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INTEGRATING REMOTE SENSING AND FIELD-BASED MODELS FOR THE ECONOMIC VALUATION OF ECOSYSTEM SERVICES PROVIDED BY ACER PLATANOIDES IN WARSAW (POLAND)

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ABSTRACT: Urban forests provide vital ecosystem services (ES), and quantifying these benefits is essential for sustainable urban planning. The i-Tree Eco tool is widely used for such assessments, but its reliance on detailed field inventories limits city-wide applications. Remote sensing offers spatial data, but cannot directly provide all the necessary model inputs. This study presents a framework combining remote sensing with field-based modelling for large-scale i-Tree Eco assessments. Applied to *Acer platanoides* in Warsaw, Poland, with data from 529 trees, econometric models predicted structural attributes from remotely sensed variables. Using these models and other remotely derived attributes, a citywide i-Tree Eco analysis was performed. The framework evaluated approximately 122,000 trees, which together remove 46 t of pollutants annually, sequester 2,440 t of carbon, and reduce stormwater runoff by 38,100 m³, with an estimated value of €787,000. This study introduces a novel, large-scale approach for the economic valuation of urban tree ES.

KEYWORDS: urban forestry, economic value, remote sensing, i-Tree Eco, urban sustainability, Warsaw

Introduction

Urban trees are increasingly recognised as essential components of green infrastructure, enhancing urban livability. They provide a wide range of ecosystem services (ES) that meet the diverse needs of rapidly urbanising societies (Locosselli & Buckeridge, 2023). These ES are typically categorised into provisioning, regulating, and cultural services (Haines-Young & Potschin, 2018).

Provisioning services include tangible products such as food, which supports human consumption, local foraging, and urban food security (Hurley and Emery, 2018; Sardeshpande & Shackelton, 2023; Schunko & Brandner, 2022), and wood, which can be used for construction, furniture, or bioenergy production (Bratkovich et al., 2010; Nowak et al., 2019).

Regulating services include carbon sequestration, which mitigates climate change (Szkop, 2022; Moreno et al., 2024; Hintural et al., 2024); temperature regulation through reduction of the urban heat island effect (Li et al., 2024; Zheng et al., 2023; Alonzo et al., 2025); and air purification through pollutant removal and air-quality improvement (Szkop, 2022; Kofel et al., 2024; Nowak et al., 2023). Urban trees also contribute to stormwater management by reducing runoff and flood risk (Berland et al., 2017; Selbig, 2022) and mitigate urban noise by absorbing, reflecting, and scattering sound waves (Fletcher et al., 2022; Van Renterghem, 2019).

Cultural services include aesthetic enhancement, which improves the visual and sensory quality of urban spaces (Wang, 2019; Wang et al., 2022; Mundher et al., 2022), as well as recreational benefits that promote physical activity, relaxation, and social interaction (Zhang et al., 2024; Nguyen et al., 2021; Wong et al., 2025).

As awareness of the multiple benefits provided by urban trees grows, a critical question arises: Do existing urban-forest management strategies effectively maximise these services? Quantifying ES is therefore essential because it strengthens the evidence base for policy and informs sustainable green infrastructure planning (Jato-Espino et al., 2023).

An overview of the literature

One of the most widely applied tools for assessing the regulating services of urban trees is i-Tree Eco. Developed from the UFORE model by the USDA Forest Service in the 1990s, the tool integrates detailed tree inventory data with local meteorological and air pollution datasets to estimate urban-forest structure and ES, including carbon sequestration, pollutant removal, and stormwater control (Nowak et al., 2008; Nowak & Crane, 2000).

i-Tree Eco is now used globally, with numerous applications in Poland (Szkop, 2016; Szkop, 2020; Szkop, 2022). Recent data indicate that the tool has been adopted in more than 185 countries and is used by over 910,000 registered users worldwide (Nowak, 2024). Its adaptability to diverse ecological and climatic conditions has been confirmed in regions as different as Northern Europe (Sjöman et al. 2024) and South Korea (Choi, et al., 2023), establishing i-Tree Eco as a standardised and globally transferable framework for evaluating urban-forest structure and ES.

Despite these advantages, the method's primary limitation is its dependence on detailed field data. While species identification and diameter at breast height (DBH) are the minimum necessary inputs, collecting additional variables – such as land use, total tree height, height to live top, height to crown base, crown width, crown-missing percentage, crown condition, and crown light exposure (CLE) – is highly recommended to improve model precision (Nowak, 2021). However, collecting these data through traditional ground-based inventories is time-consuming and costly. Given that large cities like Warsaw have an estimated 9 million trees (Długoński et al., 2023), conducting a complete i-Tree Eco inventory – where data for every individual tree is collected on-site – is practically unfeasible. Consequently, most i-Tree Eco studies remain confined to smaller areas, such as parks or districts, where full inventories are feasible (Raum et al., 2019).

To overcome these limitations, many projects have adopted sampling-based approaches in which data are collected from trees within randomly distributed plots and then extrapolated to estimate the structure and ES of the entire urban forest (Nowak et al., 2008; Kim, 2016). This method provides a statistically robust alternative to a full census, substantially reducing field effort and costs while

maintaining reasonable accuracy (U.S. Forest Service, 2013). However, plot-based sampling also has significant drawbacks, because it aggregates results and cannot capture single-tree variation in ES provision, which is increasingly important for spatially explicit urban-forest management (Velásquez-Camacho et al., 2021). The growing demand for high-resolution, spatially explicit environmental information, therefore, highlights the need for innovative assessment methodologies. Remote-sensing (RS) technologies provide a promising solution, enabling large-scale, spatially detailed inventories that complement and enhance i-Tree Eco assessments.

Although a recent review by Sharma et al. (2025) indicates that integrating RS with i-Tree Eco is an expanding area of research, no species-specific, fully compatible, citywide applications have been developed so far. Evidence from the reviewed literature shows that only a limited number of studies have successfully incorporated RS-derived parameters into i-Tree Eco, and these efforts have focused on a narrow subset of tree attributes. In particular, RS has primarily been used to estimate structural variables such as tree height and crown dimensions (e.g., Cimburova & Barton, 2020; Scholz et al., 2018), while other critical inputs required by i-Tree Eco remain largely dependent on field-based data. Consequently, current applications represent partial rather than fully operational integration of RS within the i-Tree Eco framework. In contrast, the present study introduces a complete, end-to-end workflow in which the two key i-Tree Eco parameters that cannot be directly obtained from remote sensing – diameter at breast height (DBH) and crown height – are reconstructed using species-specific econometric models and then applied to a fully citywide, individual-tree i-Tree Eco assessment. This distinguishes the proposed approach from earlier RS-assisted applications that relied on partial substitution of field data or aggregated plot-level estimates.

