# Valuing Urban Forests as Natural Capital: Climate Mitigation, Biodiversity and Recreational Ecosystem Services in a Hungarian City

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**ABSTRACT**

Urban forests can support municipal climate action while delivering a broad range of additional ecosystem services. This study assesses the city of Sárvár, Hungary (1,125 ha of forests and 470 ha of other tree-covered areas) to quantify carbon-related ecosystem services and monetize selected non-market benefits. Carbon stocks and sequestration were estimated by tree species group using National Forestry Database records (2010–2023), Copernicus Tree Cover Density data, and IPCC greenhouse-gas inventory methodology. Harvested wood products and material- and energy-substitution effects were also included. Urban forests and trees stored 366,667 tons of $CO_2$ in 2023, corresponding to a carbon-stock value of EUR 18.8 million. When biomass dynamics, harvested wood products, and substitution effects were considered jointly, the net mitigation effect offset 9.3% of total municipal greenhouse-gas emissions. Using a benefit-transfer approach and a 2% social discount rate, the capitalized value of biodiversity-related ecosystem services amounted to EUR 11.89 million, while the capitalized recreational value reached EUR 5.95 million. Overall, the findings suggest that Sárvár's urban forests operate as multifunctional natural capital assets providing climate mitigation and welfare benefits that are directly relevant to policy design, evidence-based urban planning, and ecosystem accounting.

**TANULMÁNY INFÓ**

*Kulcsszavak:*
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**KIVONAT**

**Városi erdők természeti tőke értékelése: klímavédelem, biodiverzitás és rekreációs ökoszisztéma-szolgáltatások egy magyar város példáján.** A városi erdők jelentős szerepet tölthetnek be a klímavédelemben, miközben számos további ökoszisztéma-szolgáltatást is biztosítanak. A tanulmány Sárvár városának példáján (1125 ha erdőterület és 470 ha egyéb fás terület) értékeli a klímamitigációs ökoszisztéma-szolgáltatásokat. A szénkészletek becslése az Országos Erdőállomány Adattár 2010–2023 adatai, illetve a Copernicus Tree Cover Density adatbázis alapján történt. Az elemzés kiterjedt a fatermékekben történő hosszú távú széntárolásra, valamint az anyag- és energiahelyettesítési hatásokra is. A sárvári városi erdők és fák 2023-ban összesen 366 667 tonna $CO_2$-t tároltak, ami mintegy 18,8 millió euró értékű szénkészletnek felel meg. A biomassza, a fatermékek és a helyettesítési hatások együttes figyelembevételével a nettó klímavédelmi hatás a települési üvegházhatásúgáz-kibocsátás 9,3%-át ellentételezte. A benefit transzfer értékelés szerint a biodiverzitáshoz kapcsolódó ökoszisztéma-szolgáltatások tőkésített értéke 11,89 millió euró, míg a rekreációs szolgáltatásoké 5,95 millió euró. Az eredmények azt mutatják, hogy Sárvár városi erdei jelentős klímavédelmi és jóléti értéket képviselnek.

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## 1 INTRODUCTION

Climate change is one of the most urgent global challenges of our time, and its impacts are particularly pronounced in urban areas (IPCC 2023). Cities have become central arenas of global challenges and opportunities in the 21st century. More than half of the world's population lives in urban areas, and a substantial share of global energy use, greenhouse gas emissions, material throughput, and waste generation originates from cities (Dhakal, 2010; United Nations, 2018; Hong et al., 2024). Cities are simultaneously major sources of greenhouse gas emissions and key arenas for implementing solutions, as urbanization-related pressures—such as the urban heat island effect, air pollution, and the loss and fragmentation of green space—require targeted interventions (Elmqvist et al., 2015; IPCC 2021; Choi et al., 2021; IPCC 2023; Feng et al., 2024). Nature-based solutions (Ren et al., 2019; Goodwin et al., 2023), including urban forests, are increasingly recognized as strategic instruments for climate action, as they provide multiple ecosystem services: they sequester and store atmospheric carbon, moderate temperature extremes, improve air quality, and enhance adaptive capacity and resilience in densely built environments (Cohen-Shacham et al., 2016; Feng et al., 2023; Fu et al., 2023; Mosisa et al., 2025).

In this study, the term 'urban forest' refers to all tree-covered areas within the administrative boundary of a municipality, including individual urban trees (e.g., street and yard trees), trees in parks and other public green spaces, and forest stands managed under formal forest management plans located within the municipal boundary. Under this definition, all trees within the settlement area are considered part of a single urban forest system contributing to ecosystem services and climate regulation.

Cities play a decisive role in the sustainability transition, which is understood as a comprehensive socio-economic transformation aimed at achieving environmental sustainability, social justice, and economic well-being simultaneously (Loorbach, 2010; Markard et al., 2012). From the perspective of ecological economics, economic systems must operate within the carrying capacity of nature, and natural resources should be treated not merely as production inputs but as forms of capital with intrinsic value (Costanza et al., 1997). Within this framing, cities are not only economic units but complex socio–ecological systems whose long-term viability depends on their interactions with ecological processes. Urban sustainability, therefore, requires that key ecological functions—such as carbon sequestration, temperature and water regulation, and biodiversity—are systematically integrated into planning, governance, and investment decisions (Grêt-Regamey et al., 2017). Recent urban planning concepts further emphasize the role of nature in supporting this transition. Frameworks such as biophilic cities promote the systematic integration of nature and biodiversity into urban design and governance, strengthening the relationship between people and urban ecosystems (Beatley – Newman, 2013). In parallel, practical planning guidelines such as the 3-30-300 rule propose measurable targets for urban greenery: ensuring that every resident can see at least three trees from their home, that neighborhoods reach approximately 30% tree canopy cover, and that green spaces are accessible within 300 meters (Konijnendijk, 2023). These approaches highlight the strategic importance of urban forests and tree-based green infrastructure in enhancing environmental quality and human well-being in cities (Velasco et al. 2016). Many cities have adopted policies that promote tree planting, protect existing green spaces, and integrate greenery into the built environment through green roofs and facades (Velasco et al., 2016).

Scientific and financial recognition of green infrastructure is supported by Natural Capital Accounting (NCA) approaches, which aim to integrate ecosystem services into national and local accounting and statistical systems in a measurable and trackable manner (World Bank Group, 2021; Vysna et al., 2021; UN 2024; WAVES 2025). The purpose of NCA is to ensure that nature is not treated as a background condition in decision-making, but as a measurable and comparable asset that can be incorporated into economic planning. In the urban context, NCA can support cost–benefit analysis of green-space development, monetary evaluation of climate services, and systematic reporting of ecosystem service provision.

