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Estimating carbon sequestration based on urban tree species: Findings from Bucharest

Urbanization has intensified since the First Industrial Revolution, generating acute socioeconomic and environmental pressures for local authorities, particularly in relation to air quality management. Declining air quality in urbanized areas remains a central challenge, and urban spaces with vegetation, especially urban trees, are increasingly valued for their regulatory ecosystem services. This study examines the potential of urban trees for CO_2 sequestration in Bucharest, Romania. Tree distribution and species composition were spatially represented with geographic information systems (GIS) based on data from the city's Green Registry, and sequestration potential was quantified using validated assessment tools. The results reveal pronounced spatial disparities, with substantial deficiencies in tree cover across several districts. The capacity of areas covered by trees and shrubs to sequester CO_2 is negligible relative to overall urban emission levels. Native species display greater sequestration efficiency, although nonnative species dominate urban landscapes, largely reflecting financial and aesthetic preferences in planting practices. These findings underscore the limited regulatory impact of current urban tree cover on carbon sequestration and emphasize the need for targeted, nature-based strategies – particularly the expansion of native vegetation – to support urban carbon sequestration management.

Keywords: GIS, nature-based solutions, ecosystem services, green infrastructures, Romania

1 Introduction

The Industrial Revolution and the technological advancements of the past century have accelerated the pace of global urbanization, resulting in the emergence of highly dense urban settings (Morris 2013). Historical factors, geographic location, and the availability of key resources have allowed several human settlements to evolve into major economic hubs (Gavrilidis et al., 2015). However, the polarization of resources and population often leads to overcrowding (Booth et al., 2020). If not effectively managed, overcrowding negatively affects the overall quality of urban life, acting as a key driver of urban sprawl and environmental degradation (Gavrilidis et al., 2019). Increasing urban density necessitates the expansion of built-up areas, a process that is frequently detrimental to natural and semi-natural landscapes (Dewan & Corner, 2014). The reduction of areas covered by vegetation in already densely populated urban environments has medium- and long-term consequences for the well-being of urban residents (Popa et al., 2022). Urbanization is regarded as a dynamic socioeconomic phenomenon, influenced by a range of natural and anthropogenic factors, and contributing to high population densities and increased pressure on undeveloped land. The complexity and rapid pace of transformations occurring in urban environments have compelled researchers to assess the effects of ongoing urbanization trends. In this context, policymakers and decision-makers tend to prioritize grey infrastructure and the expansion of residential, commercial, logistics, industrial, and business centres because such developments generate direct economic returns (Dong et al., 2017).

The reduction of permeable surfaces in urban areas alters stormwater runoff patterns, increasing both sewage system maintenance costs and the extent of damage during and after heavy rainfall events (Kong et al., 2017). Furthermore, the loss of vegetated areas because of infill development leads to declining air quality, increased noise pollution (Badiu et al., 2018), and intensification of the urban heat island effect (Gunawardena et al., 2017). As built-up densities increase, available land has become one of the most highly valued urban resources (Gavrilidis et al., 2020). Consequently, a key challenge for city planners, policymakers, and decision-makers is maintaining a balanced relationship between built-up and undeveloped land (Kronenberg et al. 2020). Against this backdrop, although most countries have acknowledged the importance of achieving the Sustainable Development Goals (SDGs) (United Nations, 2015), researchers have emphasized that meeting these targets entails substantial costs and requires the development of appropriate financial tools and programmes (Barua, 2020). The SDG targets and monitoring indicators highlight the need for economic development alongside the efficient management of natural resources. Three of the ten targets of SDG 11 – most relevant to this study – address the preservation of natural features and equitable access to them within urban and urbanized areas. Accordingly, a critical priority for research lies in demonstrating to local and national authorities that integrating natural features into urban landscapes offers a viable pathway to achieving multiple sustainability targets in cities. However, to meet the SDGs over the coming decade, researchers must also understand the needs of policymakers and other stakeholders, and they must develop effective methods that deliver practical and actionable evidence (Allen et al., 2021).

Undeveloped land is becoming increasingly scarce in large cities, making the planning of substantial urban green features particularly challenging. As urban expansion continues, large green spaces, such as parks and gardens, have become less accessible and increasingly subject to infill development (Stoia et al., 2022). In response to these pressures, the concept of ecosystem services has emerged as a framework to support decision-makers and the wider public in recognizing the benefits provided by ecosystems (Costanza et al., 1997). Given the relative scarcity of these benefits in urban environments, the integration of ecosystem services approaches into urban planning and management is strongly recommended (Bolund & Hunhammar, 1999). The implementation of nature-based solutions in urban planning and policy frameworks can enhance community resilience (Antuna-Rozado et al,. 2019; Bartlett & Mistry 2021). Organizing natural features into an urban green infrastructure network improves the provision of ecosystem services at the city scale (Van Oijstaeijen et al., 2020; Zhang et al. 2021). Extensive green areas dominated by trees and shrubs form the backbone of effective urban green infrastructure (Sanesi et al., 2017). Such areas, located within or at the edges of large cities, are widely recognized as critical assets for sustainability and improved quality of life (Felappi et al., 2020). The ecosystem services they provide are of considerable value (Li, 2021), placing them at the centre of multiple conservation policies (Goodspeed et al., 2022). Urban forests, although relatively uncommon in urban environments, differ substantially in definition and management from natural forests. In the context of the urgency surrounding the SDGs and carbon neutrality, local stakeholders and authorities are increasingly encouraged – through sectoral policies and financing programmes – to invest in the protection and expansion of urban forests (Wu et al., 2022).

Urban forestry is regarded as the art, science, and technology of managing trees and other forest resources within and around urban cores, with the aim of maximizing the physiological, sociological, economic, and aesthetic benefits that forests provide (Konijnendijk et al., 2006). Prior studies have highlighted how forests located within or surrounding cities can function as carbon sinks, actively sequestering carbon, as well as carbon stores, accumulating carbon in biomass. The efficiency of carbon-cycle management is strongly dependent on factors such as species composition and age structure (Boukili et al., 2017; Vais et al., 2023). Clearly, the carbon sequestration capacity of urban forests differs from that of natural forests due to intensive management practices, younger age structures, and frequent biomass removal (Fares et al., 2017). However, the amount of carbon sequestered by urban forests is considered relatively small in comparison to anthropogenic emissions, and their contribution to climate-change mitigation through sequestration is limited or negligible at the urban scale (Chen, 2015; Velasco et al., 2016). Even so, urban forests possess significant economic value as carbon sinks (Bherwani et al., 2024). In this context, planning and designating urban forests that fulfil the criteria outlined in the definition above presents significant challenges for local authorities, particularly due to high built-up densities and limited land availability. Consequently, local decision-makers should prioritize enhancing urban tree density as an alternative strategy. Although areas with higher tree density cannot fully substitute for the ecosystem services provided by forest ecosystems, the benefits they offer can substantially contribute to improving the economic, social, and environmental dimensions of urban living. The presence of tree- and shrub-covered areas within cities amplifies the benefits delivered by individual trees and shrubs, even when these elements do not collectively function as a fully integrated ecosystem. Furthermore, these benefits operate synergistically with those provided by natural and semi-natural ecosystems located at the urban periphery.

Whereas forest management typically adheres to strict regulations and requires specialized personnel (Ciornei, 2019; Ciornei & Munteanu, 2020), the management and maintenance of urban areas covered with trees and shrubs require different practices, uses, and skill sets. In this context, the focus should be on enhancing the provision of ecosystem services. The quality of these services depends on the management practices employed, as well as on species composition and vegetation quality (Mexia et al., 2018). Trees and shrubs act as significant carbon sinks, and their incorporation into urban environments plays a crucial role in climate-change adaptation and in mitigating the deterioration of urban air quality (Lashof & Neuberger, 2023). Careful species selection for planting, aimed at increasing tree density and expanding these types of areas, can strengthen cities' resilience to environmental hazards while improving residents' quality of life. This study investigates whether the density, distribution, and composition of urban trees in one of the most polluted capital cities in Europe play a role in CO_2 sequestration. To address this research question, the study's objectives were to assess the status of land covered with trees and shrubs, and associated tree densities, to identify the dominant species present, and to estimate the amount of carbon sequestered in Bucharest, disaggregated by tree species.

2 Data and methods

2.1 Study area

Bucharest, the capital of Romania, is located in the southeast of the country, in a plain. The city had a population of 1.79 million in 2021. When the additional 430,000 inhabitants of surrounding Ilfov County are included (National Institute for Statistics, 2023), Bucharest forms Romania's most densely populated urban agglomeration. Over the past thirty years, the population within the city boundaries has decreased by 1.5%, corresponding to an average annual growth rate of −0.5%. In contrast, Ilfov County's population has grown by nearly 40%, with an average annual increase of 1.82% (Figure 1). Consequently, at the regional level (Bucharest and Ilfov County combined), the population has increased by 5.95% over the last three decades. Considering the demographics of the surrounding county is essential when analysing Bucharest because a large share of the population commutes to the city for employment and social activities (Cristea et al., 2017). Examining these demographic trends alongside changes in the number of dwellings reveals a pattern of urban sprawl in Bucharest and Ilfov County, a phenomenon identified in previous studies (Suditu, 2009; Simion & Nistor, 2012). Over the past three decades, the number of dwellings in Bucharest has increased by 26%, with an average annual growth rate of 1.03%, whereas in Ilfov County the number of dwellings has surged by 69%, corresponding to an average annual increase of 3.87%. These trends indicate an expansion of built-up areas at the expense of natural and semi-natural landscapes because new residential developments are accompanied by infrastructure and other urban functions (e.g., commercial, logistics, and business uses).

Romanian regulations classify a wide range of land uses and land covers as green spaces (*Lege nr. 24/2007 (republicată)*, Monitorul Oficial, no. 764/2009). However, some of these areas, such as institutional gardens, are not open to the public, whereas others, including sports grounds or cemeteries, are largely composed of concrete structures. National statistics on green space are based on these regulatory classifications. According to official data, Bucharest has lost approximately 7% of its green space since the fall of the communist regime (National Institute for Statistics, 2023). Similar conclusions have been reached in previous studies, which identified the primary loss of green space as occurring in gardens adjacent to multi-dwelling housing projects, in which these areas were rapidly converted into parking lots (Badiu et al. 2018). When

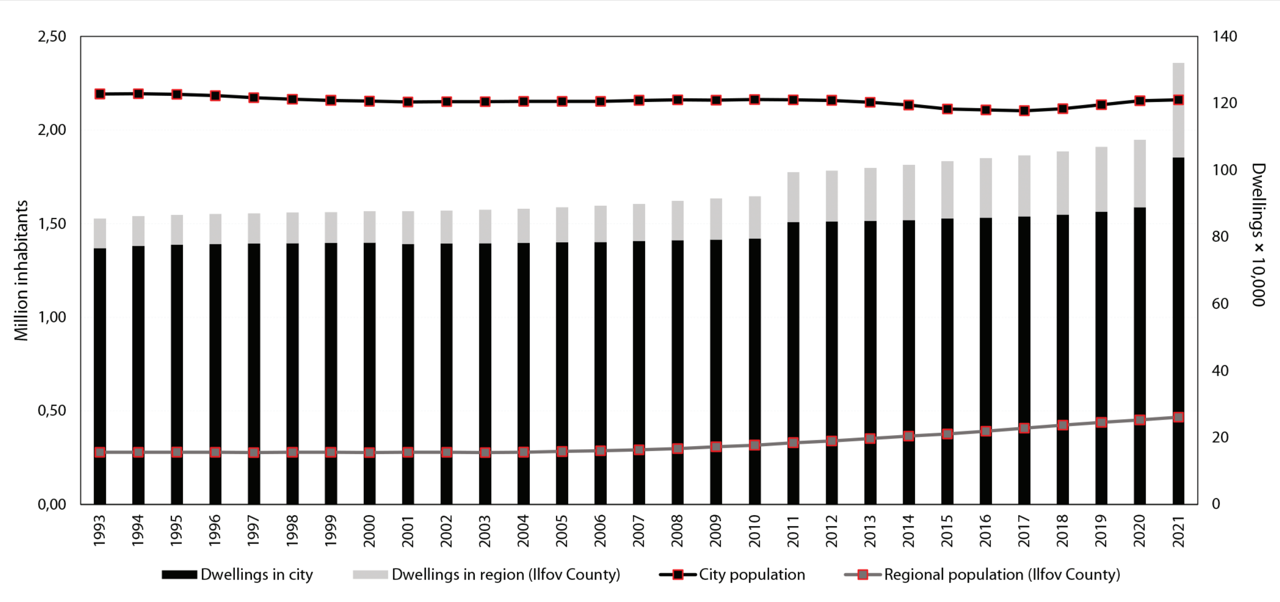

Figure 1: Population and dwelling number dynamics in Bucharest and surrounding Ilfov County in the past three decades (data source: National Institute of Statistics, 2023).

data for Bucharest are combined with those of surrounding Ilfov County, the total land area classified as green space has increased by approximately 14% over the past thirty years. This trend is attributable to the fact that in Ilfov County the development of new built-up areas has included the planning of new green spaces, classified as such under national regulations, whereas within Bucharest's administrative boundaries these urban green spaces have been reduced in size. In both Bucharest and Ilfov County, the largest and most compact natural and semi-natural areas are located in the north (Figure 2).

2.2 Analysis of urban areas covered with trees and shrubs

Areas covered with trees and shrubs were defined as land patches consistent with the FAO definition of "other land with tree cover." Specifically, this category includes urban land uses with tree cover exceeding 0.5 hectares, a canopy cover greater than 10%, and trees capable of reaching a height of at least five metres at maturity. This definition encompasses both forest and non-forest tree species (Hendriks et al., 2021). The data used to analyse the distribution of areas covered with trees and shrubs in Bucharest were derived from two sources: georeferenced point features from the Bucharest Green Registry (Primăria Municipiului București, 2010) and the 2018 small woody features vector layers from the EU's Copernicus platform. Both datasets were processed using ESRI's ArcGIS Pro software. Green Registry data were analysed by creating a grid with a cell size of 1 hectare using the Create Fishnet tool in ArcGIS Pro. The Intersect function within the same GIS environment was then used to extract the number of trees and shrubs per hectare. The small woody features layers were used to compare distribution patterns between the two datasets, given their differing methodologies (Table 1).