In Warsaw, a large-scale inventory of urban trees was recently completed using advanced RS methods. This project, based on a multi-sensor photogrammetric platform, resulted in the tree crown map (TCM) – a highly detailed map of individual tree crowns covering the entire city (Niedzielko et al., 2024). The dataset provides most of the variables required by the i-Tree Eco protocol, except DBH and crown height (defined as the difference between live tree height and height to live crown base), because both DBH and live crown base are inherently difficult to extract from aerial or satellite imagery (Ciesielski & Sterenczak, 2019). Nevertheless, the unprecedented level of detail captured in TCM opens new opportunities for applying i-Tree Eco at the scale of an entire metropolitan area.

The objective of this study is to evaluate whether RS data, complemented by targeted field measurements, can provide a reliable basis for citywide ES assessments using i-Tree Eco. The hypothesis is that an RS-based inventory can supply the necessary input data to quantify key ES – carbon sequestration, air-pollution removal, and avoided runoff – while substantially reducing the time, labour, and costs required by traditional field-based protocols. This research makes three key contributions:

- Development of a methodological framework integrating RS and field data for i-Tree Eco applications;
- Formulation and validation of species-specific models for estimating DBH and crown base height of *Acer platanoides*;
- Demonstration of the workflow's citywide implementation and its potential for large-scale, cost-efficient valuation of urban-forest ES.

While the empirical application focuses on a single dominant species (*Acer platanoides*), the proposed framework is designed to be transferable through the development of analogous species-specific or functional-group models.

Research methods

Study area

The study area encompasses the administrative boundaries of Warsaw (52°14' N, 21°01' E), covering approximately 517 km² and home to about 1.8 million inhabitants. The city is located in Central Europe on the Masovian Plain (20°51'–21°16' E, 52°6'–52°22' N), within a flat section of the Vistula River valley at elevations ranging from 80 to 120 m a.s.l. Warsaw lies in central Poland and has a humid continental climate, characterised by warm summers and cold winters (GUS, 2025).

The mean annual air temperature over the past thirty years has been 9.1°C, with the highest monthly average in July (19.3°C) and the lowest in January (−0.8°C). Mean annual precipitation is

approximately 695 mm. Winters (December–February) are cold (mean temperature 0.9°C), typically accompanied by heavy cloud cover, frequent snow or sleet, and occasional frost, whereas summers (June–August) are warm and moderately humid. Spring and autumn are transitional seasons with variable weather and notable temperature fluctuations (IMGW-PIB, 2024).

Green areas – including parks, forests, and other vegetated lands – cover roughly 24% of the city's surface, showing strong spatial contrasts between the densely built-up central districts and the more forested peripheral zones such as Bielany and Wawer (City of Warsaw, 2023).

RS data: TCM

The TCM for Warsaw was developed under commission from the City of Warsaw as part of a large-scale RS initiative led by MGGP Aero, in collaboration with the University of Łódź, the University of Warsaw, and the company Definity. Covering approximately 517 km², the project produced a detailed, object-based inventory of individual tree crowns using a multi-sensor photogrammetric platform integrating airborne LiDAR and hyperspectral imaging. Data acquisition was conducted in 2018–2019 and included RGB orthophotos (10 cm resolution), hyperspectral imagery (1 m resolution), and ALS point clouds, all collected within two consecutive days under consistent atmospheric conditions to ensure radiometric homogeneity.

Individual tree crowns were delineated from the canopy height model, derived by subtracting the digital terrain model from the digital surface model, both produced from LiDAR data. Each crown polygon was enhanced with structural, spectral, and modelled attributes describing geometry, species classification, and crown condition (MGGP Aero, 2020; GIM International, 2020; Niedzielko et al., 2024).

A summary of selected TCM attributes used in this study is provided in Table 1.

Table 1. Selected attributes of the tree crown map (TCM) used in this study

Attribute	Description
C_area_TCM	Crown area (m ²).
Height_TCM	Maximum tree height derived from the canopy height model.
Species_TCM	Tree species identified through classification modeling.
C_condition_TCM	Mean level of crown discoloration estimated from modeling.
C_missing_TCM	Mean level of crown defoliation estimated from modeling.
CLE_TCM	Percentage of crown pixels receiving direct crown light exposure (CLE).

Source: MGGP Aero (2020).

The resulting dataset provides most of the variables required by the i-Tree Eco protocol, except for DBH and crown height (defined as the difference between total tree height and height to live crown base), which are inherently difficult to extract from RS data (Ciesielski & Sterenczak, 2019). To complement the RS dataset and enable modelling of the missing parameters, a targeted field inventory was conducted.

Field data collection

Field data were collected for 529 Norway maples (*A. platanoides*) located within the administrative boundaries of Warsaw. Five representative land-use types were selected – municipal park, main road, local road, urban forest, and residential estate – to capture contrasting ecological and anthropogenic conditions (Scharenbroch et al., 2017; Roman et al., 2014; Tan & Shibata, 2022) (Figure 1).

The study area included a municipal park (Park Powstańców Warszawy), a main road (Kasprzaka and Towarowa Streets), a local road (Brożka, Księcia Janusza, and Łódzka Streets), an urban forest (Lasek na Kole), and a residential estate (area bounded by Czorsztyńska, Deotymy, and Obozowa Streets, and Al. Prymasa Tysiąclecia). Together, these locations represent the range of ecological and management contexts typical of Warsaw's urban landscape, enabling evaluation of how site conditions affect tree structure and vitality.