The System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA; United Nations 2024) provides a methodological standard for implementing such accounts and has been assessed across multiple countries and cities. Although NCA remains in an early phase in Hungary, the monetary valuation of urban forests and green spaces—demonstrated in this study—can contribute to establishing the foundations for local-level ecosystem accounting systems and evidence-based urban governance.

To operationalize this perspective within an urban ecosystem accounting framework, it is necessary to identify key ecosystem services that capture the multifunctional contributions of urban forests. Therefore, this study focuses on three service categories particularly relevant in urban contexts: climate change mitigation services through carbon sequestration, biodiversity-related ecosystem services linked to habitat provision and ecological resilience, and recreational ecosystem services reflecting direct benefits for urban residents. Together, these services represent regulating, supporting, and cultural dimensions of urban forest benefits and provide a structured basis for assessing their societal value.

## 1.1 Climate-mitigation functions of urban forests

Urban forests contribute substantially to climate change mitigation by delivering ecosystem services that simultaneously reduce heat stress (Göndöcs et al., 2017) and remove and store carbon from the atmosphere through biomass accumulation and, in some contexts, soil carbon dynamics. While earlier research often focused on carbon stocks in urban vegetation, the dynamic process of sequestration—annual net uptake of atmospheric $CO_2$—has received comparatively less attention (Velasco et al., 2016; Zhuang et al., 2023; Guo et al., 2024). Estimating sequestration commonly relies on modelling, flux analysis, or field measurements (Zhu et al., 2022), which can be costly and labor-intensive, particularly at the metropolitan scale. Tools such as i-Tree and InVEST have therefore been widely applied to quantify carbon-related ecosystem services of urban vegetation (Raum et al., 2019; Babbar et al., 2021).

Hungary provides a useful example for illustrating the relevance of urban tree carbon sequestration in a Central European context. Recent results from Budapest indicate that urban tree vegetation offsets of about 41,000 t $CO_2$ annually, corresponding to approximately 1% of the city's emissions (Király et al., 2025). This value is consistent with estimates from other large cities such as Vancouver, Mexico City, and Changchun, where urban green-space sequestration typically offsets around 1–2% of total emissions (Crawford – Christen, 2015; Velasco et al., 2016; Guo et al., 2024). Beyond carbon, studies on urban trees demonstrate additional co-benefits; for example, species-specific differences in photosynthetic performance and the retention of fine particulate matter can materially influence air-quality regulation in cities (Chen et al., 2024).

## 1.2 Biodiversity-related ecosystem services of urban forests

Beyond climate mitigation, urban forests contribute to biodiversity conservation and associated ecosystem services by providing habitat, supporting species richness, and strengthening ecological connectivity within fragmented urban landscapes. These biodiversity functions generate both intrinsic value and indirect instrumental benefits, including enhanced ecosystem stability, increased resilience to disturbances, and the reinforcement of other ecosystem services such as pollination, pest regulation, and cultural and recreational benefits (Wajchman-Świtalska et al., 2022; Guarino et al. 2024).

European evidence shows that biodiversity-oriented objectives are among the strongest drivers of engagement in ecosystem service provision. Meta-analytical results indicate that voluntary agreements explicitly targeting biodiversity achieve high participation rates, reflecting the importance of stewardship motivations alongside economic incentives (Mäntymaa et al., 2009; Boon et al., 2010; Mitani – Lindhjem, 2015; Ringier et al., 2025). These findings underscore that biodiversity conservation is increasingly perceived as a core forest function rather than a residual outcome of production-oriented management.

In urban contexts, biodiversity-related ecosystem services are particularly salient due to high land-use pressure, habitat fragmentation, and strong public demand for access to nature-rich environments. Biodiversity services valuation is typically conducted using stated-preference methods, most commonly contingent valuation, or choice experiments, which capture non-market values such as willingness to pay (WTP), i.e., the monetary amount individuals are willing to contribute to secure biodiversity protection and forest conservation outcomes (Kline et al., 2000; OECD 2002; Brouwer et al., 2015). Incorporating biodiversity into urban forest valuation is therefore essential within sustainability-transition frameworks, as it aligns municipal planning with biodiversity targets while also reinforcing environmental justice objectives through equitable access to biodiverse green spaces.

Given the scarcity of local stated-preference studies for municipal forest areas, biodiversity values are frequently incorporated through benefit transfer based on robust primary valuation studies and transparent adjustment procedures. In this study, benefit transfer is informed by the nationwide contingent valuation of biodiversity policy implementation conducted for Germany by Meyerhoff et al. (2012). Their results indicate annual WTP values ranging between EUR 2.3 and EUR 9.3 billion for implementing the German National Biodiversity Strategy, demonstrating that biodiversity protection yields substantial welfare benefits that clearly exceed opportunity and management costs.

### 1.3 Recreational ecosystem services of forests

Recreational ecosystem services are among the most directly perceived benefits that forests provide. Activities such as walking and hiking contribute to physical and mental health, stress reduction, social cohesion, and overall urban livability. In urban and peri-urban contexts, forest recreation is intricately linked to accessibility and frequent use by residents, making it a key component of sustainable urban development (Wajchman-Świtalska et al., 2022).

International evidence consistently shows that forests rank among the most highly valued landscapes for recreation, outperforming many other green-space types due to their perceived naturalness, biodiversity, and aesthetic quality (Tyrväinen – Miettinen, 2000; De Groot et al., 2012; Elmqvist et al., 2015). Meta-analyses indicate that aggregate recreational value is primarily driven by visit frequency rather than per-visit value, implying that forests located near population centers often generate the greatest overall benefits (Zandersen – Tol, 2009; Bateman et al., 2011).

The economic valuation of forest recreation has most commonly relied on the travel cost method, which infers value from the time and monetary expenses visitors incur to access recreational sites. This approach has been widely applied to urban forests, production forests, and protected areas and is considered more behaviorally robust than stated-preference methods in contexts where forest access is traditionally free of charge (Bartczak et al., 2008; Zandersen – Tol, 2009).

The most comprehensive and policy-relevant valuation of forest recreational services for Hungary was provided by Széchy and Szerényi (2023), within the national MAES-HU framework. Combining a local travel-cost case study (Pilis Biosphere Reserve) with a national-scale benefit-transfer approach, the authors demonstrated consistency between methods. Based on this integrated assessment, they report a central estimate of 101.7 million EUR per year (2020 EUR) for the recreational ecosystem services provided by Hungary's forests, primarily through hiking and walking. The study further highlights that forests composed of native species and exhibiting higher naturalness have the highest recreational potential, while accessibility and proximity to urban populations are decisive drivers of recreational demand. These characteristics are especially relevant for urban forests, where repeated local visits can generate substantial aggregate benefits.

