanisation.

Also, establishing and managing urban park forests are critical in addressing the pressing global challenges of urbanisation, climate change, and biodiversity loss. By implementing the guidelines outlined in this research, park managers can cultivate resilient, diverse forest ecosystems capable of providing various ecosystem services that benefit both natural environments and human communities.

Ongoing research, community engagement, and adaptive management practices are essential for addressing future challenges and ensuring the long-term sustainability of these vital urban green spaces. Through thoughtful planning and management, park forests can continue to serve as invaluable ecological and social resources, enhancing the overall quality of life for present and future generations.

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