2.3 Urban tree and shrub species analysis, and carbon sequestration estimates

The data used to plot the urban tree species abundance were extracted from the Bucharest Green Registry. Although the

Table 1: Input data used for the distribution analysis of urban areas covered with trees and shrubs.

Data	Type	Year	Processing method
Trees	Point	2010	The geolocations of trees and shrubs were gathered during a general survey ordered by the local municipality in 2010 to generate the Green Registry of Bucharest. This database consisted of vector points that were further processed in the study using a grid with the cell size of 1 ha.
Small woody features	Polygon	2018	Supervised classification of satellite image time series from VHR_IMAGE_2018 acquired from May 2017 to September 2019. For patchy structures of trees and scrub the MMU is > 200 m^2 (size limit of 50,000 m^2). The MMW for linear structures/elements is < 30 m. The MML for linear structures/elements is > 30 m. The positional accuracy is less than 5 m.

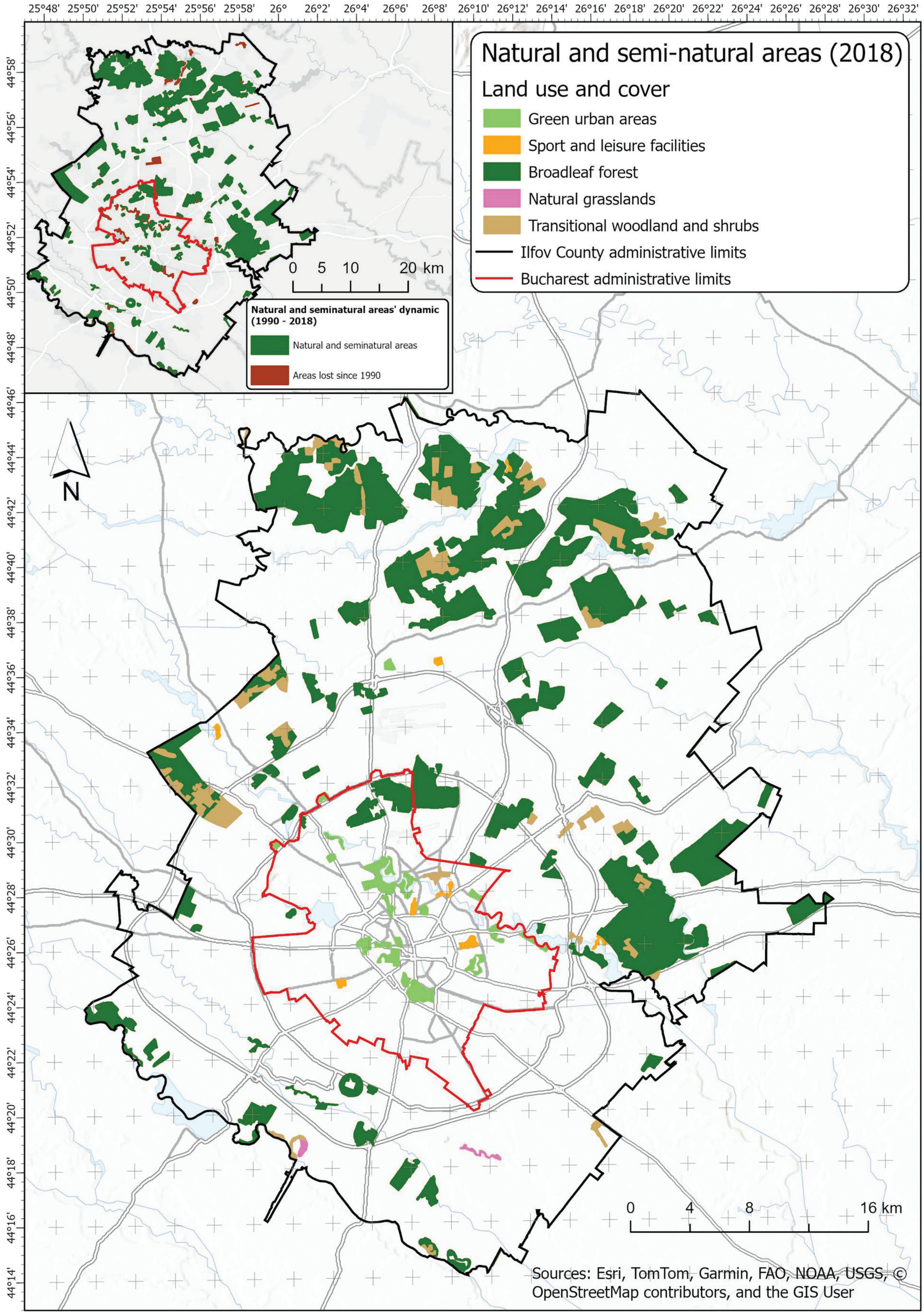

Figure 2: Distribution of natural and semi-natural areas in Bucharest and Ilfov County in 2018. Inset: Natural and semi-natural areas lost since 1990 (spatial data source: https://land.copernicus.eu/en).

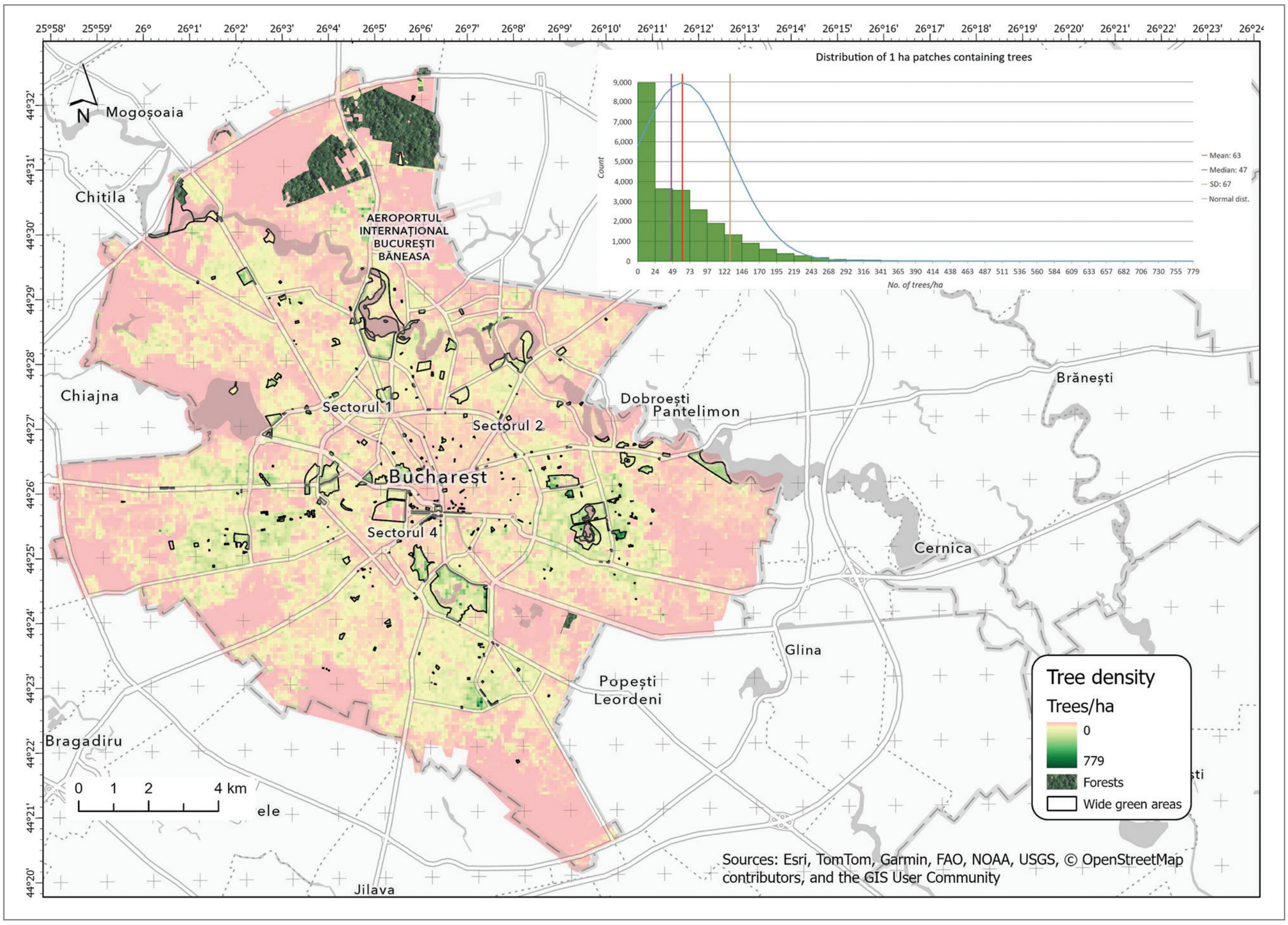

Figure 3: Urban tree density distribution within Bucharest, expressed in number of trees per hectare.

dataset lacks detailed geolocation data (such as species, age, and height), the Green Registry includes overall information on the number of individuals for each species. The data were further processed to classify species based on several criteria: plant type (tree/shrub), leaf type (coniferous/deciduous), origin (native/nonnative), and allergenic potential (allergenic/non-allergenic). In addition, the dataset was utilized to determine the total number of individuals for each species. These data were processed using Microsoft Excel. To estimate the carbon sequestration capacity of tree species in Bucharest, values reported by the European Environment Agency (EEA) and the One Tree Planted platform were aggregated. According to the EEA, a mature tree sequesters approximately 21.77 kg of CO_2 per year and releases oxygen in the process (European Environmental Agency 2010). The One Tree Planted platform estimates that an average tree absorbs around 10 kg of CO_2 annually (Bernet, 2023). Given that the atomic weight of carbon is 12 and that of oxygen is 16, the molecular weight of CO_2 is 44. Consequently, the amount of carbon in a given quantity of CO_2 can be calculated by multiplying the amount of CO_2 by 0.27 (Farquhar & Lloyd, 1993). Owing to variability in carbon sequestration rates – driven by factors such as species, age, and height – an average value of 4.29 kg of carbon sequestered per tree per year was adopted for this study. Using this estimate, the urban tree density grid created for Bucharest was applied to map the amount of carbon sequestered per hectare across the city. Furthermore, drawing on data from previous studies assessing air-pollutant sequestration by tree species (Nowak et al., 2006, 2013), the most effective native tree species in mitigating urban pollution – particularly in terms of carbon sequestration – were identified. Finally, the total amount of carbon sequestered by each urban tree species in Bucharest was estimated based on the number of individual trees and the average amount of carbon absorbed by a single mature tree.

3 Results

3.1 Distribution of urban areas covered with trees and shrubs

The urban tree density analysis in Bucharest revealed significant spatial disparities. The outskirts of the city, together with central areas, exhibit a notable lack of trees, with these zones recording a higher prevalence of one-hectare patches devoid of tree cover (Figure 3). In contrast, the intermediate zones of

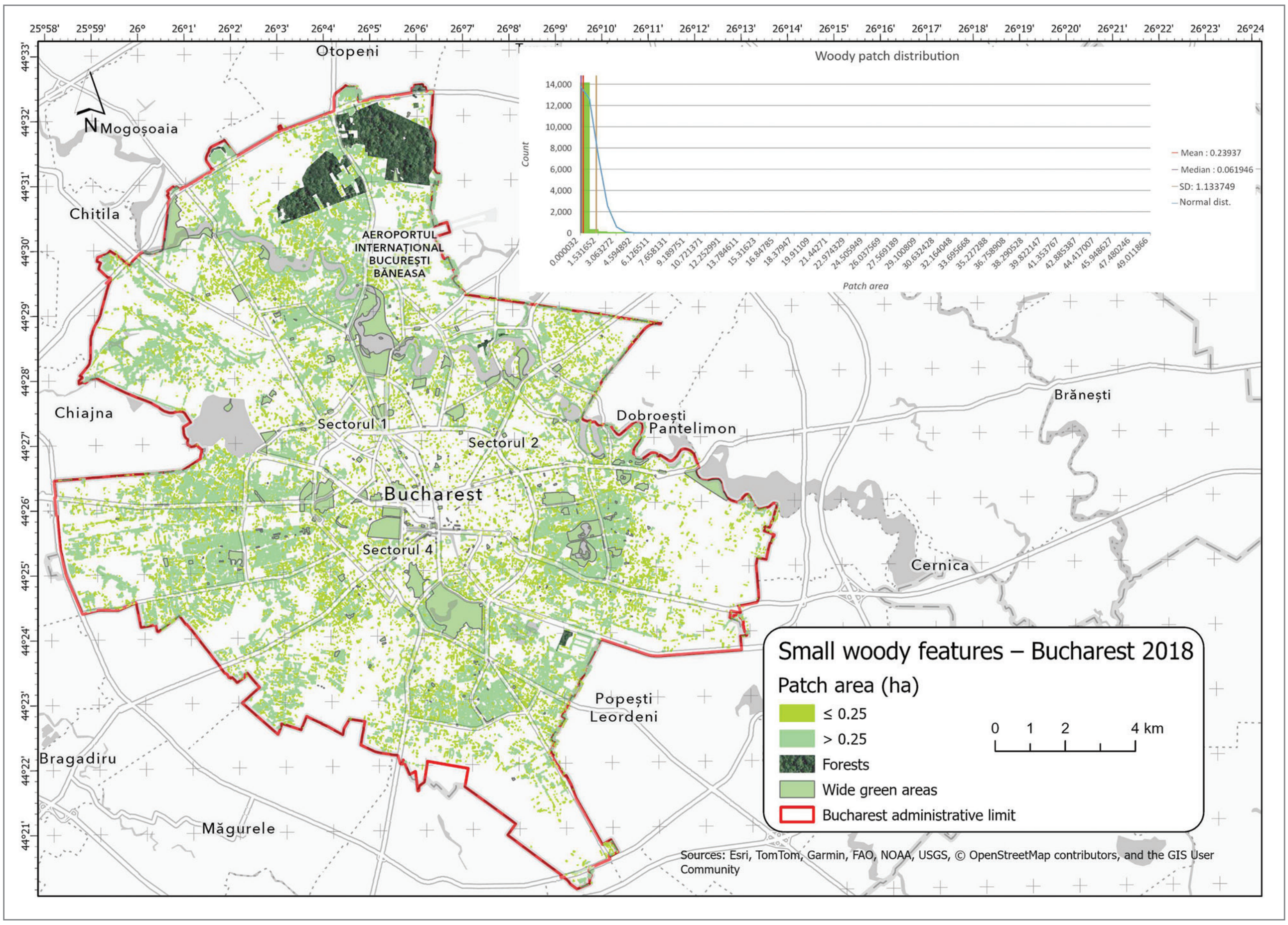

Figure 4: Small woody features distribution within Bucharest.