Building on this Hungary-specific evidence, the present study adopts the national central estimate reported by Széchy and Szerényi (2023) as the reference for valuing recreational ecosystem services in Sárvár's urban forests. Integrating recreation alongside climate-mitigation and biodiversity-related services allows for a more comprehensive assessment of the multifunctional contribution of urban forests to the sustainability transition.

### 1.4 Study objectives

The primary objective of this research is to provide a comprehensive, quantitative assessment of the climate-mitigation potential of urban forests and green spaces, using the city of Sárvár as a case study. The analysis aims to quantify the contribution of urban forest areas to climate change mitigation through multiple carbon-related pathways, including carbon stocks stored in living biomass, annual carbon sequestration, long-term carbon sink in harvested wood products, and additional climate benefits arising from material and energy substitution effects.

Beyond carbon accounting, the study adopts a multifunctional ecosystem-services perspective by explicitly incorporating the valuation of biodiversity-related and recreational ecosystem services provided by urban forests. In this context, the research seeks to assess the monetary value of urban forest-related ecosystem services through benefit-transfer-based economic valuation approaches. Integrating these services generates a more holistic evaluation of urban forests, aligning local assessments with broader sustainability and nature-restoration objectives.

In addition to its quantitative and methodological goals, the study has a strong societal objective focused on awareness raising and science-based communication. By translating biophysical indicators—such as carbon sequestration, biodiversity benefits, and recreational values—into well-communicable economic metrics, the research aims to enhance public understanding of the multifunctional role of urban green infrastructure. This approach supports increased social acceptance of nature-based solutions, encourages citizen engagement, and contributes to informed, climate- and biodiversity-conscious decision-making at the municipal level.

## 2 MATERIALS AND METHODS

### 2.1 Study area and spatial data

The analysis focused on urban forest areas located within the administrative boundary of the city of Sárvár, Hungary (*Figure 1*). The city of Sárvár represents a suitable case for analyzing urban forest ecosystem services in a smaller Central European municipality, in contrast to large metropolitan areas such as Budapest. The city hosts the headquarters of the Forest Research Institute of the University of Sopron, providing a local research base.

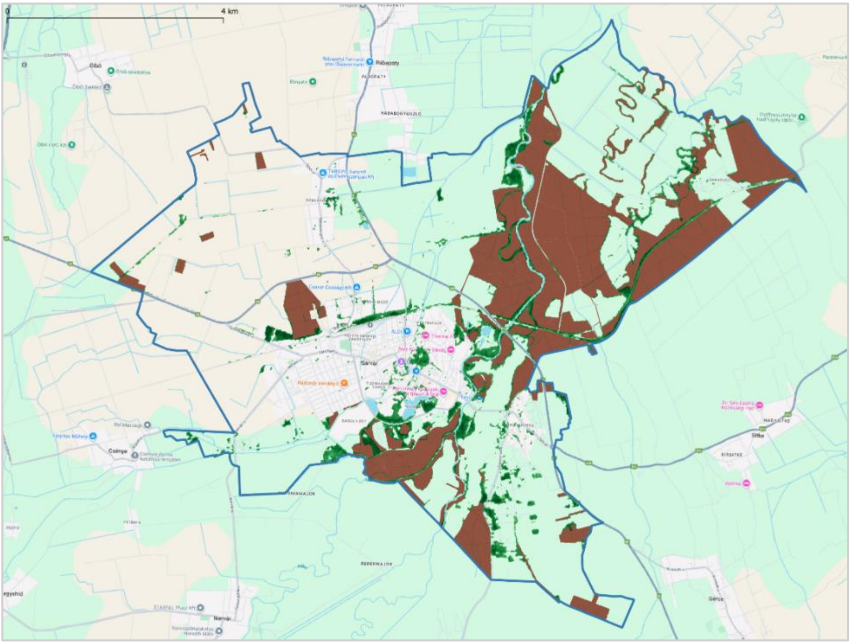


*Figure 1. Overview map of the study area. Stands under forest management planning are indicated in brown, while other tree-covered areas are dark green. Source: National Forestry Database (NFD) and TCD (2025).*

Forest stands under forest management planning (FMP) were identified based on records from the National Forestry Database (NFD) for the period 2010–2023. In this study, areas under FMP refer to forest stands that are officially classified as forests under Hungarian forestry legislation and are regulated by the national forestry authority. These areas are recorded in the National Forestry Database and are managed according to approved forest management plans. This category, therefore, differs from other urban tree-covered areas (e.g., parks, tree rows, gardens) that are not classified as forests within the forestry administration system. For tree-covered areas not registered as forest, spatial delineation was based on the Copernicus Land Monitoring Service Tree Cover Density dataset (TCD 2025). This dataset classifies tree cover into canopy-density classes at a spatial resolution of 10 × 10 m. The Copernicus-derived tree-cover map, together with carbon-stock and sequestration coefficients derived from the NFD-based forest inventory data, provided the basis for estimating carbon dynamics in non-forest tree-covered areas.

## 2.2 Carbon stock and carbon sequestration assessment

Estimation of carbon stocks stored in living biomass and annual carbon sequestration followed the methodological guidance of the IPCC (2006, 2019), complemented by calculation procedures applied in the Hungarian National Greenhouse Gas Inventory (NIR 2023).

Calculations were conducted for 22 tree species groups, allowing species-specific differentiation of biomass accumulation, carbon storage, and sequestration rates. In addition to species-level estimates, average per-hectare carbon stock and sequestration values were derived for urban forest areas.

Harvest data were obtained from the NFD. Assortment structure (fuelwood versus industrial roundwood) was estimated by tree species group following Borovics et al. (2024), using the proportions presented in *Table 1*.