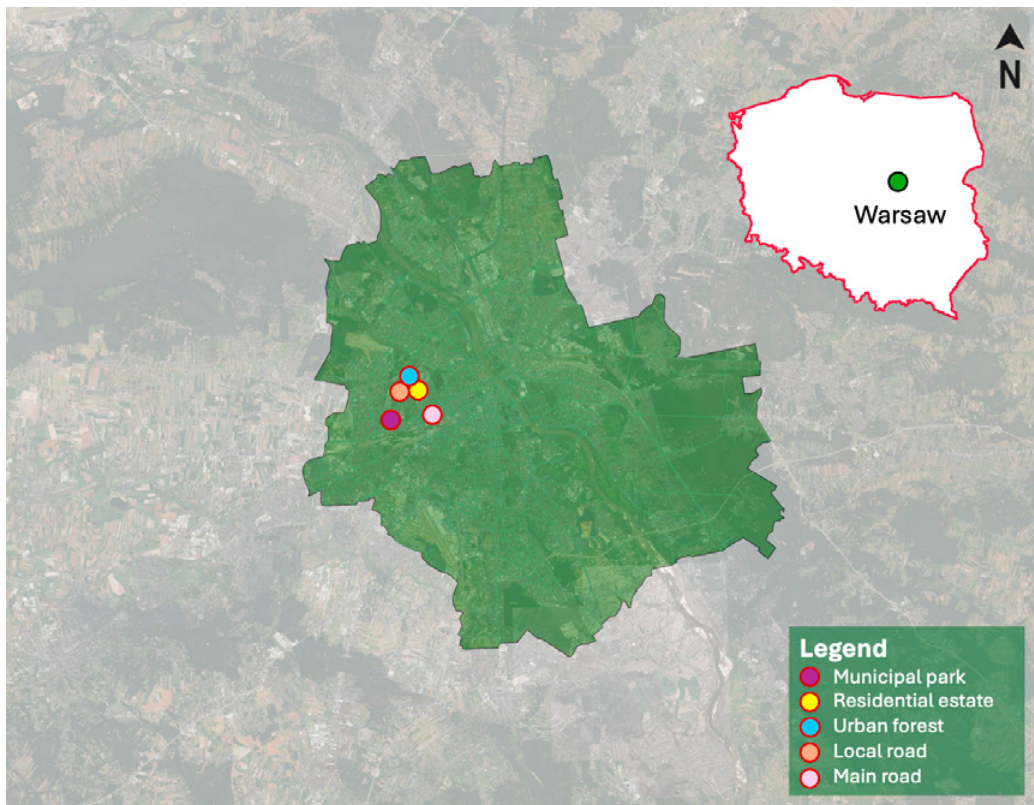


Figure 1. Five land-use types were selected in the study. Distinct colours and labels represent the spatial distribution of sampled sites across Warsaw

Fieldwork was conducted in August 2021, during the peak of the growing season, allowing accurate assessment of crown defoliation. DBH was measured at 1.4 m above the ground using a certified tape; for bifurcated trees, each stem was measured separately. Total height and crown diameters were recorded with a Leica rangefinder. All data were collected by a professional dendrological team in accordance with the i-Tree Eco v6 Field Manual (2021).

A summary of the measured variables is provided in Table 2.

Table 2. Tree parameters recorded in the field

Parameter	Variable name	Data collection method (as in i-Tree Eco)	Required
Species	Species	Species and genus of tree.	Minimum requirements
Land use	Land_use	Land use type in which the tree is located.	Highly recommended
DBH 1–6 (cm)	DBH	Diameter at breast height (1.4 m), measured for up to six stems in multi-stemmed trees.	Minimum requirements
Crown condition	C_condition	Crown condition based on visual assessment of healthy branches.	Highly recommended
Total height (m)	Height	Height from the ground to the top of the tree (alive or dead).	Highly recommended
Crown height	C_height	Difference between live tree height and height to live crown base	Highly recommended
Crown area	C_area	Area calculated by multiplying π by the lengths of the two semi-axes representing the crown width	Highly recommended
Percent crown missing	C_missing	Percent of crown volume not occupied by branches and leaves.	Highly recommended
Crown light exposure	CLE	Number of sides of the tree's crown receiving light from above or the side (maximum of five).	Highly recommended

Source: author's work based on i-Tree Eco V6 Field Manual (2021).

Data analysis

The analysis was conducted in two stages. First, descriptive statistics – including mean, standard deviation, minimum, maximum, quartiles, and coefficient of variation – along with one-way ANOVA were computed for DBH, height, crown area, crown height, crown condition, percent crown missing, and CLE across land-use categories. Because all inventoried trees were *A. platanoides*, the species was not included as a factor. This stage aimed to characterise the structural variability of trees across different land-use types and identify potential patterns relevant for subsequent modelling.

In the second stage, econometric models were developed to predict DBH and crown height (C_height) using only predictors obtainable from both ground-based measurements and RS data. Ordinary least squares (OLS) regression with heteroskedasticity-robust (HC3) standard errors was applied. A backwards-elimination approach ($p > 0.05$ for variable removal) determined the final model. Because the study trees are nested within a limited number of sites/land-use categories, mixed-effects models with random intercepts for land-use type were also estimated using the statsmodels MixedLM procedure. In both cases, the estimated variance of the random effect was near zero, indicating that the hierarchical structure added no additional explanatory power beyond the fixed effects. Therefore, the simpler OLS models were retained, as the mixed-effects specifications did not materially change coefficient estimates, model fit, or predictive accuracy. This indicates that land-use categories captured the dominant sources of hierarchical variation relevant for the modelled structural parameters.

To enhance transparency, model performance was evaluated using multiple metrics. The data were randomly split into training (70%) and testing (30%) subsets, stratified by land use, and predictive accuracy was quantified with in-sample (train) and out-of-sample (test) R^2 , root mean squared error (RMSE) and mean absolute error (MAE). The applied split was stratified by land-use type but was not designed as a strict spatial-blocking validation. Future research could apply spatially independent or site-blocked cross-validation to further test model transferability across heterogeneous urban environments. Five-fold cross-validation was performed to assess model stability. Variance inflation factors (VIFs) were computed for each predictor to evaluate multicollinearity, and Breusch–Pagan tests were used to diagnose heteroskedasticity. These diagnostics, together with a basic sensitivity assessment of the potential impact of prediction errors on ecosystem service estimates, are discussed in the Results and Discussion. All analyses were performed in Python 3.11 using the statsmodels and scikit-learn libraries. The consistency of performance metrics across the training, testing, and cross-validation procedures indicates that the final model specifications selected through backward elimination are stable and not overly sensitive to the particular sample used for estimation.