the city display a greater number of one-hectare patches with higher tree densities. Neighbourhoods in the eastern, western, and southern parts of Bucharest show relatively higher tree densities per hectare compared with other areas. The highest tree densities per hectare are concentrated in large parks, which serve as key green assets within the city. Of the total one-hectare land patches generated to cover Bucharest's administrative boundaries, approximately 36% have a tree density of fewer than twenty-four trees per hectare, and around 41% of the patches contain between twenty-five and one hundred trees. The spatial representation of the small woody features layer highlights a distribution pattern that confirms the findings from the tree density analysis (Figure 4). Neighbourhoods in the east, west, and south exhibit the highest coverage of areas covered with trees and shrubs, whereas the outskirts and the city centre continue to show a noticeable lack of such features. These areas are often located at the edge of large parks dispersed throughout the city. Of the small woody features patches covering Bucharest, approximately 87% are smaller than 0.25 hectares – a minimum threshold defined by national regulations for a group of trees to qualify as a forest. Despite these patches being smaller than 0.25 hectares, cumulatively they represent around 26% out of the total small woody features existing in Bucharest. This indicates that Bucharest benefits from larger, more compact woody features that contribute substantially to its overall tree cover.

3.2 Urban tree and shrub species and their efficiency in carbon sequestration

The Bucharest Green Registry reports a total of 1,647,517 trees and shrubs distributed across the city, comprising 219 recognized species. However, only around 11% of the recorded trees have been definitively identified at species level. As illustrated in Figure 5, of the identified species, 76% are tree species and 24% are shrubs. The majority (78%) are deciduous species. A notable finding is that most tree and shrub species are nonnative (67%), with a smaller proportion being native. In addition, a substantial number of species are considered allergenic (35% of the total species). The analysis of the number of identified individuals per tree and shrub species revealed that all species with populations exceeding 10,000 individuals are trees. Among these species, 38% are nonnative. The most widespread nonnative species include box elder (*Acer negundo*), black locust (*Robinia pseudoacacia*), Oriental arborvitae (*Platycladus orientalis*), arborvitae (*Thuja occidentalis*), white ash (*Fraxinus americana*), tree of heaven (*Ailanthus altissima*), and lilac (*Syringa vulgaris*), each with more than twenty thousand individuals recorded across the city. The most abundant species in Bucharest is pedunculate oak (*Quercus robur*), with 114,250 individuals, accounting for 9% of the total number of trees and shrubs identified in the city.

Using the previously established average carbon sequestration capacity of an adult tree (4.29 kg/year), it is estimated that trees and shrubs in Bucharest sequester approximately 6,090 tonnes of carbon annually. As expected, neighbourhoods with higher urban tree densities per hectare correspond to areas where the largest amounts of carbon are sequestered (Figure 6). The highest recorded value for a single one-hectare patch was 3.34 tonnes of carbon sequestered in one year. Based on the gross carbon sequestration capacity of various tree and shrub species, the most effective native species in Bucharest are silver birch (*Betula pendula*), cherry plum (*Prunus cerasifera*), sessile oak (*Quercus petraea*), downy oak (*Quercus pubescens*), pedunculate oak (*Quercus robur*), sycamore (*Acer pseudoplatanus*), field maple (*Acer campestre*), hornbeam (*Carpinus betulus*), and manna ash (*Fraxinus ornus*). Each of these species can sequester more than 5 kg of carbon per year. When considering both the number of individuals present in Bucharest and their carbon sequestration capacity, it is noteworthy that four of the five most efficient tree and shrub species for carbon sequestration are nonnative (Figure 7). However, the superior performance of these nonnative species is primarily attributable to their higher abundance rather than to greater carbon sequestration capacity at the individual tree level.

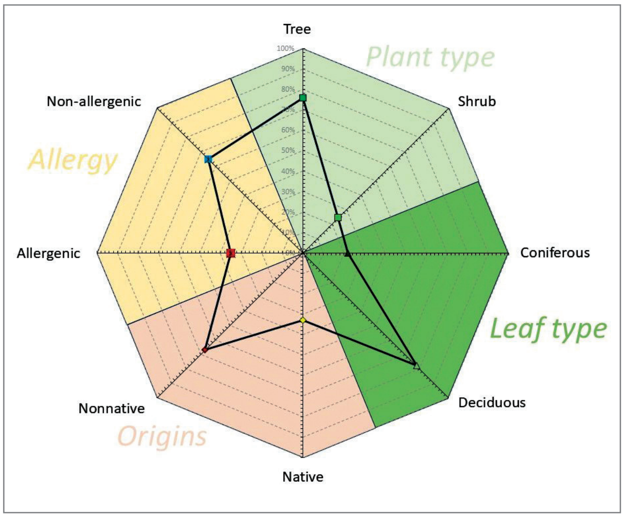

Figure 5: Characteristics of species among urban trees and shrubs in Bucharest.

4 Discussion

This study identified critical areas in Bucharest in terms of urban tree and shrub cover. This was complemented by an estimation of carbon sequestration capacity based on the tree species present in the city. Together, these results may provide a foundation for the development of coherent and effective plans aimed at expanding areas covered with trees and shrubs in Bucharest. Urban environments are dynamic systems, and unbuilt land is a vital resource. In this context, planning or designing urban forests for climate-change adaptation and carbon sequestration becomes a multifaceted challenge. The specific challenges associated with urban green infrastructure planning are largely linked to governance and management, particularly due to the weak integration of urban forestry into urban planning frameworks. These concerns generally relate to species and layout selection, maintenance and monitoring costs, and the survival of planted specimens (Suhane et al., 2024). The last issue is not necessarily related to the selection of tree or shrub species suited to local climatic conditions, but rather to the quality and quantity of urban soils (Jim et al., 2018). Therefore, although establishing extensive urban forests in large cities is constrained by land scarcity, increasing the density of trees and shrubs on available land may be a suitable alternative approach.

The distribution of trees in Bucharest can be explained by the challenges outlined above because land availability for planting is limited in the city centre, and suitable soils are either absent or inadequate in terms of quality. Higher tree densities were recorded further from the city centre, particularly in neighbourhoods planned during the communist period, supporting findings related to uneven green space distribution in large cities (Tatlić et al., 2024). As an eastern European city where post-communist planning approaches overlapped with the centralized communist planning paradigm (Csomós et al., 2021), Bucharest shows disparities in the distribution of areas covered with trees and shrubs that resemble patterns identified in previous studies conducted in post-communist cities. Sector-based and fragmented planning systems, combined with weak legal enforcement mechanisms, are considered key drivers of disparities in urban green space distribution (Vasiljević et al., 2018). Previous studies have associated the distribution of urban areas covered with trees and shrubs primarily with social and economic factors rather than environmental or ecological ones. In Bucharest, the distribution of such green urban areas is strongly linked to the current planning framework and the legacy of earlier planning approaches, whereas in other contexts this distribution is associated with racial segregation, population density, income, and housing characteristics, alongside physical landscape features (Schwarz et al., 2015; Foster et al., 2024). Analyses from Western societies support the idea that wealthier neighbourhoods are greener, whereas poorer and mi-

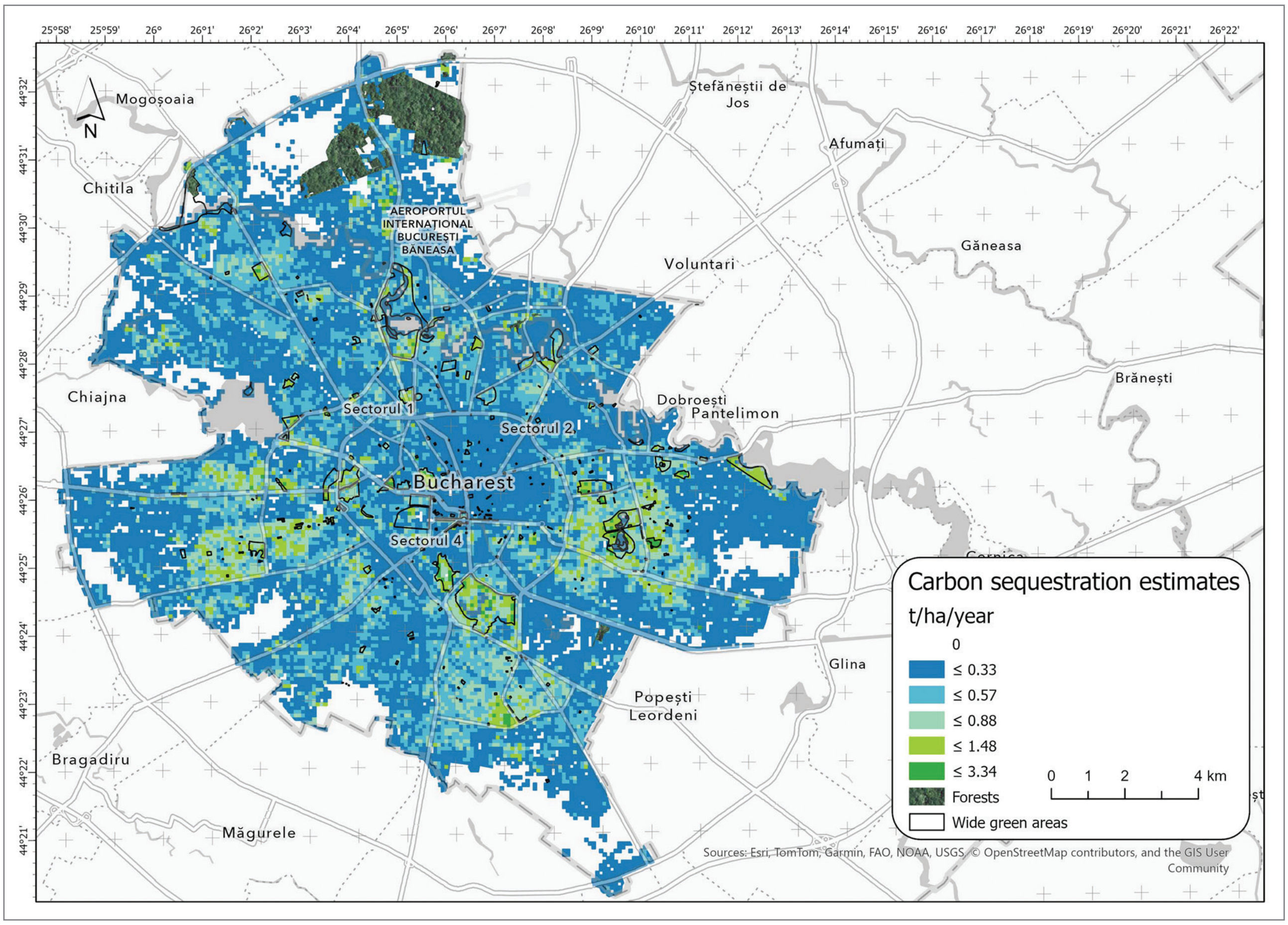

Figure 6: Carbon sequestration by urban trees (t/ha/year) in Bucharest.

nority-populated areas tend to have less green space. However, in Bucharest, newly planned neighbourhoods, typically inhabited by higher middle-class populations, are often deprived of areas covered with trees and shrubs, whereas older neighbourhoods, predominantly inhabited by lower middle-class populations, tend to be greener. This outcome reflects the market-led planning approaches introduced in the 1990s and continuing today, under which land parcels generate higher returns for developers when built up. Consequently, the provision of urban green spaces in such neighbourhoods is treated as a legal obligation and is often reduced to the minimum area required, with the lowest possible level of investment.