*Table 1. Assortment shares by tree-species group* (source: Borovics et al., 2024).*

| | Oaks | Turkey oak | European beech | Hornbeam | Black locust | Hard broadleaved | Hybrid poplars | Native poplars | Willows | Soft broadleaved | Conifers |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Firewood | 69% | 93% | 59% | 88% | 80% | 82% | 8% | 18% | 33% | 65% | 14% |
| Industrial wood | 31% | 7% | 40% | 12% | 20% | 18% | 91% | 81% | 67% | 35% | 86% |

*Oaks: main oak species of Hungary: pedunculate oak (*Q.robur*), sessile oak (*Q. petraea*), pubescent oak (*Q. pubescens*), Hungarian oak (*Q. frainetto*), red oak (*Q. rubra*), and related species. Hard broadleaved species: a diverse group of minor hardwood species including walnuts (Juglans spp.), wild cherry and related Prunus species, wild apple and pear (*Malus, Pyrus*), mulberry (*Morus alba*), rowans and service trees (*Sorbus* spp.), sweet chestnut (*Castanea sativa*), plane trees (*Platanus* spp.), hackberries (*Celtis* spp.), Turkish hazel (*Corylus colurna*), and other minor hardwood species. Native poplars: indigenous poplar species: white poplar (*Populus alba*), grey poplar (*Populus × canescens*), and black poplar (*Populus nigra*). Willows: native willow species: white willow (*Salix alba*), crack willow (*Salix fragilis*), goat willow (*Salix caprea*), and regionally selected willow clones. Soft broadleaved species: birches (Betula spp.), horse chestnut (Aesculus hippocastanum), tree of heaven (*Ailanthus altissima*), Indian bean tree (*Catalpa bignonioides*), and other minor soft species. Conifers: primarily Scots pine (*Pinus sylvestris*) and black pine (*Pinus nigra*), Norway spruce (*Picea abies*), and other conifer species such as Douglas-fir (*Pseudotsuga menziesii*), firs (*Abies* spp.), cedars (*Cedrus* spp.), junipers (*Juniperus* spp.), cypresses, yew (*Taxus baccata*), and arborvitae (*Thuja* spp.).

## 2.3 Harvested wood products and substitution effects

Long-term carbon storage in harvested wood products, as well as material and energy substitution effects, were quantified following the methodological framework described by Király et al. (2024). An energy-substitution factor of 0.67 tC/tC was applied, while material substitution was calculated using a factor of 1.2 tC/tC, consistent with literature-based averages (Knauf et al., 2015, 2016; Härtl et al., 2017; Leskinen et al., 2018; Schweinle et al., 2018) for wood-based product substitution effects.

## 2.4 Monetary valuation of carbon-related ecosystem services

The monetary value of carbon sequestration, carbon storage, and substitution-related ecosystem services was quantified following the valuation framework proposed by Borovics et al. (2025) as follows.

$$V_{seq} = Q_{seq} \cdot P_{VCM} \quad (1)$$

$$V_{stor} = Q_{stor} \cdot P_{VCM} \quad (2)$$

$$V_{sub} = Q_{sub} \cdot P_{ETS} \quad (3)$$

Where:

- $V_{seq}$ : value of annual net carbon sequestration services;
- $V_{stor}$ : value of carbon storage services;
- $V_{sub}$ : value of avoided fossil $CO_2$ emissions through substitution;
- $Q_{seq}$ : annual net carbon sequestration;
- $Q_{stor}$ : carbon storage;
- $Q_{sub}$ : avoided fossil $CO_2$ emissions through substitution;
- $P_{VCM}$: carbon price applied to biological sequestration and storage consistent with the voluntary carbon market prices;
- $P_{ETS}$ : ETS carbon price applied to substitution effects.

For carbon sequestration and storage services, a carbon price of 50 EUR per $tCO_2$ was applied, reflecting prevailing price levels in voluntary carbon markets (VCMs). In contrast, substitution effects were valued using a price of 100 EUR per $tCO_2$, corresponding to the average allowance price observed in the EU Emissions Trading System (Borovics – Király, 2024).

This valuation approach does not represent a WTP-based estimate of social preferences. Instead, it constitutes a market-price-based proxy valuation, grounded in observed policy-relevant carbon prices applied within existing carbon-market and regulatory contexts. The applied prices reflect revealed values embedded in climate-policy instruments, namely voluntary carbon markets for biological carbon services and compliance markets for avoided fossil emissions. Accordingly, the resulting monetary values should be interpreted as policy-consistent, market-based climate-mitigation values expressing the contribution of urban forest ecosystem services in terms directly comparable to carbon-market benchmarks and mitigation costs.

### 2.5 Biodiversity-related ecosystem service valuation: benefit transfer approach

Biodiversity-related ecosystem services of Sárvár's urban forests were valued using a benefit transfer approach. The objective was to derive a WTP-based annual value per hectare and its capitalized natural-capital equivalent, suitable for integration into urban ecosystem-service accounting and municipal decision-support frameworks. Due to the absence of local stated-preference studies at the municipal scale, a unit value transfer methodology was applied, combining inflation adjustment and income scaling to adapt an existing peer-reviewed valuation to the Hungarian context.

The base valuation was derived from Meyerhoff et al. (2012), who estimated societal WTP for biodiversity-related forest ecosystem services in Germany using a nationwide contingent valuation survey. The study reports an aggregate annual WTP of EUR 2.22 billion (2012 prices) for approximately 11 million hectares of forest.
The per-hectare unit value was calculated as:

$$V_{DE,2012} = \frac{WTP_{DE,2012}}{A_{DE}} \quad (4)$$

Where:

$V_{DE,2012}$: is the German Biodiversity-related ecosystem service value per hectare per year;
$WTP_{DE,2012}$: is the German willingness to pay for the total forested area;
$A_{DE}$: is the German forest area.

To ensure temporal comparability, the 2012 German unit value was adjusted to the target price level using the Harmonized Index of Consumer Prices (HICP) for Germany:

$$V_{DE,t} = V_{DE,2012} \times \frac{HICP_{DE,t}}{HICP_{DE,2012}} \quad (5)$$

HICP data were obtained from the Federal Reserve Bank of St. Louis (FRED 2026).

Income differences between Germany and Hungary were accounted for using an income elasticity of WTP:

$$\varepsilon = 0.6 \quad (6)$$

consistent with meta-analytical evidence reported by Drupp et al. (2025). Income was represented by real GDP per capita from Eurostat (2026).
The income-adjusted Hungarian unit value was calculated as:

$$V_{HU,t} = V_{DE,t} \times \left(\frac{GDP_{HU}}{GDP_{DE}}\right)^{\varepsilon} \quad (7)$$

The aggregate annual biodiversity-related ecosystem service value was calculated by scaling the income- and price-adjusted unit value to the total extent of urban forests of Sárvár. The aggregate annual biodiversity-related ecosystem service value was calculated as:

$$V_{Sárvár,t} = V_{HU,t} \times A_{Sárvár} \quad (8)$$

Where:

| | |
|---|---|
| $V_{\text{Sárvár},t}$ | is the total annual biodiversity-related ecosystem service value; |
| $V_{\text{HU},t}$ | is the adjusted WTP unit value per hectare; |
| $A_{\text{Sárvár}}$ | denotes the total urban forest area of the city of Sárvár. |

## 2.6 Recreational ecosystem service valuation

Recreational ecosystem services were estimated using a national-level benefit transfer from Széchy and Szerényi (2023), who report a central estimate of EUR 101.7 million per year (2020 EUR) for recreational services (hiking and walking) provided by Hungarian forests. The national value was converted into a per-hectare unit value using a reference forest area of 2,000,000 ha and subsequently scaled to the urban forest area of Sárvár. Values were inflated from 2020 to 2024 using Hungarian HICP data from the Hungarian Central Statistical Office (2026) and converted to Hungarian forints using the 2024 annual average EUR/HUF exchange rate.