This modelling framework allowed DBH and crown height to be estimated for all *A. platanoides* trees in Warsaw, providing the basis for subsequent ES calculations using the i-Tree Eco tool.

Integration of RS and field data

The regression models were applied to the TCM dataset to enable an i-Tree Eco analysis for all *A. platanoides* trees across Warsaw. Required or recommended field parameters were substituted with the corresponding TCM-derived variables (Table 3).

To assign land-use categories, spatial layers from the national topographic database (BDOT) were overlaid with TCM polygons using QGIS 3.40.5. Trees located within forest polygons were classified as “Urban forest,” those within 30 m of main roads or 20 m of local roads were categorised accordingly, and

Table 3. Correspondence between i-Tree Eco variables and TCM substitutes

i-Tree Eco variable name	TCM substitute
Species	Species_TCM
Land_use	-
DBH	-
C_condition	C_condition_TCM
Height	Height_TCM
C_height	-
C_area	C_area_TCM
C_missing	C_missing_TCM
CLE	CLE_TCM

Source: author's work based on i-Tree Eco V6 Field Manual (2021) and MGGP Aero (2020).

trees inside BDOT “tree stands” were labelled “Municipal park.” The remaining records were assigned to the “Residential estate” category.

CLE_TCM values (0–100%) were converted to the i-Tree Eco ordinal scale (0–5) following the scheme below.

Table 4. Conversion of CLE_TCM to i-Tree Eco CLE scale

CLE_TCM (%)	CLE (0–5)
>90%	5
70–90%	4
50–70%	3
30–50%	2
10–30%	1
<10%	0

Source: author's work based on i-Tree Eco V6 Field Manual (2021) and MGGP Aero (2020).

i-Tree Eco Analysis

The i-Tree Eco analysis was performed using version 6.035 of the software. ES estimates for carbon sequestration (kg yr^{-1}), air-pollutant removal (kg yr^{-1}), and avoided runoff ($\text{m}^3 \text{yr}^{-1}$) were monetised (€ yr^{-1}) using local external unit costs. Specifically, stormwater treatment costs in Warsaw (City of Warsaw, 2025) were used to value runoff, while the economic values of carbon sequestration and pollutant removal were adapted from Szkop (2022) and adjusted to 2025 prices using the national Consumer Price Index (GUS, 2025). All monetary values were converted to euros (€) at the mean 2025 exchange rate ($\text{€1} = 4.25 \text{ PLN}$).

Additionally, a sensitivity analysis was carried out to examine how uncertainties in the modelled structural parameters might affect the i-Tree Eco results. Predicted DBH values were multiplied by 0.85 and 1.15, and crown-height predictions were multiplied by 0.89 and 1.11 to generate low and high scenarios, respectively. These factors correspond to the average relative errors identified in the model-validation exercises. i-Tree Eco was then run separately for the lower and upper estimates, and the resulting ranges are reported alongside in Section “i-Tree Eco results”.

Importantly, the sensitivity analysis was implemented as a combined scenario approach, in which both DBH and crown-height predictions were adjusted simultaneously to their lower or upper bounds. This design represents a conservative best-case and worst-case assessment of joint parameter uncertainty, rather than an independent one-at-a-time sensitivity analysis of individual inputs. The adopted approach was chosen to reflect the cumulative effect of structural-parameter uncertainty on ecosystem-service estimates at the city scale.

Results of the research

Descriptive analysis of tree structural variables

Descriptive statistics for *A. platanoides* across the five land-use categories are summarised in Table 5.

Substantial variation was observed among land-use types for all measured variables, including DBH, height, crown height, crown area, crown condition, percent crown missing, and CLE. Mean DBH ranged from 24.5 cm in forest areas to 39.7 cm in parks, with intermediate values for local roads (35.4 cm), residential areas (35.7 cm), and main roads (30.3 cm). The widest DBH range (6–96 cm) occurred in forests, reflecting a heterogeneous age and size structure.

Table 5. Descriptive statistics (mean $\pm$ SD, range) by land use

Variable	Land_use	Mean $\pm$ SD
DBH	Urban forest	24.5 $\pm$ 12.6
	Local_road	35.4 $\pm$ 10.8
	Main_road	30.3 $\pm$ 14.0
	Municipal park	39.7 $\pm$ 21.8
	Residential estate	35.7 $\pm$ 19.2
Height	Urban forest	20.0 $\pm$ 4.0
	Local_road	15.3 $\pm$ 3.4
	Main_road	11.0 $\pm$ 3.6
	Municipal park	17.2 $\pm$ 6.5
	Residential estate	15.9 $\pm$ 6.2
C_height	Urban forest	14.6 $\pm$ 4.5
	Local_road	11.4 $\pm$ 3.7
	Main_road	8.3 $\pm$ 3.7
	Municipal park	14.3 $\pm$ 5.9
	Residential estate	13.1 $\pm$ 5.5
C_area	Urban forest	39.4 $\pm$ 27.3
	Local_road	69.5 $\pm$ 31.2
	Main_road	50.7 $\pm$ 36.8
	Municipal park	93.9 $\pm$ 66.6
	Residential estate	67.3 $\pm$ 53.1
C_missing	Urban forest	57.7 $\pm$ 10.3
	Local_road	49.4 $\pm$ 17.0
	Main_road	45.6 $\pm$ 21.3
	Municipal park	41.4 $\pm$ 21.3
	Residential estate	35.5 $\pm$ 19.6
CLE	Urban forest	0.7 $\pm$ 0.6
	Local_road	2.4 $\pm$ 1.1
	Main_road	2.7 $\pm$ 0.9
	Municipal park	1.6 $\pm$ 0.8
	Residential estate	2.6 $\pm$ 1.1
C_conditio	Urban forest	84.7 $\pm$ 6.3
	Local_road	80.3 $\pm$ 15.3
	Main_road	84.3 $\pm$ 17.6
	Municipal park	87.1 $\pm$ 9.6
	Residential estate	86.2 $\pm$ 10.2

Tree height exhibited marked differences between land-use types. Trees in forest areas attained the greatest mean height (20.0 m), whereas those along main roads were the shortest (11.0 m). Crown height followed a similar spatial trend, ranging from 8.3 m along main roads to 14.6 m in forests, with parks and residential areas showing intermediate values (14.3 m and 13.1 m, respectively).