The results of the tree species analysis in Bucharest were as expected, given the biogeographical region the city is located in. However, a significant concern remains the high prevalence of nonnative species, some of which are invasive or have the potential to become invasive. Consistent with previous studies, the most common nonnative species in Bucharest include box elder (*Acer negundo*), tree of heaven (*Ailanthus altissima*), black locust (*Robinia pseudoacacia*), and white mulberry (*Morus alba)* (Sîrbu et al., 2021; Gavrilidis et al., 2023). Large urban environments often act as hubs for the introduction

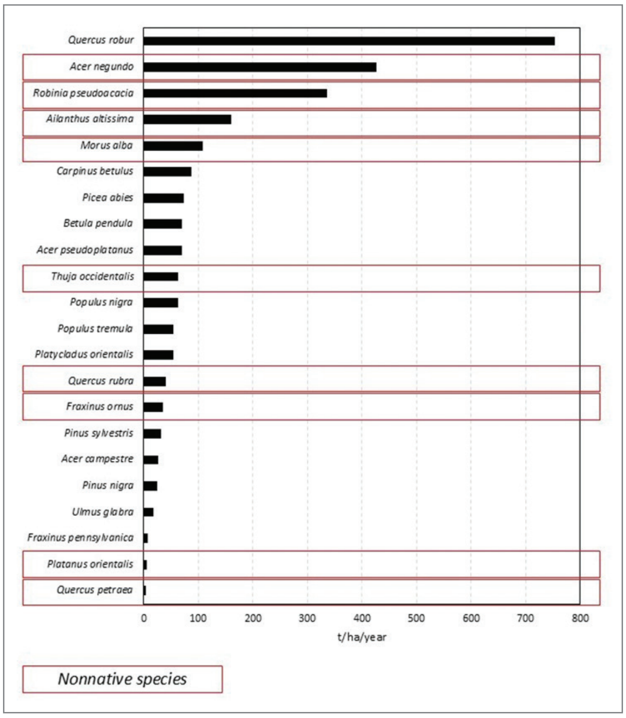

Figure 7: Tree/shrub species contributing the most to carbon sequestration per year in Bucharest (number of individuals multiplied by gross carbon sequestration expressed in t/ha/year).

of nonnative species into national ecosystems (Kaczorowska 2020), and Bucharest is no exception. Most of the dominant nonnative tree species in the city were deliberately introduced at various times, primarily for aesthetic purposes. Following their introduction, these species have thrived and have become dominant components of Bucharest's urban landscape. Nonnative invasive tree and shrub species thrive in urban settings due to the urban microclimate, which is warmer and drier, as well as their relatively low ecological requirements. As highlighted in previous studies, black locust (*Robinia pseudoacacia*) performs particularly well in urban environments because its ecological requirements align closely with urban ecological conditions (Franceschi et al., 2023). This species is often preferred in cities because of its lower acquisition and maintenance costs and the comparatively lower mortality rates of planted specimens. Previous research on urban tree species has also shown that ash (*Fraxinus* spp.) and maple (*Acer* spp.) are characterized by higher drought tolerance (Sjöman et al. 2024); therefore, the presence of these species in Bucharest is consistent with earlier findings.

Regardless of whether a tree species is native or nonnative, its contribution to carbon sequestration is unequivocally positive (Lashof & Neuberger, 2023). The findings of this study indicate that, in addition to the forest located in the northern part of Bucharest, the city relies on three other major carbon sinks in the east, west, and south. However, the lack of interconnectivity among these sinks limits their overall efficiency, preventing the city from fully benefiting from their regulatory ecosystem services. Furthermore, the absence of linkages between these carbon sequestration sinks – whether through linear green corridors or smaller areas covered with trees and shrubs – poses a risk of gradual degradation and reduced effectiveness in carbon retention (Hansen et al., 2022). Previous research suggests that, although urban forests are an important asset for climate-change adaptation, relying exclusively on them to achieve carbon neutrality is insufficient (Velasco et al., 2016). In-depth studies on the carbon sequestration capacity of urban trees remain relatively scarce in Europe, and most research estimates sequestration based on tree cover or species composition using allometric relationships developed for American tree species (Bherwani et al., 2024). For Bucharest, the average estimated carbon sequestration by trees and shrubs is approximately 0.26 t/ha/year. By comparison, studies have reported average urban forest sequestration rates of around 2 t/ha/year in Chinese cities (Chen, 2015), and estimates for Tehran suggest values of approximately 1 t/ha/year (Rasoolzadeh et al., 2024). Species with high carbon sequestration capacity identified in the Tehran study include black locust (*Robinia pseudoacacia*), elm (*Ulmus* spp.), ash (*Fraxinus* spp.), pine (*Pinus* spp.), and plane (*Platanus* spp.), which is consistent with the findings of this study for Bucharest. Analyses from American cities indicate that urban trees in Baltimore – a city comparable to Bucharest in terms of area, climate, and vegetation – exhibit an annual gross carbon sequestration of approximately 14,800 t (≈ 0.62 t/ha/year; Nowak & Crane, 2002).

The literature has clearly established the importance of urban areas covered with trees and shrubs for carbon sequestration efforts. Recent studies have highlighted CO_2 as a major air pollutant due to its role in driving climate change (Hadipoor et al., 2021). Estimates of CO_2 sequestration by four urban parks in Rome correspond to approximately 3.5% of the city's total greenhouse-gas emissions (Gratani et al., 2016), whereas in Beijing the estimated annual CO_2 sequestration is equivalent to only 0.2% of total emissions (Tang et al., 2016). In Indian cities, trees planted along roadsides were estimated to sequester carbon equivalent to 22% of urban CO_2 emissions (Kiran & Kinnary, 2011). Despite these findings, it remains unclear to what extent the costs and efforts incurred by municipalities to expand and develop robust and functional green infrastructure networks are justified solely in terms of carbon sequestration outcomes. Even the monetary valuation of the carbon sequestration capacity of urban trees – although useful for policy framing and illustrating economic relevance – is not sufficiently precise to be treated as an exact financial figure (Nowak & Crane, 2002; Bherwani et al., 2024). Furthermore, growing urban populations are associated with increasing demand for affordable housing and transport infrastructure. Preserving unbuilt land therefore becomes an increasingly complex challenge for local decision-makers because social pressure intensifies from both directions: the need to provide housing and the need to ensure adequate urban green spaces. The carbon sequestration values reported in this and previous studies may appear insufficiently compelling to motivate stronger regulation of urban planning frameworks focused on the quality and quantity of green infrastructure. Nevertheless, there is no scientific doubt that the loss of existing urban green space would lead to a critical decline in urban quality of life.

4.1 This study's strengths and limitations

A key asset of this study was the availability of the tree location database from the Bucharest Green Registry. In the absence of this resource, the only alternative would have been the small woody features layer, which is sufficiently accurate for general assessments. However, access to both datasets allowed cross-validation of the information. The replicability of the methods applied in this study depends on the availability of geospatial data on urban trees and shrubs. When such data are complemented by information on tree and shrub species, similar assessments can be readily replicated in other urban contexts. Nevertheless, Bucharest's Green Registry has not been updated since 2012; therefore, conditions may have changed significantly over the years. An updated assessment of tree distribution and species composition could reveal changes in certain parts of the city, but the overall patterns identified in this study are unlikely to differ substantially. Furthermore, the lack of data on tree age and species linked to specific locations limited the depth of the analysis. Despite this limitation, the general statistics on tree species still provide a broad overview of the species that Bucharest relies on for carbon sequestration.

5 Conclusion

This study underscores that achieving carbon neutrality through nature-based solutions in Bucharest will require substantial effort, expert-driven planning, and politically prudent decision-making. Continuing with a "business as usual" approach could yield outcomes worse than maintaining the current status quo, underscoring the urgency of adopting informed and strategic actions. By achieving the proposed objectives, this study revealed that Bucharest is underperforming in comparison with similar cities in terms of carbon sequestration capacity through urban trees and shrubs. However, the areas covered with a significant density of trees and shrubs are mostly dispersed throughout the city. The current situation provides a proper foundation for the further development of Bucharest's urban green infrastructure, with a particular focus on expanding the areas covered by trees and shrubs. Priority should be given to the city's outskirts, where sufficient land is still available for the design and implementation of such features. In contrast, the city centre, where land availability is more constrained, would benefit from innovative approaches, such as suspended or vertical forests.

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Data availability statement

The land-cover and land-use data for Bucharest and Ilfov County were obtained from the Corine Land Cover (CLC) database and Urban Atlas, and they are freely accessible upon registration. Tree geolocation data were provided by Bucharest City Hall and are available upon request but cannot be shared with third parties. Derived datasets produced in this study, such as tree densities and annual carbon sequestration per hectare, and the species-level tree and shrub counts, are openly available in the OSF repository at https://osf.io/g3xva/overview (Gavrilidis, 2026); this article must be cited if these data are used in other publications.

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Proučevanje vezave ogljika na podlagi drevesnih vrst v mestih: izsledki iz Bukarešte

Urbanizacija se je od prve industrijske revolucije okrepila, kar je povzročilo resne družbeno-gospodarske in okoljske pritiske na lokalne oblasti, zlasti na področju upravljanja kakovosti zraka. Čedalje slabša kakovost zraka ostaja glavni izziv na urbaniziranih območjih, zato so mestni zeleni prostori, zlasti tisti, porasli z drevesi, zaradi svojih regulacijskih ekosistemskih storitev vse bolj cenjeni. Avtorja v članku proučujeta zmožnost dreves v Bukarešti, da vežejo CO_2. Prostorsko razporeditev dreves in njihovo vrstno sestavo sta prikazala z uporabo geografskih informacijskih sistemov na podlagi podatkov iz mestnega registra zelenih površin, zmožnost vezave pa sta določila s preizkušenimi ocenjevalnimi orodji. Rezultati so pokazali izrazite prostorske razlike, pri čemer je za več mestnih okrožij značilno precejšnje pomanjkanje dreves. Količina CO_2, ki ga vežejo območja, poraščena z drevesi in grmovjem, je v primerjavi s skupnimi ravnmi emisij v mestu zanemarljiva. Avtohtone vrste učinkoviteje vežejo ogljik, vendar v mestni krajini prevladujejo tujerodne vrste, kar je posledica predvsem finančnih in estetskih preferenc v zasaditvenih praksah. Navedene ugotovitve poudarjajo majhen regulacijski vpliv mestnih dreves na vezavo ogljika in izpostavljajo potrebo po ciljno usmerjenih, na naravi temelječih strategijah, zlasti širjenju avtohtone vegetacije, kar bi olajšalo upravljanje vezave ogljika v mestih.

Ključne besede: geografski informacijski sistem, na naravi temelječe rešitve, ekosistemske storitve, zelena infrastruktura, Romunija

1 Uvod

Industrijska revolucija je skupaj s tehnološkim napredkom v 20. stoletju pospešila urbanizacijo po svetu, zaradi česar so nekatera mestna območja izjemno gosto poseljena (Morris, 2013). Zaradi zgodovinskih dejavnikov, geografske lege in razpoložljivosti ključnih virov so se številna naselja razvila v pomembna gospodarska središča (Gavrilidis idr., 2015). Polarizacija virov in prebivalstva pa pogosto vodi v prenatrpanost (Booth idr., 2020) in če ta ni ustrezno upravljana, negativno vpliva na splošno kakovost življenja v mestu, pri čemer je prav ta ključni vzrok nenačrtnega širjenja mest in razvrednotenja okolja (Gavrilidis idr., 2019). Zaradi čedalje večje gostote mestnega prebivalstva je treba širiti pozidavo, kar pogosto negativno vpliva na naravne in polnaravne krajine (Dewan in Cornerc, 2014). Krčenje zelenih površin v gosto poseljenih mestnih okoljih ima srednjeročne in dolgoročne posledice za blaginjo mestnih prebivalcev (Popa idr., 2022). Urbanizacija je dinamičen družbeno-gospodarski pojav, na katerega vplivajo raznovrstni naravni in antropogeni dejavniki, hkrati pa prispeva k veliki gostoti prebivalstva in povečanemu pritisku na nepozidana zemljišča. Zapletenost mestnih okolij in kako hitro se ta preobrazijo, sta raziskovalce spodbudila k proučevanju učinkov aktualnih urbanizacijskih trendov. V tem okviru oblikovalci politik in odločevalci pogosto dajejo prednost sivi infrastrukturi ter širitvi stanovanjskih naselij ter trgovskih, logističnih, industrijskih in poslovnih središč, saj takšni posegi ustvarjajo neposredne gospodarske donose (Dong idr., 2017).

Zaradi krčenja prepustnih površin v mestih se spreminjajo značilnosti odtekanja padavinskih voda, kar povečuje stroške vzdrževanja kanalizacijskih sistemov ter škodo med intenzivnimi padavinami in po njih (Kong idr., 2017). Poleg tega se z izgubo zelenih površin zaradi dopolnilne gradnje slabša kakovost zraka, povečuje obremenitev s hrupom (Badiu idr., 2018) in krepijo učinki mestnih toplotnih otokov (Gunawardena idr., 2017). Z naraščanjem gostote pozidave postajajo razpoložljiva zemljišča eden najdragocenejših mestnih virov (Gavrilidis idr., 2020). Ključni izziv za urbaniste, oblikovalce politik in odločevalce je zato ohranjanje uravnoteženega razmerja med pozidanimi in nepozidanimi površinami (Kronenberg idr., 2020). Čeprav večina držav priznava pomen doseganja ciljev trajnostnega razvoja (Združeni narodi, 2015), raziskovalci poudarjajo, da je uresničevanje teh ciljev povezano s precejšnjimi stroški, hkrati pa je za to treba razviti ustrezna finančna orodja in pripraviti programe (Barua, 2020). Cilji trajnostnega razvoja in pripadajoči kazalniki poudarjajo potrebo po hkratnem gospodarskem razvoju in učinkovitem upravljanju naravnih virov. Trije izmed desetih podciljev cilja 11, ki je za analizo v tem članku najpomembnejši, se nanašajo na ohranjanje naravnih prvin ter enakopraven dostop do njih na mestnih in urbaniziranih območjih. Posledično je ena ključnih raziskovalnih prednostnih nalog lokalnim in državnim oblastem dokazati, da vključevanje naravnih prvin v mestno krajino odpira učinkovito pot k hkratnemu doseganju več trajnostnih ciljev v mestih. Za dosego ciljev trajnostnega razvoja v prihodnjem desetletju pa morajo raziskovalci razumeti tudi potrebe oblikovalcev politik in drugih deležnikov ter oblikovati učinkovite metode, ki zagotavljajo praktične in uporabne rezultate (Allen idr., 2021).