## 2.7 Capitalization of ecosystem service flows

To express annual ecosystem service flows as long-term natural-capital values, benefits were capitalized using a perpetuity assumption:

$$PV = \frac{V_{Sárvár,t}}{r} \quad (9)$$

Where:

| | |
|---|---|
| $PV$: | is the present value; |
| $V_{\text{Sárvár},t}$: | is the total annual ecosystem service value; |
| $r$: | is the social discount rate of 2%. |

A social discount rate of 2% was applied, reflecting the long-term public-benefit perspective typically adopted in municipal and public-sector investment appraisal.

# 3 RESULTS AND DISCUSSION

The total area of urban forest stands under forest management within the administrative boundary of Sárvár amounted to 1,125 hectares. The total area of urban tree-covered areas not under forest management was 470 hectares. Areas under forest management were characterized by higher canopy closure than tree-covered areas not under forest management (*Figure 2*).

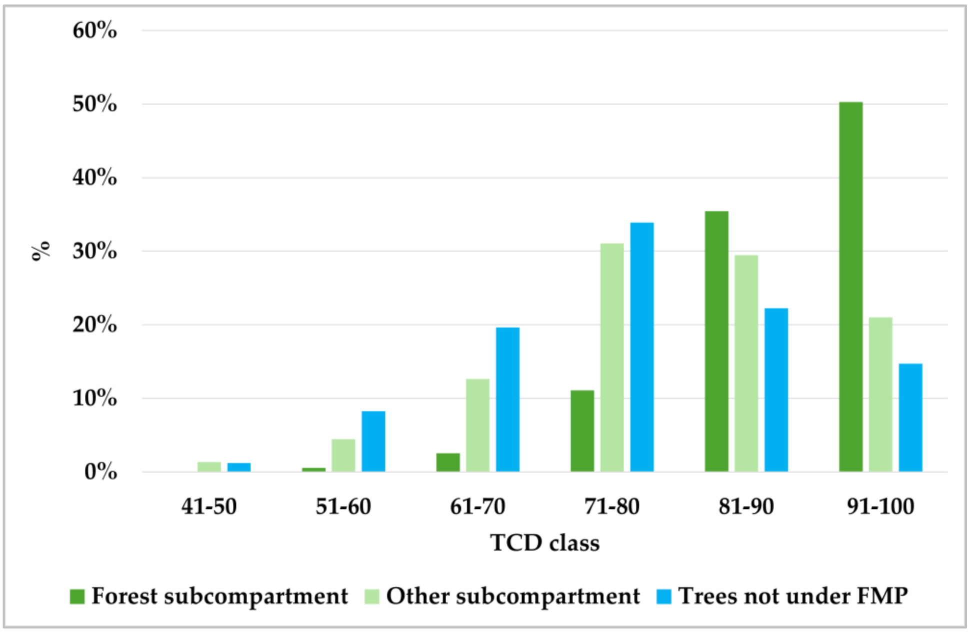


*Figure 2. Distribution of urban forest areas under forest management and other tree-covered areas by canopy-closure class according to TCD (2025).*

### 3.1 Climate mitigation-related ecosystem services

Our results indicate that urban forest stands under forest management store more than 80,000 t of carbon in above- and below-ground biomass, constituting a substantial natural carbon reservoir (*Figure 3*). The highest carbon stocks were observed in stands dominated by pedunculate oak (*Quercus robur*). Tree-covered areas not subject to forest management were estimated to store over 20,000 t of carbon in biomass; however, for these areas, tree species composition is not available. Across the study area, the average carbon stock exceeded 100 t C $ha^{-1}$ in 2023.

The net carbon balance of urban forest areas subject to forest management planning was negative over the study period, indicating that these forests functioned as net carbon sinks. Beyond carbon sequestration in living biomass, timber harvesting also contributed to climate-mitigation outcomes, as a portion of the harvested carbon is retained in harvested wood products. In addition, material and energy substitution effects associated with wood products and fuelwood generated further avoided emissions by replacing fossil energy carriers and carbon-intensive materials (*Figure 4*).

The average annual carbon sequestration occurring in the biomass of urban forest stands under forest management during the study period was approximately –4,950 tons of $CO_2$ equivalents, offsetting 4.6 % of the city's total greenhouse-gas emissions based on the emissions inventory reported by the Municipality of Sárvár (2020). The combined carbon-sequestration and emission-offsetting effect of urban forests averaged –10,116 tons of $CO_2$ equivalents over the study period, corresponding to 9.3 % of the city's total greenhouse-gas emissions. This offset volume is equivalent to the average annual emissions of 1,792 Hungarian households (Central Statistical Office 2025a,b) or 4,334 passenger cars (Central Statistical Office 2025c). Annual carbon sequestration per hectare in the biomass of areas under forest management ranged between –3.5 and –7.6 $tCO_2\ ha^{-1}\ yr^{-1}$ during the study period. The total average per-hectare carbon balance ranged between –8.7 and –12.8 $tCO_2\ ha^{-1}\ yr^{-1}$.

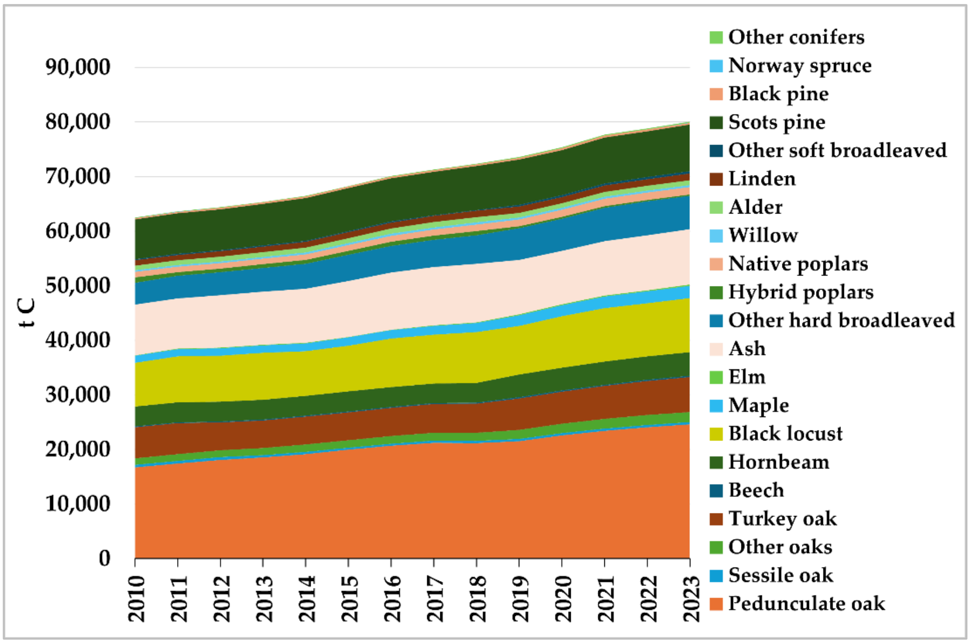


*Figure 3. Carbon stored in the biomass of urban forest stands under forest management planning during the study period, disaggregated by tree-species group. Calculated based on data from the National Forestry Database (NFD).*