Variation in crown area was particularly large, from 39.4 m² in forests to 93.9 m² in parks, indicating that trees growing in less constrained spaces develop broader crowns. High coefficients of variation across all categories underscore the structural heterogeneity of *A. platanoides* in Warsaw.

Vitality- and light-related parameters also differed considerably. Mean crown-missing percentage was highest in forests (57.7%) and lowest in residential areas (35.5%), suggesting greater shading and intraspecific competition within forest stands. CLE ranged from 0.7 in forests to 2.7 along main roads, reflecting differences in canopy openness and sunlight availability. Overall crown-condition values were high (> 80%) across all categories, with the highest mean in parks (87.1%), indicating generally good tree health throughout the city.

Differences among land-use categories

One-way ANOVA results (Table 6) confirmed that almost all structural variables differed significantly ($p < 0.05$) among land-use categories. The strongest effects were observed for tree height ($F = 50.26$, $p = 8.3 \times 10^{-36}$) and crown height ($F = 34.40$, $p = 1.6 \times 10^{-25}$), highlighting major site-related differences in vertical structure. DBH ($F = 13.69$, $p = 1.3 \times 10^{-10}$) and crown area ($F = 21.67$, $p = 1.5 \times 10^{-16}$) also varied significantly, with larger trees typically found in parks and residential areas.

Table 6. One-way ANOVA summary for differences between land uses

Variable	F	p-value
DBH	13.69	1.2591e-10
Height	50.26	8.3120e-36
C_height	34.40	1.6395e-25
C_area	21.67	1.4537e-16
C_missing	21.60	1.6370e-16
CLE	91.06	9.6592e-59
C_condition	4.37	1.7368e-03

Light-related and vitality indicators were similarly influenced by land use. CLE exhibited the highest statistical contrast ($F = 91.06$, $p < 10^{-58}$), distinguishing shaded forest interiors from open roadside environments. Both crown-missing percentage ($F = 21.60$, $p = 1.6 \times 10^{-16}$) and crown condition ($F = 4.37$, $p = 1.7 \times 10^{-3}$) differed significantly across land uses, confirming that environmental pressures and management practices shape the structural and physiological characteristics of *A. platanoides* in Warsaw.

Regression models for DBH and crown height

OLS regression models were developed to predict DBH and crown height using variables available from the TCM and field measurements (Table 7). Both models were statistically significant and consistent with expected ecological relationships.

For DBH, significant predictors included land use, tree height, crown area, crown condition, and CLE. Compared with the reference category (forest), trees in main-road (+14.8 cm, $p < 0.001$), residential (+10.4 cm, $p < 0.001$), local-road (+10.0 cm, $p < 0.001$), and park (+8.3 cm, $p < 0.001$) environments had larger mean diameters. Height ($\beta = 1.43$, $p < 0.001$) and crown area ($\beta = 0.19$, $p < 0.001$) were strong positive predictors, while crown condition had a weak but significant negative effect ($\beta = -0.11$, $p < 0.001$). CLE also contributed positively ($\beta = 0.77$, $p < 0.01$), suggesting that higher light exposure supports radial growth.

For crown height, significant predictors were height, land use, crown condition, and crown-missing percentage. Height ($\beta = 0.93$, $p < 0.001$) had the strongest positive effect, whereas crown-missing percentage ($\beta = -0.024$, $p < 0.001$) was negatively associated with crown height. Crown condition

($\beta = 0.036$, $p < 0.05$) had a modest positive influence. All non-forest land-use types exhibited higher crown heights than the forest reference, with the largest effect observed in parks (+1.85 m, $p < 0.001$).

Table 7. Ordinary least squares regression results (robust SE; significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

Predictor	DBH β (SE)	C_height β (SE)
Local_road	10.044 (1.340)***	1.109 (0.329)***
Main_road	14.785 (1.472)***	1.713 (0.319)***
Park	8.299 (1.428)***	1.847 (0.349)***
Residential	10.411 (1.323)***	1.769 (0.327)***
CLE	0.773 (0.288)**	–
C_area	0.192 (0.015)***	–
C_condition	–0.112 (0.026)***	0.036 (0.015)*
C_missing	–	–0.024 (0.006)***
Height	1.433 (0.109)***	0.930 (0.020)***
Intercept	–2.759 (3.393)	–5.703 (1.661)***

Model performance and diagnostics

Model evaluation metrics are summarised in Table 8. For both DBH and C_height, the training sets explained around 88 % of the observed variation, and the predictive R^2 on the held-out test sets remained high (≈ 0.87 for DBH and 0.86 for C_height). The corresponding RMSEs were 6.15 cm (DBH) and 1.97 m (C_height), while the mean absolute errors were approximately 4.5 cm and 1.5 m. Five-fold cross-validation produced mean R^2 values of 0.863 for DBH and 0.866 for C_height, indicating stable model performance across different partitions of the data. VIF values for all predictors were below 4, suggesting low multicollinearity, and Breusch–Pagan tests revealed heteroskedasticity ($p < 0.05$), which justifies the use of HC3 robust standard errors.

Table 8. Performance metrics for the DBH and crown-height models

Statistic (units)	DBH model	C_height model
Train R^2	0.875	0.876
Test R^2	0.872	0.857
Train RMSE	5.89 cm	1.85 m
Test RMSE	6.15 cm	1.97 m
Train MAE	4.36 cm	1.39 m
Test MAE	4.54 cm	1.51 m
5-fold CV mean R^2	0.863	0.866
5-fold CV mean RMSE	6.09 cm	1.91 m
5-fold CV mean MAE	4.55 cm	1.45 m

These errors correspond to relative uncertainties of roughly 15 % for DBH and 11 % for crown height when compared to their respective means in Table 5. Such uncertainties propagate through to ecosystem-service estimates and should be considered when interpreting the citywide valuations.

i-Tree Eco results

For each of the 121,703 *A. platanoides* trees identified in the TCM dataset, DBH and crown height were modelled and combined with other RS attributes (height, crown area, crown-missing percent-

age, CLE, and crown condition) to perform a citywide i-Tree Eco analysis following the procedure described in Section “i-Tree Eco Analysis”. The aggregated results are presented in Table 9. The values in parentheses represent the low and high scenarios from the sensitivity analysis, and they reflect the cumulative effect of simultaneous uncertainty in both modelled structural parameters (DBH and crown height), rather than the isolated sensitivity of individual inputs.