V velikih mestih so nepozidana zemljišča čedalje redkejša, kar pomembno otežuje načrtovanje večjih zelenih površin. Z nadaljnjim širjenjem mestnih območij postajajo večji zeleni prostori, kot so parki in vrtovi, vse manj dostopni in vse bolj izpostavljeni dopolnilni gradnji (Stoia idr., 2022). Kot odziv na te pritiske se je uveljavil koncept ekosistemskih storitev, ki odločevalcem in širši javnosti daje okvir za prepoznavanje koristi, ki jih zagotavljajo ekosistemi (Costanza idr., 1997). Zaradi precejšnjega pomanjkanja teh koristi v mestnih okoljih se močno priporoča vključevanje pristopov, ki upoštevajo ekosistemske storitve, v urbanistično načrtovanje in upravljanje prostora (Bolund in Hunhammar, 1999). Uvajanje na naravi temelječih rešitev v urbanistične in politične okvire lahko poveča odpornost skupnosti (Antuna-Rozado idr., 2019; Bartlett in Mistry, 2021). Z ureditvijo naravnih prvin v mrežo mestne zelene infrastrukture se izboljša zagotavljanje ekosistemskih storitev na ravni mesta (Van Oijstaeijen idr., 2020; Zhang idr., 2021). Obsežne zelene površine, na katerih prevladujejo drevesa in grmovje, so hrbtenica učinkovite mestne zelene infrastrukture (Sanesi idr., 2017). Tovrstna območja, umeščena znotraj velikih mest ali na njihovih robovih, so splošno prepoznana kot ključni viri za doseganje trajnostnega razvoja in izboljšanje kakovosti življenja (Felappi idr., 2020). Ekosistemske storitve, ki jih zagotavljajo, imajo precejšnjo vrednost (Li, 2021), zato so v ospredju številnih varstvenih politik (Goodspeed idr., 2022). Čeprav so mestni gozdovi razmeroma redki, se po opredelitvi in upravljanju precej razlikujejo od naravnih gozdov. Glede na to, da je nujno doseči cilje trajnostnega razvoja in ogljične nevtralnosti, se lokalni deležniki in oblasti s sektorskimi politikami in programi financiranja vse pogosteje spodbujajo k vlaganju v varstvo in širitev mestnih gozdov (Wu idr., 2022).

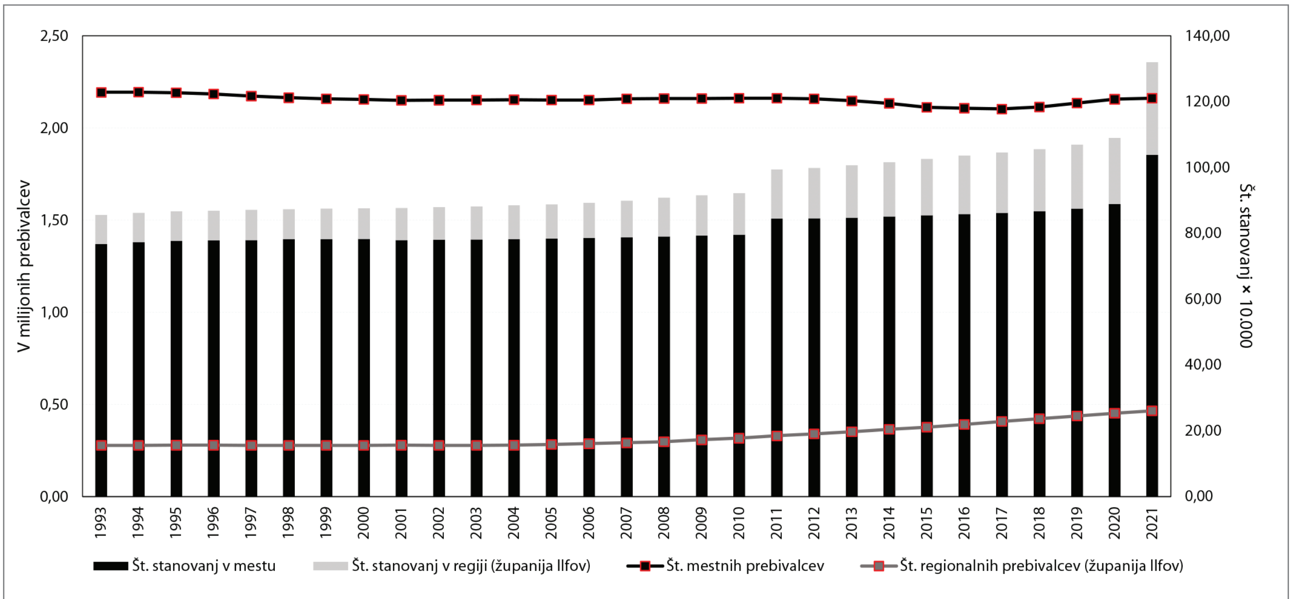
Urbano gozdarstvo je umetnost, znanost in tehnologija upravljanja dreves in drugih gozdnih virov v urbanih središčih in njihovi okolici, da se ustvarijo večje fiziološke, sociološke, gospodarske in estetske koristi, ki jih zagotavljajo gozdovi (Konijnendijk idr., 2006). Prejšnje raziskave so pokazale, da lahko gozdovi v mestih ali v njihovi neposredni okolici delujejo kot ponori ogljika, ki aktivno vežejo ogljik, in kot zbiralniki ogljika, v katerih se ogljik kopiči v biomasi. Učinkovitost upravljanja kroženja ogljika je močno odvisna od dejavnikov, kot sta vrstna sestava in starostna struktura gozdov (Boukili idr., 2017; Vais idr., 2023). Jasno je, da se zaradi intenzivnega upravljanja, mlajših dreves in pogostega odstranjevanja biomase zmožnost mestnih gozdov za vezavo ogljika razlikuje od zmožnosti naravnih gozdov (Fares idr., 2017). Kljub temu je količina ogljika, ki ga vežejo mestni gozdovi, razmeroma majhna v primerjavi z antropogenimi emisijami, prispevek teh gozdov k blaženju podnebnih sprememb z vezavo ogljika pa je na ravni celotnega mesta majhen ali zanemarljiv (Chen, 2015; Velasco idr., 2016). Vseeno imajo mestni gozdovi kot ponori ogljika precejšnjo gospodarsko vrednost (Bherwani idr., 2024). V tem okviru sta načrtovanje in opredelitev mestnih gozdov, ki izpolnjujejo merila iz zgornje opredelitve, za lokalne oblasti velik izziv, zlasti zaradi velike gostote pozidave in omejene razpoložljivosti zemljišč. Posledično bi morali lokalni odločevalci dati prednost povečevanju gostote mestnih dreves kot alternativni strategiji. Čeprav območja z večjo gostoto dreves ne morejo v celoti nadomestiti ekosistemskih storitev gozdnih ekosistemov, lahko njihove koristi pomembno prispevajo k izboljšanju gospodarskih, socialnih in okoljskih razsežnosti življenja v mestu. Območja, porasščena z drevesi in grmičevjem, v mestih krepijo koristi posameznih dreves in grmovnic, tudi ko ti ne delujejo kot v celoti povezan ekosistem. Poleg tega te koristi delujejo v sinergiji s koristmi naravnih in polnaravnih ekosistemov na mestnem obrobju.

Za upravljanje gozdov praviloma veljajo strogi predpisi in je zanj potrebno specializirano osebje (Ciornei, 2019; Ciornei in Munteanu, 2020), upravljanje in vzdrževanje mestnih območij, porasščenih z drevesi in grmičevjem, pa terjata drugačne prakse, rabe in znanja. V tem okviru mora biti poudarek na boljšem zagotavljanju ekosistemskih storitev. Njihova kakovost je odvisna od uporabljenih upravljavskih praks ter od vrstne sestave in kakovosti vegetacije (Mexia idr., 2018). Drevesa in grmičevje so pomembni ponori ogljika, njihova vključitev v mestno okolje pa ima ključno vlogo pri prilagajanju na podnebne spremembe in blaženju čedalje slabše kakovosti mestnega zraka (Lashof in Neuberger, 2023). Premišljena izbira vrst za zasaditve, usmerjena v povečanje gostote dreves in širjenje tovrstnih območij, lahko okrepi odpornost mest proti okoljskim nevarnostim in hkrati izboljša kakovost življenja prebivalcev. Avtorja sta proučila, ali gostota, prostorska razporeditev in sestava dreves v eni izmed najbolj onesnaženih evropskih prestolnic vplivajo na vezavo CO_2. Cilji njune raziskave so bili analizirati stanje zemljišč, porasščenih z drevesi in grmovjem, in pripadajočo gostoto dreves, opredeliti prevladujoče vrste in oceniti količino vezanega ogljika v Bukarešti, ločeno po drevesnih vrstah.

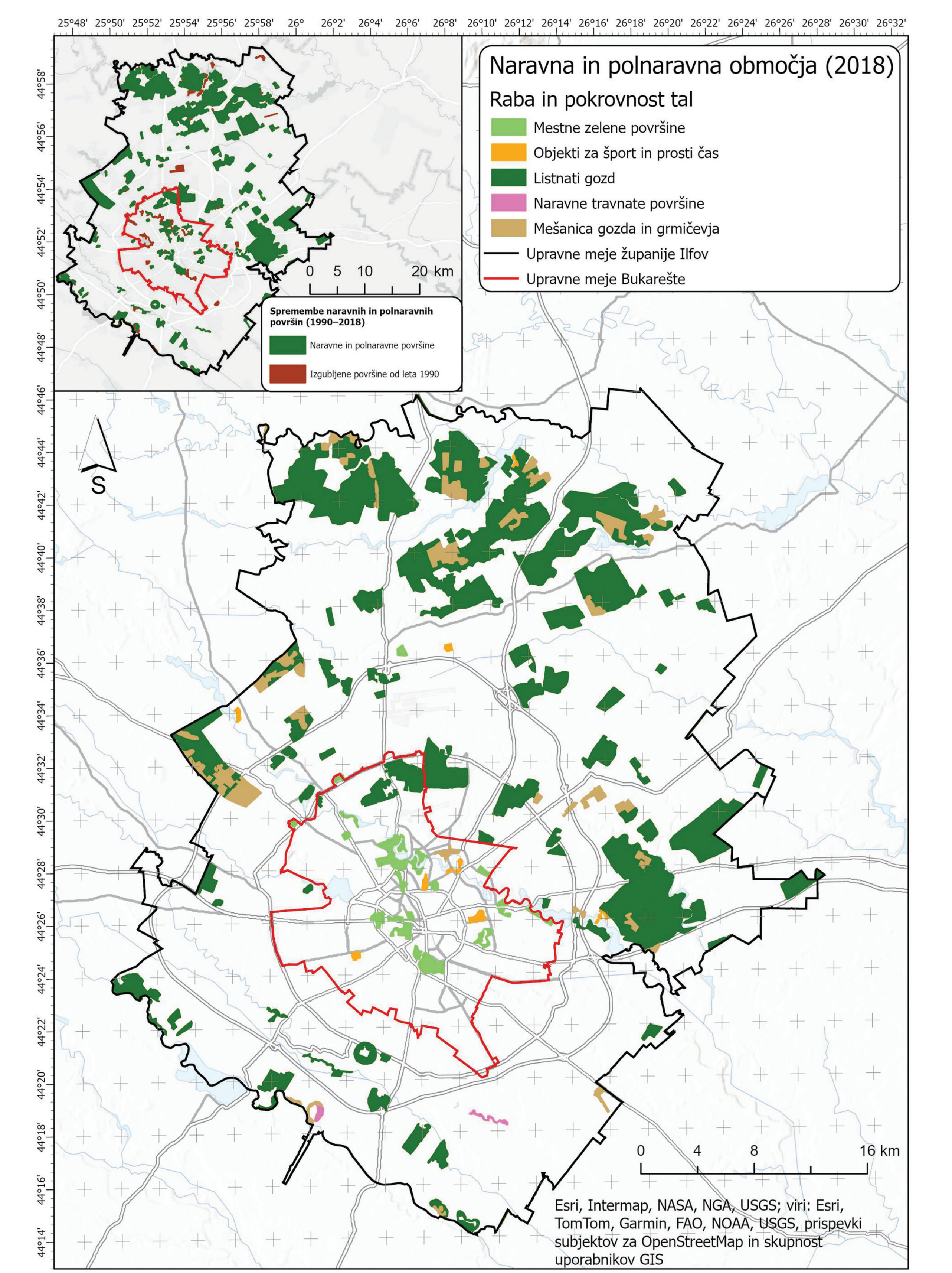
2 Podatki in metode

2.1 Območje raziskave

Bukarešta, glavno mesto Romunije, leži na ravnini v jugovzhodnem delu države. Leta 2021 je imela 1,79 milijona prebivalcev. Če upoštevamo še dodatnih 430.000 prebivalcev županije Ilfov, ki jo obdaja (Nacionalni inštitut za statistiko, 2023), tvori najgosteje poseljeno urbano aglomeracijo v Romuniji. V zadnjih 30 letih se je število prebivalcev znotraj mestnih meja zmanjšalo za 1,5 %, kar se ujema s povprečno letno stopnjo rasti – 0,5 %. Nasprotno pa se je prebivalstvo županije Ilfov povečalo za skoraj 40 %, s povprečno letno rastjo 1,82 % (slika 1). Na regionalni ravni (Bukarešta in županija Ilfov skupaj) se je prebivalstvo v zadnjih treh desetletjih tako povečalo za 5,95 %. Upoštevanje demografskih značilnosti županije Ilfov je pri analizi Bukarešte ključno, saj se velik delež njenih



Slika 1: Spremembe v številih prebivalstva in stanovanj v Bukarešti in županiji Ilfov v zadnjih 30 letih (vir: Nacionalni inštitut za statistiko, 2023)



Slika 2: Razporeditev naravnih in polnaravnih območij v Bukarešti in županiji Ilfov leta 2018. Okvirček zgoraj levo: izgubljene naravne in polnaravne površine od leta 1990 (vir: https://land.copernicus.eu/en)

Preglednica 1: Vhodni podatki, uporabljeni za analizo porazdelitve mestnih območij, poraslih z drevesi in grmičevjem

Podatki	Vrsta	Leto	Metodologija obdelave
Drevesa	Točke	2010	Podatki o geolokaciji dreves in grmičevja so bili zbrani leta 2010 s splošno anketo, izvedeno po naročilu lokalnih oblasti. Na njihovi podlagi je bil izdelan register zelenih površin Bukarešte z vektorskimi točkami, ki sta jih avtorja članka nato obdelala v mreži z velikostjo celic 1 ha.
Majhna drevesa in grmičevje	Poligoni	2018	Nadzorovano razvrščanje časovnih nizov satelitskih posnetkov iz podatkovne baze VHR_IMAGE_2018, narejenih med majem 2017 in septembrom 2018. Za zaplate dreves in grmičevja je najmanjša enota kartiranja 200 m^2 (največja pa 50.000 m^2). Največja širina in najmanjša dolžina linearnih elementov znašata 30 m. Prostorska ločljivost je manj kot 5 m.

prebivalcev zaradi dela in družabnih aktivnosti dnevno vozi v mesto (Cristea idr., 2017). Analiza teh demografskih trendov skupaj s spremembami v številu stanovanj je pokazala, da je za Bukarešto in županijo Ilfov značilno nenačrtno prostorsko širjenje, kar potrjujejo tudi predhodne raziskave (Suditu 2009; Simion in Nistor 2012). V zadnjih treh desetletjih se je število stanovanj v Bukarešti povečalo za 26 %, s povprečno letno stopnjo rasti 1,03 %, v županiji Ilfov pa za kar 69 %, kar ustreza povprečni letni rasti 3,87 %. Ti trendi kažejo na širjenje pozidanih površin na račun naravnih in polnaravnih krajin, saj se skupaj z novimi stanovanjskimi soseskami gradijo tudi infrastruktura in drugi objekti z raznovrstnimi urbanimi funkcijami (npr. trgovine, logistični centri in poslovne stavbe).