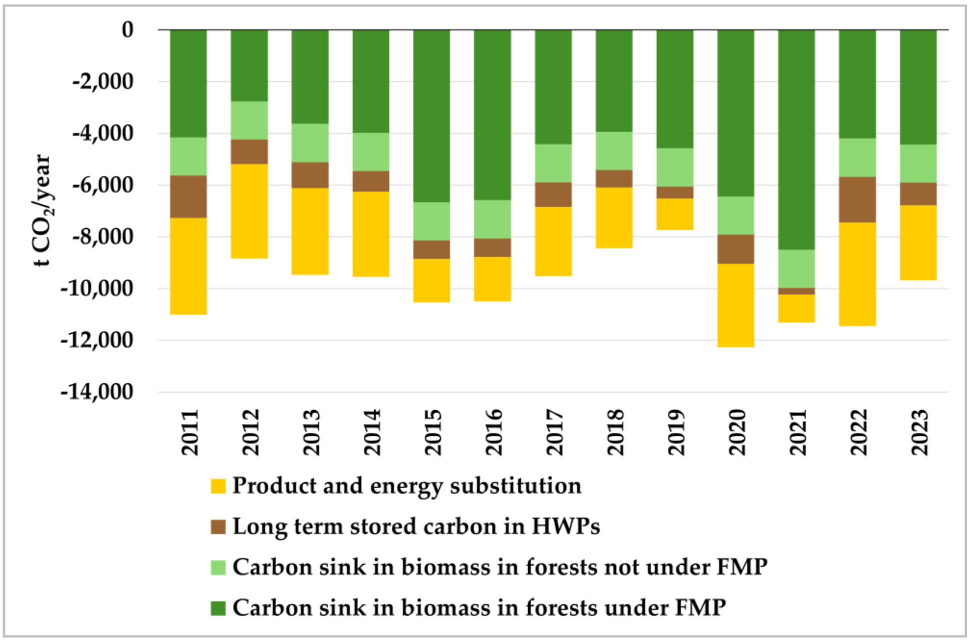


*Figure 4. Net annual carbon sequestration in the biomass of urban forest areas under forest management planning (FMP) and tree-covered areas not under forest management planning, together with long-term carbon storage in harvested wood products and product- and energy-substitution effects, expressed in $CO_2$ equivalents. Negative values indicate carbon sequestration. Calculated based on data from the National Forestry Database (NFD).*

*Table 2* presents the financial valuation of climate-mitigation ecosystem services provided by urban forests and tree-covered areas in Sárvár. The results indicate that approximately 366,667 tons of $CO_2$ equivalents are stored in the biomass of Sárvár's urban forests and trees, representing a financial value exceeding EUR 18.8 million (HUF 7.3 billion). Annual carbon sequestration amounts to 6,423 tons of $CO_2$, corresponding to an annual climate-mitigation value of EUR 0.33 million (HUF 128.5 million). An additional 932 tons of $CO_2$ per year are stored in newly harvested wood products originating from areas under forest management (EUR 0.05 million, HUF 18.6 million), while material and energy substitution effects associated with harvested wood result in avoided $CO_2$ emissions of approximately 2,761 t per year, corresponding to an economic value of EUR 0.28 million (HUF 110.4 million). Through carbon storage, continuous carbon sequestration, and long-term utilization of wood products, urban forests make a measurable financial contribution to the city's climate-neutrality objectives.

*Table 2. Financial value of climate-mitigation ecosystem services provided by urban forests and tree-covered areas in Sárvár.*

| Description | Carbon sequestration / storage volume | Unit | Average carbon sequestration / storage volume per area | Unit | Financial value (EUR) | Financial value (million HUF) | Average financial value per area (EUR/ha) | Average financial value per area (HUF/ha) |
|---|---|---|---|---|---|---|---|---|
| Carbon stored in the biomass of forests and trees in Sárvár in 2023. | 366,667 | tons $CO_2$ | 326 | tons $CO_2$/ha | 18,803,419 | 7,333.33 | 11,789 | 4,597,701 |
| Carbon sequestration in the biomass of forests and trees in Sárvár, average for 2011–2023. | 6,423 | tons $CO_2$/yr | 6 | tons $CO_2$/yr/ha | 329,385 | 128.46 | 207 | 80,539 |
| Carbon stored in new harvested wood products originating from Sárvár's forests, average for 2011–2023. | 932 | tons $CO_2$/yr | 1 | tons $CO_2$/yr/ha | 47,795 | 18.64 | 30 | 11,687 |
| Avoided emissions through material and energy substitution, average for 2011–2023. | 2,761 | tons $CO_2$/yr | 2 | tons $CO_2$/yr/ha | 283,179 | 110.44 | 178 | 69,241 |

## 3.2 Biodiversity-related ecosystem services

Using a benefit-transfer approach, unit ecosystem service values for biodiversity-related forest services were derived from the German WTP estimates reported by Meyerhoff et al. (2012). After inflation adjustment to 2024 price levels and income-based scaling to Hungarian conditions ($\varepsilon = 0.6$), the resulting unit value amounts to 149 EUR $ha^{-1}$ $yr^{-1}$.

Applying this Hungary-adjusted unit value to the total urban forest area of Sárvár (1,125 ha forest and 470 ha tree-covered area) yields an aggregate annual biodiversity-related ecosystem service value of 237,871 EUR, corresponding to approximately 92.77 million HUF (*Table 3*). This value represents the annual societal WTP for biodiversity-related ecosystem services provided by Sárvár's urban forests.

To express the long-term asset value of this ecosystem service flow, annual benefits were capitalized assuming a perpetual provision of services and applying a social discount rate of 2%. Under this assumption, the natural capital value of biodiversity-related ecosystem services provided by Sárvár's urban forests amounts to approximately 11.89 million EUR (4.64 billion HUF).