Table 9. Summary of i-Tree Eco results for *Acer platanoides* in Warsaw

ES	Biophysical value	Economic value (€ × 10 ³ yr ⁻¹)
Pollution removal (t yr ⁻¹)	46.0 (42.9–49.3)	215.9 (201.4–231.4)
Carbon sequestration (t yr ⁻¹)	2,440.9 (2,003.2–2 852.9)	495.5 (406.6–579.1)
Avoided runoff (10 ³ m ³ yr ⁻¹)	38.1 (27.3–41.3)	75.8 (54.3–82.2)
Total annual value	-	787.3 (662.3–892.7)

The i-Tree Eco analysis demonstrated that *A. platanoides* provides substantial regulating ES within Warsaw. Collectively, these trees remove approximately 46 t of air pollutants each year – including O₃, NO₂, PM_{2.5}, and SO₂ – corresponding to an estimated economic value of €216,000 annually. They also sequester 2,441 t of carbon per year ($\approx$ €496,000 yr⁻¹) and reduce surface runoff by 38,100 m³ ($\approx$ €76,000 yr⁻¹). The combined annual value of €787,000 underscores the significant ecological and economic role of this species in Warsaw’s green infrastructure.

These quantitative results provide the basis for the Discussion, where structural variability, model performance, the uncertainty assessment and the broader implications for ES are interpreted in detail.

Discussion

This study demonstrates that integrating RS data with field-based modelling provides a reliable foundation for city-scale i-Tree Eco analyses. By conducting a targeted field inventory to enable econometric estimation of DBH and crown height from RS variables in the TCM, this research successfully bridged a major methodological gap between traditional field-based inventories and spatially continuous RS datasets. The results confirm that RS, when complemented by ground measurements, can yield accurate estimates of key i-Tree Eco input variables, thus enabling large-scale quantification of urban-tree ES.

Structural differentiation across land-use categories

The structural variation of *A. platanoides* across land-use categories reflects the combined influence of site conditions, space availability, and management intensity. Trees in parks and residential areas exhibited higher mean DBH, larger crown area, and better crown condition, indicating favourable growing environments with adequate rooting space and regular maintenance. In contrast, individuals along main roads and within forest stands displayed smaller dimensions and higher crown-missing percentages, suggesting the effects of competition, shading, and stress from proximity to infrastructure. These results align with previous research showing that environmental context and management practices strongly influence tree vitality and morphology (Scharenbroch et al., 2017; Roman et al., 2014; Tan & Shibata, 2022).

Differences in CLE further highlight the role of light availability in structural development. Low CLE in forests corresponds to limited light under closed canopies, whereas high CLE along roads and in residential areas reflects open-grown conditions that promote crown expansion. The negative relationship between crown-missing percentage and crown condition suggests that crown vitality declines under environmental stress or inter-tree competition. Collectively, these findings demonstrate how urban heterogeneity shapes tree structure and physiological performance, and consequently, the spatial distribution of ES potential.

Predictive modeling and methodological integration

The econometric models for DBH and crown height achieved strong explanatory power and produced relationships consistent with ecological theory. For DBH, positive coefficients for height and crown area confirm expected allometric scaling, while the positive influence of CLE underscores the importance of light exposure for radial growth. The small negative coefficient for crown condition likely indicates that younger or smaller individuals exhibit proportionally healthier crowns. For crown height, total height emerged as the dominant predictor, whereas crown-missing percentage had a strong negative effect, confirming that defoliation and canopy loss reduce crown height.

Land-use type emerged as a significant predictor in both models, indicating that site-specific environmental and management factors influence tree growth beyond structural attributes. Model diagnostics confirm the robustness of the modelling framework: predictive accuracy remained high across training, testing, and cross-validation subsets (test $R^2 > 0.85$), multicollinearity was limited ($VIF < 4$), and heteroskedasticity was addressed using robust standard errors. Mixed-effects specifications yielded negligible random-effect variance, indicating that site differences were adequately captured by fixed effects. Overall, these results demonstrate that key i-Tree Eco parameters – traditionally obtained through field surveys – can be reliably inferred from remote-sensing data using parsimonious and statistically sound models.

This research represents the first fully compatible, species-specific, citywide application of RS data to drive i-Tree Eco assessments via modelled parameters. Although previous studies (Sharma et al., 2025) discussed integration concepts, a clear operational workflow from RS inventory to monetary valuation had not yet been demonstrated.

Implications for ES valuation

The i-Tree Eco analysis confirms that *A. platanoides* provides substantial regulating ES in Warsaw. Annual removal of approximately 46 t of air pollutants, sequestration of 2,441 t of carbon, and reduction of 38,100 m³ of stormwater runoff together correspond to an estimated annual value of €787,000. Of this total, roughly €711,000 derives from pollution removal and carbon sequestration, and €76,000 from avoided runoff. These values are broadly consistent with previous i-Tree Eco assessments in Poland (Szkop, 2016, 2020, 2022), confirming both the ecological significance of *A. platanoides* and the credibility of the integrated modelling framework.

It should be noted that the reported monetary values depend on the adopted external cost coefficients and price adjustments. Because the valuation framework applies these coefficients in a linear manner, changes in economic assumptions (e.g., unit costs or price indices) would translate proportionally into the total estimated value, while the underlying biophysical quantities of ecosystem services remain unchanged. This distinction is important when interpreting the results for policy or comparative purposes.

Beyond quantifying biophysical and economic benefits, the hybrid RS-field approach provides spatially explicit outputs that can directly support urban-management decisions. Maps identifying service “hotspots” can inform priority planting areas, guide maintenance schedules, and integrate ES metrics into climate-adaptation and spatial-planning strategies. In this way, the study advances i-Tree Eco from plot-based analysis toward operational, decision-relevant applications at the metropolitan scale.

Methodological considerations and future research

Although the framework proved effective, several limitations should be noted. First, the models were developed for a single species, *A. platanoides*, which limits their direct applicability to other taxa. Extending this approach to multiple species would enable a more comprehensive assessment of Warsaw’s urban-forest composition and functional diversity.

Second, future research should incorporate sensitivity analyses comparing i-Tree Eco outputs derived from purely field-based data with those generated through RS models. Parameters such as DBH are typically measured more accurately in the field, whereas tree height can often be obtained more precisely from LiDAR or photogrammetry. Such comparisons would help quantify uncertainty and inform optimised hybrid-data protocols.