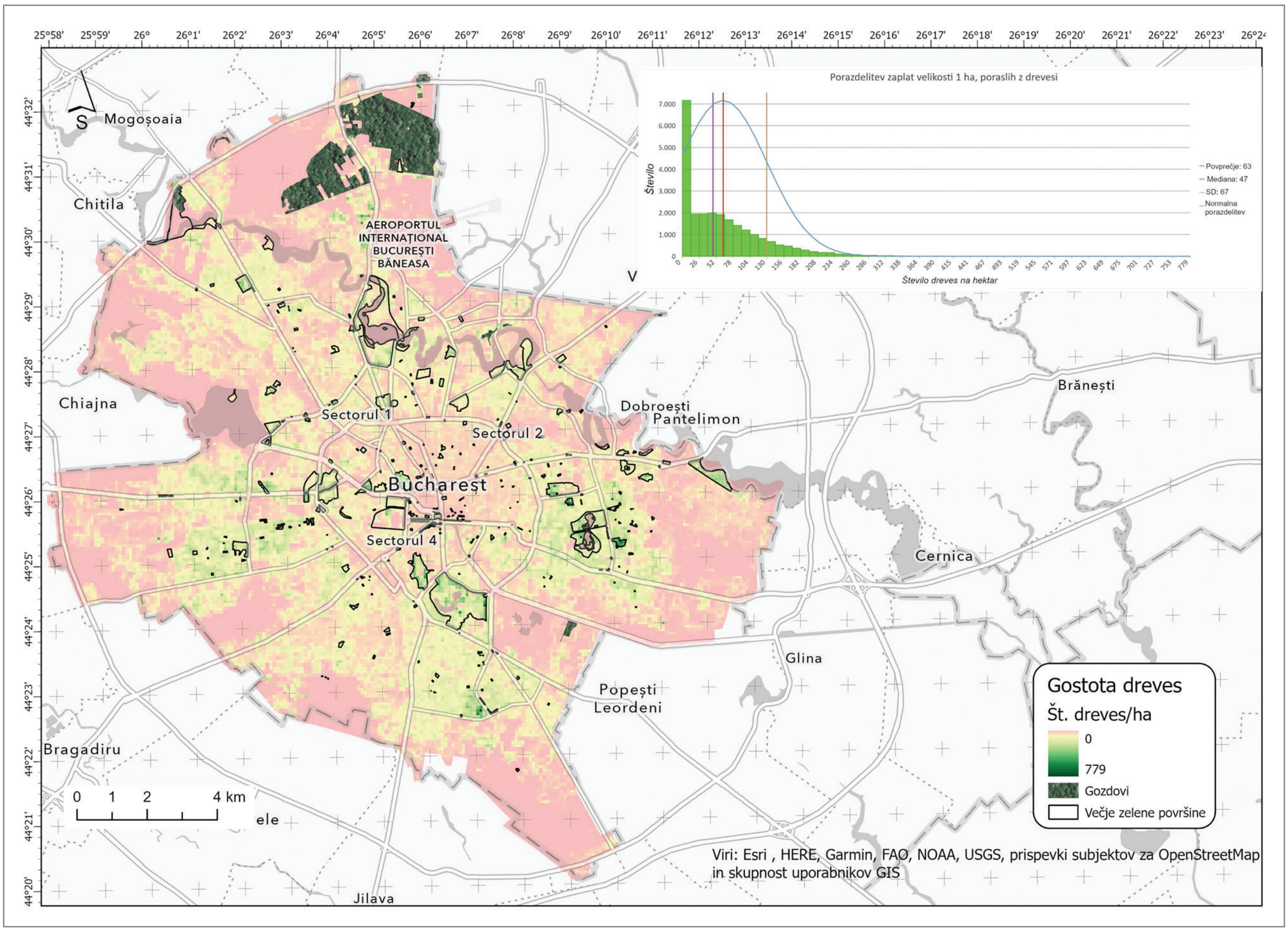
V romunskih predpisih so kot zelene površine opredeljene najrazličnejše vrste rab in pokrovnosti tal (*Lege nr. 24/2007 (republicată)*, Monitorul Oficial, št. 764/2009), vendar nekatere od teh površin (npr. vrtovi javnih ustanov) niso javno dostopne, druge, vključno s športnimi igrišči ali pokopališči, pa sestavljajo pretežno betonski elementi in objekti. Državni statistični podatki o zelenih površinah temeljijo na teh regulativnih opredelitvah. Po uradnih podatkih je Bukarešta od padca komunističnega režima izgubila približno 7 % zelenih površin (National Institute for Statistics, 2023). Podobno so ugotovili tudi v drugih raziskavah, te so pokazale, da se je največ zelenih površin izgubilo na vrtovih ob novih večstanovanjskih stavbah, kjer so bile hitro preoblikovane v parkirišča (Badiu idr., 2018). Na podlagi skupnih podatkov za Bukarešto in županijo Ilfov se je skupna površina zemljišč, kategoriziranih kot zelene površine, v zadnjih 30 letih povečala za približno 14 %. Navedeno je posledica dejstva, da so novogradnje v županiji Ilfov vključevale tudi načrtovanje novih zelenih površin, ki so kot take opredeljene tudi po državnih predpisih, medtem ko so se znotraj upravnih meja Bukarešte zelene površine skrčile. Tako v Bukarešti kot v županiji Ilfov so največja in najbolj sklenjena naravna in polnaravna območja na severu (slika 2).

2.2 Analiza mestnih območij, poraslih z drevesi in grmičevjem

Območja, poraščena z drevesi in grmičevjem, so bila opredeljena skladno z definicijo »drugih zemljišč, poraslih z drevesi«, ki jo uporablja Organizacija združenih narodov za hrano in kmetijstvo. Ta kategorija vključuje mestna zemljišča, ki so večja od 0,5 ha in so porasla z drevesi, višjimi od pet metrov, katerih krošnje pokrivajo več kot 10 % površine. Opredelitev vključuje tako gozdne kot negozdne drevesne vrste (Hendriks idr., 2021). Za analizo prostorske porazdelitve območij, poraščenih z drevesi in grmičevjem v Bukarešti, sta bili uporabljeni dve vrsti podatkov: georeferencirani točkovni elementi iz mestnega registra zelenih površin Bukarešte (Primăria Municipiului București, 2010) ter vektorski sloji majhnih dreves in grmičevja iz evropskega programa Copernicus iz leta 2018. Oba podatkovna niza sta bila obdelana s programskim orodjem ESRI ArcGIS Pro. Za analizo podatkov registra zelenih površin je bila z orodjem *Create Fishnet* v programu ArcGIS Pro izdelana mreža s celicami velikosti 1 ha. Nato je bilo s funkcijo *Intersect* (presek) v istem okolju geografskih informacijskih sistemov pridobljeno število dreves in grmovnic na hektar. Na podlagi slojev majhnih dreves in grmičevja je bila primerjana prostorska porazdelitev mestnih območij, poraslih z drevjem in grmičevjem, med obema podatkovnima nizoma, ki sta bila zbrana in obdelana z različno metodologijo (preglednica 1).

2.3 Analiza mestnih drevesnih in grmovnih vrst ter ocene vezave ogljika

Podatki za prikaz številčnosti vrst mestnih dreves so bili pridobljeni iz registra zelenih površin Bukarešte. Ta ne vsebuje podrobnih geolokacijskih podatkov (npr. o vrsti, starosti in višini dreves), vključuje pa podatke o številu primerkov vsake vrste. Z nadaljnjo obdelavo podatkov so bile vrste razvrščene na podlagi več meril: vrste rastline (drevo/grm), vrste listov (iglavci/listavci), izvora (avtohtona/tujerodna vrsta) in alergenosti (alergena/nealergena vrsta). Poleg tega je bilo navedeno



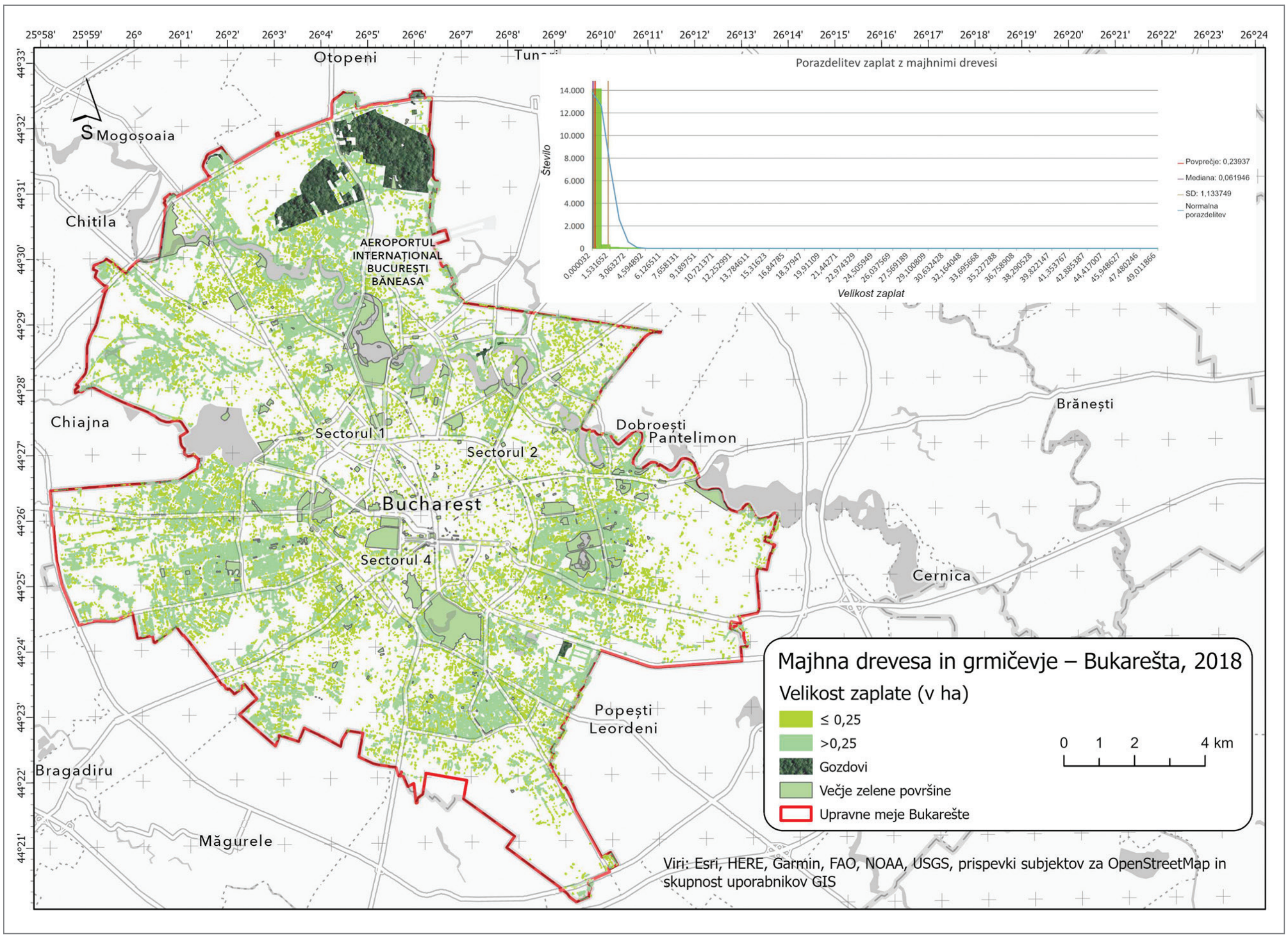
Slika 3: Porazdelitev gostote dreves v Bukarešti, izražene s številom dreves na hektar.

skupno število primerkov vsake vrste. Podatki so bili obdelani v programu Microsoft Excel. Za oceno zmožnosti vezave ogljika v drevesnih vrstah v Bukarešti so bile združene vrednosti, ki jih navajata Evropska agencija za okolje in platforma One Tree Planted. Po podatkih Evropske agencije za okolje (2010) odraslo drevo letno veže približno 21,77 kg CO_2 in pri tem sprošča kisik, po podatkih platforme One Tree Planted pa povprečno drevo letno absorbira približno 10 kg CO_2 (Bernet, 2023). Ker je relativna atomska masa ogljika 12, kisika pa 16, znaša molekulska masa CO_2 44. Količino ogljika v izbrani količini CO_2 je zato mogoče izračunati tako, da količino CO_2 pomnožimo z 0,27 (Farquhar in Lloyd, 1993). Zaradi spremenljivosti stopenj vezave ogljika, ki je odvisna od dejavnikov, kot so vrsta, starost in višina dreves, je bila v raziskavi uporabljena povprečna vrednost 4,29 kg vezanega ogljika na drevo na leto. Na podlagi te ocene je bila mreža gostote mestnih dreves, izdelana za Bukarešto, uporabljena za kartiranje količine vezanega ogljika na hektar po celotnem mestu. Poleg tega so bile na podlagi podatkov prejšnjih raziskav o vezavi onesnaževal zraka po drevesnih vrstah (Nowak idr., 2006, 2013) opredeljene avtohtone drevesne vrste, ki najbolj učinkovito blažijo urbano onesnaženje, zlasti z vidika vezave ogljika. Nazadnje je bila na podlagi števila posameznih dreves in povprečne količine ogljika, ki ga absorbira eno odraslo drevo, določena skupna količina ogljika, ki jo veže posamezna drevesna vrsta v Bukarešti.