The results indicate that even under conservative, income-adjusted WTP assumptions, biodiversity-related ecosystem services constitute a significant and economically meaningful asset for the municipality.

*Table 3. Monetary valuation of biodiversity-related ecosystem services provided by the urban forests of Sárvár.*

| Category | EUR | HUF | EUR/ha | HUF/ha |
|---|---|---|---|---|
| Total annual biodiversity-related ecosystem service value | 237,871 | 92,769,496 | 149 | 58,163 |
| Capitalized biodiversity-related ecosystem service value (r = 2%) | 11,893,454 | 4,638,447,147 | 7,457 | 2,908,117 |

## 3.3 Recreational ecosystem services

Recreational ecosystem service values were estimated using a benefit-transfer approach based on the national central estimate for Hungary reported by Széchy and Szerényi (2023). The original 2020 EUR value was updated to the 2024 price, using an inflation factor of 1.4676. Accordingly, the national aggregate recreational ecosystem service value increased to approximately 149.25 million EUR per year in real 2024 prices.

Normalizing this national value by the total forest area of Hungary (2 million ha) yields a recreational ecosystem service value of 74.63 EUR $ha^{-1}$ $yr^{-1}$. Applying this unit value to the total area of urban forests in Sárvár (1,125 ha forest and 470 ha tree-covered area) resulted in an estimated annual recreational ecosystem service value of 119,027 EUR, corresponding to approximately 46.42 million HUF.

To express the long-term asset value of recreational ecosystem services, annual benefits were capitalized assuming a perpetual provision of services and applying a 2% social discount rate. Under this assumption, the capitalized recreational ecosystem service value of Sárvár's urban forests amounted to approximately 5.95 million EUR, equivalent to 2.32 billion HUF (*Table 4*).

*Table 4. Monetary valuation of recreational ecosystem services provided by the urban forests of Sárvár.*

| Category | EUR | HUF | EUR/ha | HUF/ha |
|---|---|---|---|---|
| Annual recreation value | 119,027 | 46,420,412 | 75 | 29,104 |
| Capitalized recreation value (r = 2%) | 5,951,356 | 2,321,028,901 | 3,731 | 1,455,191 |

Overall, the results indicate that recreational ecosystem services alone represent a substantial non-market benefit generated by Sárvár's urban forests.

## 3.4 Integrated valuation of urban forest ecosystem services

Taken together, the valuation results demonstrate that Sárvár's urban forests deliver a diverse portfolio of ecosystem services whose economic significance becomes particularly evident when annual service flows and long-term capitalized values are assessed jointly (*Figures 5* and *6*).

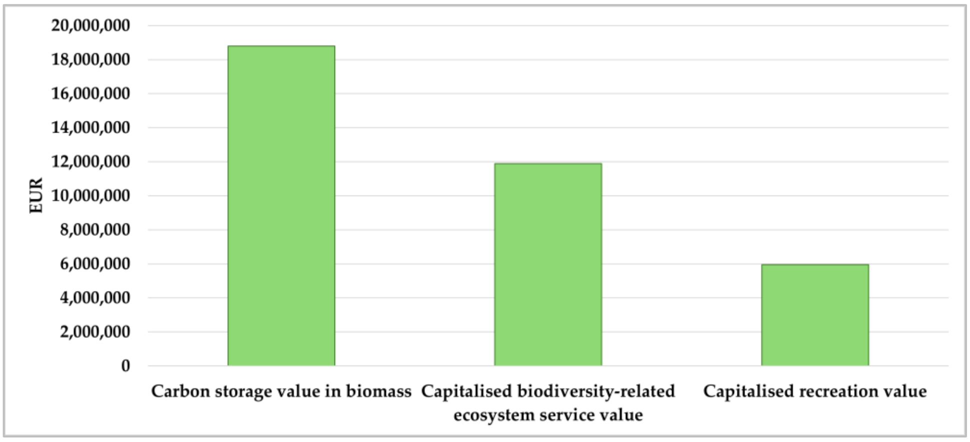


*Figure 5. Comparison of capitalized ecosystem-service values provided by the urban forests of Sárvár, based on own calculations. Annual flows of recreational and biodiversity-related ecosystem services were capitalized using a perpetuity approach and a social discount rate, whereas carbon storage is not capitalized. Instead, the value of carbon storage is estimated as a stock value, calculated by multiplying the total amount of carbon stored in urban forest biomass by the prevailing voluntary carbon market (VCM) carbon price.*

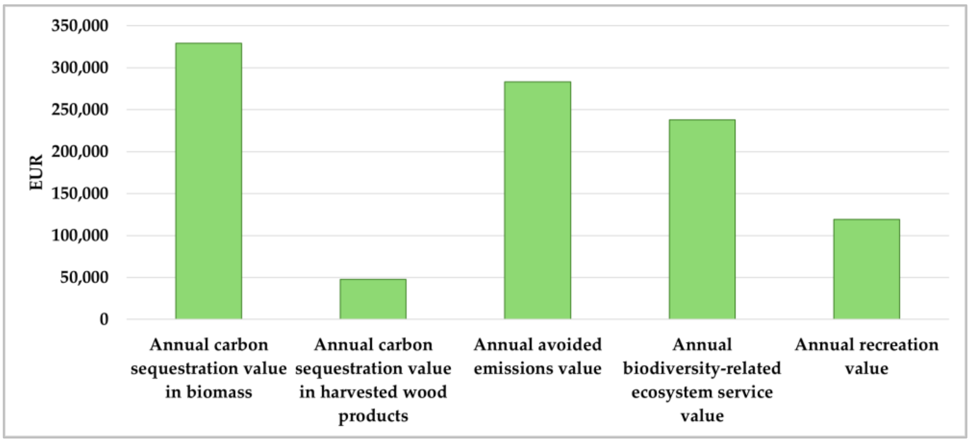


*Figure 6. Annual monetary value of selected ecosystem services provided by the urban forests of Sárvár, based on own calculations.*

The comparison of capitalized ecosystem-service values highlights the dominant role of climate-mitigation services in the overall natural capital stock of urban forests (*Figure 5*). The value of carbon stored in forest biomass clearly exceeds all other capitalized components, reaching approximately EUR 18.8 million, reflecting the long-term accumulation of carbon in standing biomass. This stock value alone is higher than the capitalized value of biodiversity-related ecosystem services (EUR 11.89 million) and more than three times the capitalized recreational ecosystem-service value (EUR 5.95 million). This pattern underscores the importance of urban forests as long-lived carbon reservoirs and highlights their relevance for long-term climate-neutrality strategies at the municipal level.