Third, despite the methodological innovation, certain intrinsic limitations of i-Tree Eco remain. As noted by Szkop (2020), the pollution-removal module does not fully account for spatial heterogeneity in pollutant concentrations, which can vary widely across urban areas. While some methodological adjustments have been developed, challenges remain – such as capturing local variation in impervious surfaces that influence avoided runoff. Addressing these issues would further improve model realism and predictive accuracy.

Conclusions

This study provides a species-specific, city-scale assessment that integrates RS data with i-Tree Eco modelling to quantify urban-tree ES. By combining remotely derived attributes – height, crown area, crown condition, crown-missing percentage, and CLE – with econometric estimates of DBH and crown-base height, a complete i-Tree Eco analysis was performed for over 120,000 *A. platanoides* trees across Warsaw, Poland.

The results indicate that this species alone contributes approximately €711,000 per year through air-pollution removal and carbon sequestration, with an additional €76,000 through avoided runoff, yielding a total annual value of around €787,000. These estimates are enabled by the RS-based modelling approach adopted in this study and, as a consequence, should be interpreted as approximate ranges rather than exact point values, reflecting uncertainty associated with modelled structural parameters.

From a methodological perspective, the study demonstrates that city-scale ES assessments can be achieved without exhaustive field measurements by bridging RS inventories with the detailed input requirements of i-Tree Eco. Properly calibrated RS predictors substantially reduce data-collection costs and processing time, making large-scale, spatially explicit valuation feasible for management and policy applications. At the same time, because DBH and crown height were inferred rather than directly measured for the full tree population, prediction uncertainty propagates into ES estimates.

Within these methodological bounds, the resulting framework provides a replicable and operational approach for large-scale valuation of urban-tree ES that can be readily integrated into municipal spatial-planning and climate-adaptation programs. However, the present implementation is limited to a single species, and extending the framework to multispecies urban forests will require additional field data and the development of species-specific or functional-group models.

Future research should advance this approach in three complementary directions:

- Develop multispecies DBH and crown-height models to enable comprehensive urban-forest valuation;
- Conduct systematic sensitivity and uncertainty analyses comparing field- and RS-based i-Tree Eco outputs; and
- Enhance i-Tree Eco to better capture spatial variability in ES.

In conclusion, the study establishes a validated, scalable, and cost-efficient framework that expands the operational reach of i-Tree Eco from plot-level to metropolitan-scale assessments. By explicitly acknowledging the methodological limitations and associated uncertainties, the framework enables robust and transparent interpretation of spatially explicit ES estimates and provides both scientific insight and practical guidance for sustainable urban-forest management and the integration of ES valuation into municipal policy and planning.

References

- Alonzo, M., Ibsen, P. C., & Locke, D. H. (2025). Urban trees and cooling: A review of the recent literature (2018–2024). *Arboriculture & Urban Forestry*, 51(5), 420–444. <https://doi.org/10.48044/jauf.2025.023>
- Berland, A., Shiflett, S. A., Shuster, W. D., Garmestani, A. S., Goddard, H. C., Herrmann, D. L., & Hopton, M. E. (2017). The role of trees in urban storm-water management. *Landscape and Urban Planning*, 162, 167–177. <https://doi.org/10.1016/j.landurbplan.2017.02.017>