3 Rezultati

3.1 Razporeditev mestnih območij, poraslih z drevesi in grmičevjem

Analiza gostote dreves v Bukarešti je pokazala precejšnje prostorske razlike. Za obrobje mesta in osrednja območja je opazno precejšnje pomanjkanje dreves, saj je na teh območjih večji delež zaplat velikosti 1 ha brez drevesnega pokrova kot drugje v mestu (slika 3). Več zaplat z večjo gostoto dreves je na vmesnih območjih. V soseskah v vzhodnem, zahodnem in južnem delu Bukarešte je gostota dreves na hektar razmeroma večja kot na drugih območjih. Največje gostote dreves na hektar so bile ugotovljene v večjih parkih, ki so ključne zelene strukture mesta. Od vseh zaplat velikosti 1 ha znotraj upravnih meja Bukarešte jih ima približno 36 % manj kot 24 dreves na hektar, približno 41 % pa med 25 in 100. Iz prostorskega

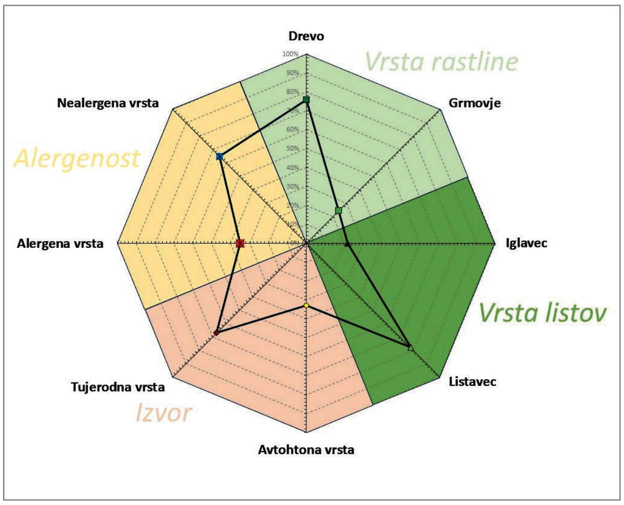


Slika 4: Porazdelitev majhnih dreves in grmičevja v Bukarešti

prikaza sloja majhnih dreves in grmičevja je razviden vzorec porazdelitve, ki se ujema z ugotovitvami analize gostote dreves (slika 4). Soseske na vzhodu, zahodu in jugu imajo največ območij, poraslih z drevesi in grmičevjem, za obrobje in mestno središče pa je značilno izrazito pomanjkanje takšnih prvin. Območja, porasla z majhnimi drevesi in grmičevjem, pogosto ležijo ob robovih večjih parkov, razpršenih po mestu. Približno 87 % jih je manjših od 0,25 ha, kar je v skladu z državnimi predpisi najnižji prag za to, da se skupina dreves lahko opredeli kot gozd. Kljub majhnosti posameznih zaplat te obsegajo samo 26 % skupne površine, poraščene z majhnimi drevesi in grmičevjem v mestu. Navedeno kaže, da v Bukarešti k skupnemu drevesnemu pokrovu pomembno prispevajo večja in bolj strnjena drevesa.

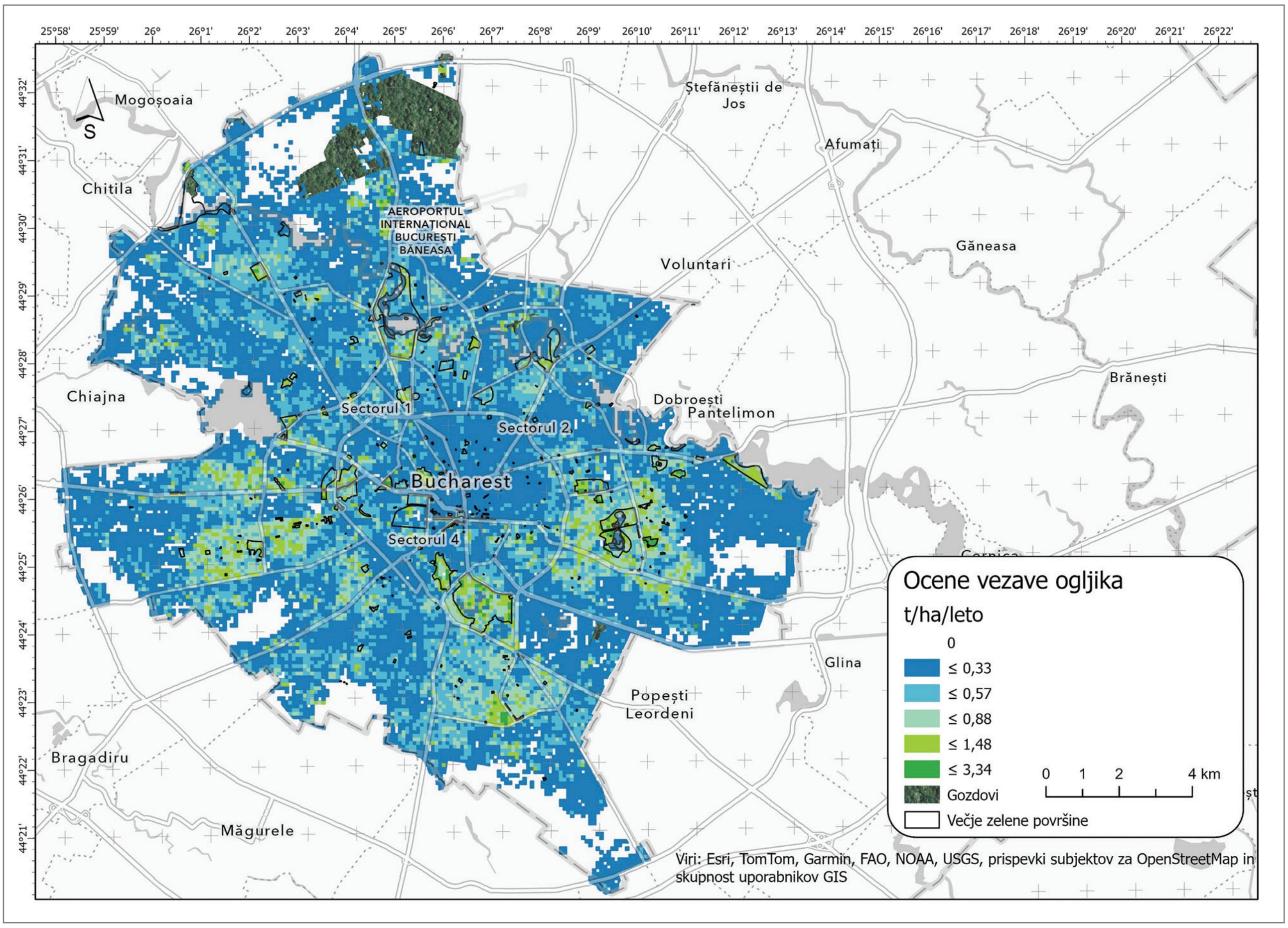
3.2 Drevesne in grmovne vrste ter njihova učinkovitost pri vezavi ogljika

V registru zelenih površin Bukarešte je skupno 1.647.517 dreves in grmovnic, razvrščenih v 219 vrst, pri čemer je vrsta zanesljivo določena za samo približno 11 % evidentiranih dreves. Kot je razvidno s slike 5, je med evidentiranimi vrstami



Slika 5: Značilnosti drevesnih in grmovnih vrst v Bukarešti

76 % drevesnih vrst in 24 % grmovnic. Prevladujejo listavci (78 %). Pomembna ugotovitev je, da je večina vrst tujerodnih (67 %), avtohtonih pa je manjši delež. Precejšen delež vrst je opredeljen kot alergen (35 %). Analiza števila evidentiranih primerkov po posameznih vrstah je pokazala, da so vse vrste z več kot 10.000 primerki drevesa. Med njimi je 38 % tujero-



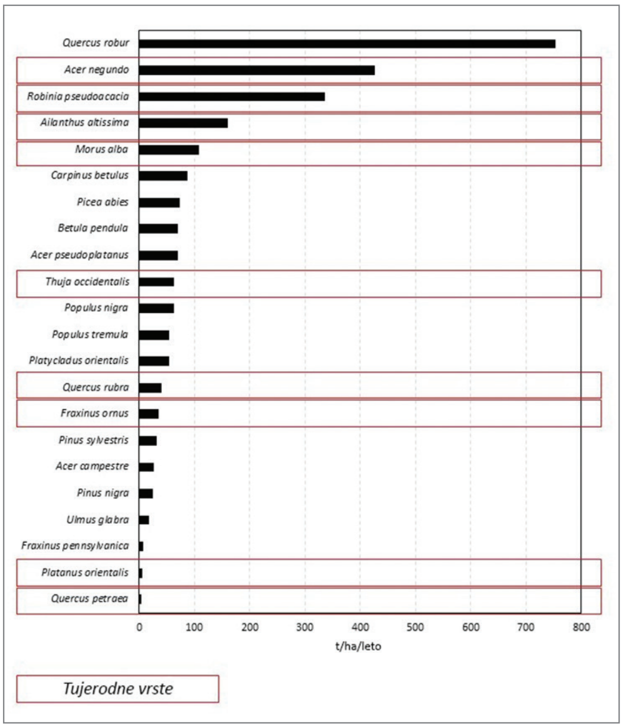
Slika 6: Vezava ogljika v drevesih (v t/ha/leto) v Bukarešti

dnih. Najbolj razširjene tujerodne vrste so ameriški javor (*Acer negundo*), navadna robinija (*Robinia pseudoacacia*), vzhodni klek (*Platycladus orientalis*), ameriški klek (*Thuja occidentalis*), ameriški jesen (*Fraxinus americana*), veliki pajesen (*Ailanthus altissima*) in španski bezeg (*Syringa vulgaris*), pri čemer je za vsako v mestu evidentiranih več kot 20.000 primerkov. Najštevilčnejša vrsta v Bukarešti je dob (*Quercus robur*) s 114.250 primerki, kar pomeni 9 % skupnega števila evidentiranih dreves in grmovnic v mestu.

Ob upoštevanju zgoraj navedene povprečne količine ogljika, ki ga veže odraslo drevo (4,29 kg/leto), se predvideva, da drevesa in grmičevje v Bukarešti letno vežejo približno 6.090 ton ogljika. Pričakovano se soseske z večjo gostoto dreves na hektar ujemajo z območji, kjer se vežejo največje količine ogljika (slika 6). Najvišja ugotovljena vrednost za posamezno zaplato velikosti 1 ha je znašala 3,34 tone vezanega ogljika v enem letu. Na podlagi bruto količine vezanega ogljika v različnih drevesnih in grmovnih vrstah so najučinkovitejše avtohtone vrste v Bukarešti navadna breza (*Betula pendula*), rdečelistna sliva (*Prunus cerasifera*), graden (*Quercus petraea*), puhasti hrast (*Quercus pubescens*), dob (*Quercus robur*), beli javor (*Acer pseudoplatanus*), poljski javor (*Acer campestre*), beli gaber (*Carpinus betulus*) in mali jesen (*Fraxinus ornus*). Vsaka od teh vrst lahko letno veže več kot 5 kg ogljika. Ob upoštevanju tako števila primerkov v Bukarešti kot količine ogljika, ki ga lahko vežejo, je opazno, da so štiri od petih najučinkovitejših drevesnih in grmovnih vrst z vidika vezave ogljika tujerodne (slika 7). Boljša učinkovitost teh tujerodnih vrst pa je bolj posledica njihove večje razširjenosti kot pa večje zmožnosti vezave ogljika na ravni posameznega drevesa.

4 Razprava

V raziskavi so bila opredeljena kritična območja v Bukarešti z vidika poraščenosti z drevesi in grmičevjem. Poleg tega je bila ocenjena zmožnost vezave ogljika pri posameznih drevesnih vrstah v mestu. Ti rezultati so lahko izhodišče za pripravo usklajenih in učinkovitih načrtov za širjenje območij v Bukarešti, poraščenih z drevesi in grmovjem. Mestna okolja so dinamični sistemi, v katerih so nepozidana zemljišča pomemben vir. V tem okviru postaja načrtovanje ali oblikovanje mestnih gozdov kot način prilagajanja podnebnim spremembam in povečanja vezave ogljika večplastni izziv. Izzivi v praksi, povezani z načrtovanjem mestne zelene infrastrukture, se večinoma



Slika 7: Drevesne in grmovne vrste, ki najbolj prispevajo k letni vezavi ogljika v Bukarešti (število primerkov, pomnoženo z bruto količino vezanega ogljika, izraženo v t/ha/leto).

nanašajo na upravljanje in vodenje, zlasti zaradi slabe vključenosti urbanega gozdarstva v urbanistične okvire. Ti izzivi so po navadi povezani z izborom vrst in zasnove zasaditve, stroški vzdrževanja in spremljanja ter preživetjem zasajenih rastlin (Suhane idr., 2024). Zadnje navedeno ni nujno povezano z izbiro drevesnih ali grmovnih vrst, prilagojenih lokalnim podnebnim razmeram, temveč zlasti s kakovostjo in količino prsti v mestu (Jim idr., 2018). Ker pomanjkanje zemljišč vpliva na oblikovanje obsežnih gozdov v velikih mestih, bi bila lahko primerna alternativa povečanje gostote dreves in grmičevja na razpoložljivih površinah.