At the same time, the capitalized biodiversity and recreation values represent substantial non-market natural capital assets. Although smaller in magnitude than carbon storage, these values demonstrate that urban forests provide durable benefits related to habitat provision, species conservation, landscape quality, and human well-being. The coexistence of high carbon-storage value with significant biodiversity and recreational capital values suggests that climate mitigation in Sárvár operates in synergy with other ecosystem services.

A complementary perspective emerges when focusing on annual ecosystem-service values (*Figure 6*). Here, the relative importance of different services becomes more balanced. Annual climate-mitigation benefits are distributed across several components: carbon sequestration in biomass represents the largest single annual contribution, followed closely by the value of avoided emissions through material and energy substitution, while carbon sequestration in harvested wood products adds a smaller but still measurable contribution. Together, these climate-related annual flows illustrate that the mitigation effect of urban forests is not limited to biomass growth but is reinforced by sustainable wood use and substitution effects.

Beyond climate mitigation, biodiversity-related ecosystem services generate an annual value comparable in magnitude to avoided emissions, emphasizing that conservation and habitat functions provide benefits of a similar economic order to certain climate-related flows. Recreational ecosystem services, while smaller in annual monetary terms, still contribute tens of thousands of euros per year and represent direct, locally experienced benefits for residents. These services are particularly relevant from a social perspective, as they are closely linked to daily use, physical and mental health, and quality of life.

Viewed together, *Figures 5* and *6* illustrate a key insight: climate-mitigation services dominate the long-term capital value of urban forests in Sárvár, whereas annual ecosystem-service flows are more evenly distributed across climate, biodiversity, and recreation. This distinction is important for policy interpretation. Carbon storage reflects the accumulated outcome of past forest development and management, while annual service flows are more sensitive to current management decisions and land-use pressures.

Overall, the integrated results confirm that Sárvár's urban forests function as multifunctional natural capital assets. They simultaneously support municipal climate objectives through carbon storage and sequestration, contribute to biodiversity conservation and ecological resilience, and provide recreational benefits with direct social relevance. The coexistence of substantial capitalized values and significant annual flows highlights the strategic importance of urban forests in local sustainability planning, demonstrating that investments in their protection and management yield returns across multiple ecosystem-service dimensions.

## 4 CONCLUSIONS

This study demonstrates that urban forests of Sárvár constitute a multifunctional nature-based solution with clearly measurable climate-mitigation and non-market ecosystem-service benefits at a scale relevant for municipal policy. Carbon-related services indicate a substantial natural-capital stock and a meaningful annual mitigation contribution, reaching approximately 9.3% of total municipal greenhouse-gas emissions when biomass dynamics, harvested wood products, and substitution effects are considered jointly. In monetary terms, the dominant component of the capital stock is carbon storage in biomass (EUR 18.8 million), complemented by capitalized values for biodiversity-related ecosystem services (EUR 11.89 million) and recreational ecosystem services (EUR 5.95 million).

Three overarching conclusions emerge. First, urban forests should be regarded as strategic municipal infrastructure, delivering climate regulation, biodiversity conservation, and social benefits simultaneously, rather than as residual or purely amenity-oriented land uses. Second, the results underscore the importance of a portfolio-based perspective on ecosystem services: the coexistence of climate, biodiversity, and recreational values strengthens the economic and policy rationale for urban forest protection and investment across multiple governance domains. Third, tree-covered areas not under forest management, while characterized by lower carbon stocks than managed stands, form an integral part of the urban green-infrastructure system and should be systematically incorporated into planning, monitoring, and reporting frameworks.

### 4.1 Policy implications and recommendations

Based on the findings, the following policy-relevant recommendations can be formulated:

1. **Formal recognition of urban forests in local climate and sustainability strategies:** Urban forests and tree-covered areas should be explicitly embedded in municipal climate, adaptation, and sustainability strategies, supported by a limited set of stable and transparent indicators.
2. **Adaptation-oriented species and stand strategies:** Urban forest planning and renewal should prioritize climate-resilient species and stand structures that maintain long-term carbon-sink capacity while supporting biodiversity and ecosystem stability.
3. **Systematic integration of non-forest tree-covered areas:** Tree-covered areas outside formal forest management should be comprehensively inventoried and integrated into urban green-infrastructure governance to safeguard their ecosystem-service contributions.
4. **Science-based communication and public engagement:** Translating ecosystem-service outcomes into well-communicable indicators can enhance public awareness, strengthen social acceptance, and support citizen participation in urban green-infrastructure stewardship.
5. **Regular updating of ecosystem-service valuations:** Periodic revision of ecosystem-service valuations is recommended to ensure that information remains relevant for urban development, climate planning, and budgeting processes, reinforcing the treatment of green infrastructure as a long-term investment.
6. **Pilot implementation of local Natural Capital Accounting:** Applying a local-level natural capital accounting framework aligned with SEEA-EA principles would improve transparency and policy usability, enabling ecosystem-service values to be systematically incorporated into municipal decision-making.

### 4.2 Limitations and future research

This study focuses on a selected set of ecosystem services—climate-mitigation, biodiversity-related, and recreational services—chosen for their policy relevance, data availability, and compatibility with natural-capital accounting frameworks at the municipal scale. Consequently, the results do not capture the full range of ecosystem services provided by Sárvár's urban forests and tree-covered areas.

Some limitations that merit consideration. First, carbon-related estimates for tree-covered areas not subject to forest management planning rely on remotely sensed canopy data and forest-based coefficients, as detailed species composition and stand structure information are not available for these areas. Future research would benefit from improved urban tree inventories or high-resolution field surveys to refine carbon-stock and sequestration estimates outside the formal forest estate.

Second, biodiversity-related and recreational ecosystem services were valued using benefit-transfer approaches based on national or international primary studies. While this approach is consistent with established practice and suitable for policy screening, locally tailored stated-preference studies at the municipal or regional scale would allow more precise estimation of WTP values and reduce uncertainty associated with income adjustment and contextual transferability.

Third, some important urban ecosystem services were beyond the scope of the present analysis. Future research should extend the valuation framework to include microclimate regulation (including urban heat-island mitigation), air quality improvement, stormwater regulation, and public health-related benefits. These services are particularly relevant in urban contexts and may increase the estimated natural-capital value of urban forests, especially when health-related outcomes are considered.

Expanding the assessment to incorporate these additional service categories, combined with improved local biophysical data and primary valuation evidence, would support the development of a more comprehensive and robust urban natural-capital account. Such advances would further enhance the usefulness of ecosystem-service valuation for evidence-based urban planning, climate adaptation strategies, and long-term sustainability governance at the municipal level.

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