Razporeditev dreves v Bukarešti je mogoče pojasniti z navedenimi izzivi, saj je razpoložljivost zemljišč za sajenje v mestnem središču okrnjena, pogosto ni dovolj prsti ali ta ne dosega ustrezne kakovosti. Večje gostote dreves so bile zaznane dlje od mestnega središča, zlasti v soseskah, načrtovanih in zgrajenih med komunizmom, kar se ujema z ugotovitvami o neenakomerni razporeditvi zelenih površin v velikih mestih (Tatlić idr., 2024). Kot vzhodnoevropsko mesto, v katerem so se postkomunistični načrtovalski pristopi prekrivali s centralizirano komunistično plansko paradigmo (Csomós idr., 2021), Bukarešta kaže razlike v razporeditvi območij, poraščenih z drevesi in grmovjem, ki so podobne vzorcem, prepoznanim v drugih postkomunističnih mestih. Sektorsko usmerjeni in razdrobljeni načrtovalski sistemi v kombinaciji s šibkimi mehanizmi izvrševanja zakonskih določb so ključni vzroki neenakomerne razporeditve mestne zelene infrastrukture (Vasiljević idr., 2018). Prejšnje raziskave so razporeditev mestnih območij, poraščenih z drevesi in grmičevjem, povezovale zlasti s socialnimi in gospodarskimi dejavniki, manj pa z okoljskimi ali ekološkimi. V Bukarešti je razporeditev takih zelenih območij tesno povezana z veljavnim načrtovalskim okvirom in preteklimi načrtovalskimi pristopi, drugje pa je ta razporeditev povezana z rasno segregacijo, gostoto prebivalstva, dohodki, značilnostmi stanovanjskega fonda in fizičnimi krajinskimi prvinami (Schwarz idr., 2015; Foster idr., 2024). Analize, izvedene v zahodnih družbah, podpirajo tezo, da so premožnejše soseske bolj zelene, revnejša območja in tista, na katerih živijo manjšine, pa imajo manj zelenih površin. Nasprotno pa v Bukarešti novejše soseske, v katerih praviloma živi višji srednji sloj, pogosto nimajo veliko površin, poraščenih z drevesi in grmičevjem, starejše soseske, v katerih živijo večinoma pripadniki nižjega srednjega sloja, pa so po navadi bolj zelene. Navedeno je posledica tržno usmerjenih načrtovalskih pristopov, ki so bili uvedeni v devetdesetih letih prejšnjega stoletja in so opazni še danes, v okviru katerih zemljiške parcele investitorjem prinašajo večje donose, če so pozidane. Zagotavljanje zelenih površin v takšnih soseskah se zato dojema zgolj kot zakonska obveznost, ki se pogosto omeji na najmanjšo zahtevano površino ob najmanjšem možnem finančnem vložku.

Glede na biogeografsko regijo, v kateri je Bukarešta, so bili rezultati analize drevesnih vrst v mestu pričakovani. Kljub temu še naprej ostaja precejšnja težava velika razširjenost tujerodnih vrst, med katerimi so nekatere invazivne ali bi lahko take postale. Skladno s prejšnjimi raziskavami med najpogostejše tujerodne vrste v Bukarešti spadajo ameriški javor (*Acer negundo*), veliki pajesen (*Ailanthus altissima*), navadna robinija (*Robinia pseudoacacia*) in bela murva (*Morus alba*) (Sîrbu idr., 2021; Gavrilidis idr., 2023). Večja mestna okolja so pogosto žarišča vnosa tujerodnih vrst v nacionalne ekosisteme (Kaczorowska, 2020), pri čemer Bukarešta ni izjema. Večina prevladujočih tujerodnih drevesnih vrst v mestu je bila v preteklosti namerno vnesena, zlasti iz estetskih razlogov. Po vnosu so te vrste dobro uspevale in postale prevladujoče prvine urbane krajine. Tujerodne invazivne drevesne in grmovne vrste v mestnih okoljih uspevajo zaradi toplejše in bolj suhe mikroklime ter zaradi svojih razmeroma skromnih ekoloških potreb. Kot poudarjajo izsledki prejšnjih raziskav, robinija še posebej dobro uspeva v mestnih okoljih, ker se njene ekološke potrebe dobro ujemajo z mestnimi ekološkimi razmerami (Franceschi idr., 2023). Ta vrsta je v mestih pogosto zaželena zaradi nižjih stroškov nabave in vzdrževanja ter sorazmerno nižje smrtnosti posajenih primerkov. Prejšnje raziskave mestnih drevesnih vrst so poleg tega pokazale, da sta jesen (*Fraxinus* spp.) in javor (*Acer* spp.) bolj odporna proti suši kot druge vrste (Sjöman idr., 2024), kar pomeni, da se njuna prisotnost v Bukarešti ujema s starejšimi izsledki.

Ne glede na to, ali je drevesna vrsta avtohtona ali tujerodna, je njen prispevek k vezavi ogljika nedvoumno pozitiven (Lashof in Neuberger, 2023). Ugotovitve opravljene raziskave kažejo, da se Bukarešta poleg gozda v severnem delu mesta opira še na tri druge pomembne ponore ogljika na vzhodu, zahodu in jugu. Nepovezanost teh ponorov pa omejuje njihovo skupno učinkovitost, zaradi česar mesto ne more v celoti izkoristiti njihovih regulacijskih ekosistemskih storitev. Poleg tega odsotnost povezav med temi ponori bodisi prek linearnih zelenih koridorjev bodisi manjših površin, poraslih z drevjem in grmičevjem, pomeni tveganje za njihovo postopno degradacijo in manj učinkovito zadrževanje ogljika (Hansen idr., 2022). Pretekle kažejo, da so mestni gozdovi pomemben dejavnik prilagajanja na podnebne spremembe, vendar zgolj zanašanje nanje za doseganje ogljične nevtralnosti ne zadostuje (Velasco idr., 2016). Poglobljene študije zmožnosti mestnih dreves za vezavo ogljika so v Evropi še vedno razmeroma redke, večina pa vezavo ogljika proučuje na podlagi drevesnega pokrova ali vrstne sestave z uporabo alometričnih razmerij, razvitih za ameriške drevesne vrste (Bherwani idr., 2024). Za Bukarešto je povprečna ocenjena količina vezanega ogljika v drevesih in grmičevju približno 0,26 t/ha/leto. Za primerjavo: povprečna stopnja vezave ogljika v gozdovih kitajskih mest naj bi bila približno 2 t/ha/leto (Chen, 2015), v gozdovih v Teheranu pa približno 1 t/ha/leto (Rasoolzadeh idr., 2024). Raziskava iz Teherana je pokazala, da med vrste z veliko zmožnostjo vezave ogljika spadajo robinija (*Robinia pseudoacacia*), brest (*Ulmus* spp.), jesen (*Fraxinus* spp.), bor (*Pinus* spp.) in platana (*Platanus* spp.). Podobno sta v svoji raziskavi za Bukarešto ugotovila avtorja tega članka. Analize iz ameriških mest kažejo, da je letna bruto zmogljivost dreves v Baltimoru – mestu, ki je po površini, podnebju in rastlinstvu primerljivo z Bukarešto – približno 14.800 t vezanega ogljika (≈ 0,62 t/ha/leto) (Nowak in Crane, 2002).

Izsledki v literaturi jasno potrjujejo velik pomen mestnih površin, poraslih z drevjem in grmičevjem, pri prizadevanjih za doseganje večje vezave ogljika v mestih. Zaradi vloge, ki jo ima CO_2 pri pospeševanju podnebnih sprememb, je v novejših raziskavah izpostavljen kot eden glavnih onesnaževal zraka (Hadipoor idr., 2021). Ocenjena količina vezanega CO_2 v štirih parkih v Rimu pomeni približno 3,5 % skupnih emisij toplogrednih plinov v mestu (Gratani idr., 2016), v Pekingu pa ocenjena letna količina vezanega CO_2 zajema samo približno 0,2 % skupnih emisij (Tang idr., 2016). V indijskih mestih naj bi bila količina ogljika, vezanega v drevesih, zasajenih ob cestah, enakovredna 22 % mestnih emisij CO_2 (Kiran in Kinnary, 2011). Kljub navedenim ugotovitvam ostaja nejasno, koliko so stroški in prizadevanja občin za širitev ter razvoj robustnih in funkcionalnih omrežij zelene infrastrukture upravičeni zgolj z vidika rezultatov vezave ogljika. Tudi denarno vrednotenje zmožnosti mestnih dreves za vezavo ogljika, čeprav je uporabno za oblikovanje politik in ponazoritev gospodarskega pomena, ni dovolj natančno, da bi lahko ugotovljene vrednosti obravnavali kot točen finančni podatek (Nowak in Crane, 2002; Bherwani idr., 2024). Poleg tega je rast mestnega prebivalstva povezana z naraščajočim povpraševanjem po dostopnih stanovanjih in prometni infrastrukturi. Ohranjanje nepozidanih zemljišč tako postaja čedalje zahtevnejši izziv za lokalne odločevalce, saj se družbeni pritisk stopnjuje z obeh strani: tako z vidika potrebe po zagotavljanju stanovanj kot z vidika potrebe po ustreznih mestnih zelenih površinah. Vrednosti vezanega ogljika, navedene v tem članku in prejšnjih raziskavah, se morda zdijo premalo prepričljive, da bi same po sebi spodbudile strožjo regulacijo urbanističnega načrtovanja, ki bi se osredotočala na kakovost in obseg zelene infrastrukture. Kljub temu z znanstvenega stališča ni nobenega dvoma, da bi se z izgubo mestnih zelenih površin močno poslabšala kakovost življenja v mestih.

Ključna prednost raziskave, predstavljene v tem članku, je bila razpoložljivost podatkovne baze o lokacijah dreves iz registra zelenih površin Bukarešte. Brez tega vira bi bila edina druga možnost uporaba sloja majhnih dreves in grmičevja, ki je dovolj natančen za splošne ocene. Dostop do obeh podatkovnih virov pa je omogočil medsebojno preverjanje podatkov. Ponovljivost uporabljenih metod je odvisna od dostopnosti geoprostorskih podatkov o mestnih drevesih in grmičevju. Če so taki podatki dopolnjeni z informacijami o drevesnih in grmovnih vrstah, je mogoče podobne analize brez težav ponoviti tudi v drugih mestih. Vendar register zelenih površin Bukarešte ni bil posodobljen vse od leta 2012, zato so se razmere v tem času lahko precej spremenile. Posodobljena analiza razporeditve dreves in vrstne sestave bi lahko pokazala spremembe v nekaterih delih mesta, vendar se splošni vzorci, ugotovljeni v tej raziskavi, verjetno ne bi pomembno razlikovali. Dodatna omejitev je bila, da ni podatkov o starosti dreves in vrstah na zadevnih lokacijah. Kljub temu splošni statistični podatki o drevesnih vrstah še vedno zagotavljajo dober vpogled v to, katere vrste pomembno prispevajo k vezavi ogljika v Bukarešti.

5 Sklep

Izsledki raziskave poudarjajo, da bodo za doseganje ogljične nevtralnosti na podlagi na naravi temelječih rešitev v Bukarešti potrebni precejšnja prizadevanja, strokovno podprto načrtovanje in politično preudarno odločanje. Nadaljnja uporaba dosedanjega pristopa lahko privede do rezultatov, ki so slabši od ohranjanja trenutnega stanja, kar dodatno izpostavlja nujnost strateških ukrepov, ki temeljijo na relevantnih informacijah. Raziskava je pokazala, da Bukarešta v primerjavi s podobnimi mesti zaostaja z vidika zmožnosti mestnih dreves in grmičevja za vezavo ogljika. Območja z večjo gostoto dreves in grmičevja so razpršena po vsem mestu. Trenutno stanje je ustrezno izhodišče za nadaljnji razvoj zelene infrastrukture v mestu s poudarkom na širjenju površin, poraslih z drevjem in grmičevjem. Pri tem bi bilo treba dati prednost obrobju mesta, kjer je še vedno na voljo dovolj zemljišč za načrtovanje in oblikovanje tovrstnih prvin. Nasprotno pa bi bili v mestnem središču, kjer je razpoložljivost zemljišč omejena, koristni inovativni pristopi, kot so vertikalne ozelenitve.

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Izjava o razpoložljivosti podatkov

Podatki o pokrovnosti in rabi tal za Bukarešto in županijo Ilfov so bili pridobljeni iz podatkovnih baz Corine Land Cover (CLC) in Urban Atlas ter so ob registraciji prosto dostopni. Podatke o geolokaciji dreves je zagotovila mestna uprava Bukarešte in so na voljo na zahtevo, ni pa jih dovoljeno deliti s tretjimi osebami. Izpeljani podatki, oblikovani v tej raziskavi, kot so gostota dreves in letna količina vezanega ogljika na hektar ter število dreves in grmovnic po posameznih vrstah, so javno dostopni v repozitoriju ORF na povezavi https://osf.io/g3xva/overview (Gavrilidis, 2026); če so ti podatki uporabljeni v drugih publikacijah, je treba citirati tudi ta članek.

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