- Bratkovich, S., Bowyer, J., Stai, S., Fernholz, K., Bratkovich, J., & Howe, J. (2010). *Urban forestry: An evolving discipline*. Dovetail Partners, Inc. http://www.dovetailinc.org/report_pdfs/2010/dovetailurbanforestry1010-1.pdf
- Ciesielski, M., & Sterenczak, K. (2019). Accuracy of determining specific parameters of the urban forest using remote sensing. *iForest – Biogeosciences and Forestry*, 12(6), 498–510. <https://doi.org/10.3832/for3024-012>
- Cimburova, Z., & Barton, D. N. (2020). The potential of geospatial analysis and Bayesian networks to enable i-Tree Eco assessment of existing tree inventories. *Urban Forestry & Urban Greening*, 55, 126801. <https://doi.org/10.1016/j.ufug.2020.126801>
- City of Warsaw. (2023). *Raport o zieleni miejskiej w Warszawie 2023* [Report on urban greenery in Warsaw 2023]. Warsaw: Department of Greenery. (in Polish).
- City of Warsaw. (2025). *Tariff for water and sewage for Warsaw residents*. Municipal Contact Center Warsaw 19115. <https://warszawa19115.pl/web/guest/-/taryfa-za-wod%C4%99-i-%C5%9Bcieki-dla-mieszka%C5%84c%C3%B3w-warszawy> (in Polish).
- Długoński, A., Wellmann, T., & Haase, D. (2023). Old-growth forests in urban nature reserves: Balancing risks for visitors and biodiversity protection in Warsaw (Poland). *Land*, 12(2), 275. <https://doi.org/10.3390/land12020275>
- Fletcher, D. H., Garrett, J. K., Thomas, A., Fitch, A., Cryle, P., Shilton, S., & Jones, L. (2022). Location, location, location: Modelling of noise mitigation by urban woodland shows the benefit of targeted tree planting in cities. *Sustainability*, 14(12), 7079. <https://doi.org/10.3390/su14127079>
- GIM International. (2020). *Warsaw maps its trees in 3D using airborne LiDAR and hyperspectral data*. <https://www.gim-international.com/content/article/warsaw-maps-its-trees-in-3d>
- Główny Urząd Statystyczny (GUS). (2025). *Consumer Price Index*. <https://stat.gov.pl>
- Haines-Young, R., & Potschin, M. (2018). Common International Classification of Ecosystem Services (CICES) Version 5.1: A policy brief. *One Ecosystem*, 3, e27108. <https://doi.org/10.3897/oneeco.3.e27108>
- Hintural, W. P., Jeon, H. J., Kim, S. Y., Go, S., & Park, B. B. (2024). Quantifying regulating ecosystem services of urban trees: A case study of a green space at Chungnam National University using i-Tree Eco. *Forests*, 15(8), 1446. <https://doi.org/10.3390/f15081446>
- Hurley, P. T., & Emery, M. R. (2018). Locating provisioning ecosystem services in urban forests: Forageable woody species in New York City, USA. *Landscape and Urban Planning*, 170, 266–275. <https://doi.org/10.1016/j.landurbplan.2017.09.025>
- i-Tree. (2021). *i-Tree Eco v6 field manual*. USDA Forest Service & Davey Institute. <https://www.itreetools.org/documents/274/EcoV6.FieldManual.2021.10.06.pdf>
- IMGW-PIB. (2024). *Rocznik meteorologiczny Warszawa*. https://danepubliczne.imgw.pl/data/dane_pomiarowo_observacyjne/Roczniki/Rocznik%20meteorologiczny/Rocznik%20Meteorologiczny%202023.pdf (in Polish).
- Jato-Espino, D., Capra-Ribeiro, F., Moscardó, V., Bartolomé del Pino, L. E., Mayor-Vitoria, F., Gallardo, L. O., Carracedo, P., & Dietrich, K. (2023). A systematic review on the ecosystem services provided by green infrastructure. *Urban Forestry & Urban Greening*, 86, 127998. <https://doi.org/10.1016/j.ufug.2023.127998>
- Kim, G. (2016). Assessing Urban Forest Structure, Ecosystem Services, and Economic Benefits on Vacant Land. *Sustainability*, 8(7), 679. <https://doi.org/10.3390/su8070679>
- Kofel, D., Bourgeois, I., Paganini, R., Pulfer, A., Grossiord, C., & Schmale, J. (2024). Quantifying the impact of urban trees on air quality in Geneva, Switzerland. *Urban Forestry & Urban Greening*, 101, 128513. <https://doi.org/10.1016/j.ufug.2024.128513>
- Choi, Y., Machado, J., & Kim, G. (2023). A Comparative Evaluation of Ecosystem Services Provided by Street Trees in Seoul for the Suggestion of Social Equity. *Land*, 13(2), 235. <https://doi.org/10.3390/land13020235>
- Li, H., Zhao, Y., Wang, C., Ürges-Vorsatz, D., Carmeliet, J., & Bardhan, R. (2024). Cooling efficacy of trees across cities is determined by background climate, urban morphology, and tree trait. *Communications Earth & Environment*, 5, 754. <https://doi.org/10.1038/s43247-024-01908-4>
- Locosselli, G. M., & Buckeridge, M. S. (2023). The science of urban trees to promote well-being. *Trees – Structure and Function*, 37, 2389. <https://doi.org/10.1007/s00468-023-02389-2>
- MGGP Aero. (2020). *Tree Crown Map for Warsaw – Project documentation prepared for the City of Warsaw*. MGGP Aero Sp. z o.o., Tarnów, Poland. (in Polish).
- Moreno, R., Nery, A., Zamora, R., Lora, Á., & Galán, C. (2024). Contribution of urban trees to carbon sequestration and reduction of air pollutants in Lima, Peru. *Ecosystem Services*, 67, 101618. <https://doi.org/10.1016/j.ecoser.2024.101618>
- Mundher, R., Abu Bakar, S., Al-Helli, M., Gao, H., Al-Sharaa, A., Mohd Yusof, M. J., & Aziz, A. (2022). Visual aesthetic quality assessment of urban forests. *Urban Science*, 6(4), 79. <https://doi.org/10.3390/urbansci6040079>
- Nguyen, P.-Y., Astell-Burt, T., Rahimi-Ardabili, H., & Feng, X. (2021). Green space quality and health: A systematic review. *International Journal of Environmental Research and Public Health*, 18(21), 11028. <https://doi.org/10.3390/ijerph182111028>
- Niedzielko, J., Chormański, J., Wylazłowska, J., Kopeć, D., Lewandowska, A., & Matuszko, A. (2024). Airborne data and machine learning for urban tree species mapping: Enhancing the legend design to improve the map

- applicability for city greenery management. *Remote Sensing of Environment*, 308, 114314. <https://doi.org/10.1016/j.jag.2024.103719>
- Nowak, D. J. (2021). *Understanding i-Tree: Summary of programs and methods* (Gen. Tech. Rep. NRS-200). U.S. Department of Agriculture, Forest Service, Northern Research Station. <https://doi.org/10.2737/NRS-GTR-200>
- Nowak, D. J. (2024). *Understanding i-Tree: 2023 summary of programs and methods* (Gen. Tech. Rep. NRS-200-2023). U.S. Department of Agriculture, Forest Service, Northern Research Station. <https://doi.org/10.2737/NRS-GTR-200-2023>
- Nowak, D. J., & Crane, D. E. (2000). The Urban Forest Effects (UFORE) model: Quantifying urban forest structure and functions. In M. Hansen & T. Burk (Eds.), *Integrated tools for natural resources inventories in the 21st century* (Gen. Tech. Rep. NC-212, pp. 714–720). U.S. Department of Agriculture, Forest Service.
- Nowak, D. J., Crane, D. E., Stevens, J. C., Hoehn, R. E., Walton, J. T., & Bond, J. (2008). A ground-based method of assessing urban forest structure and ecosystem services. *Arboriculture & Urban Forestry*, 34(6), 347–358. <https://doi.org/10.48044/jauf.2008.048>
- Nowak, D. J., Greenfield, E. J., & Ash, R. M. (2019). Annual biomass loss and potential value of urban tree waste in the United States. *Urban Forestry & Urban Greening*, 46, 126469. <https://doi.org/10.1016/j.ufug.2019.126469>
- Nowak, D. J. et al. (2023). *Improved air quality and other services from urban trees and forests*. Forest Science Research Report, USDA Forest Service. https://doi.org/10.1007/978-3-031-35692-6_10
- Raum, S., Hand, K. L., Hall, C., Edwards, D. M., O'Brien, L., & Doick, K. J. (2019). Achieving impact from ecosystem assessment and valuation of urban greenspace: The case of i-Tree Eco in Great Britain. *Landscape and Urban Planning*, 190, 103590. <https://doi.org/10.1016/j.landurbplan.2019.103590>
- Roman, L. A., Battles, J. J., & McBride, J. R. (2014). Determinants of establishment survival for residential trees in Sacramento County, CA. *Landscape and Urban Planning*, 129, 22–31. <https://doi.org/10.1016/j.landurbplan.2014.05.004>
- Sardeshpande, M., & Shackleton, C. M. (2023). Fruits of the city: The nature, nurture and future of urban foraging. *People and Nature*, 5(1), 203–215. <https://doi.org/10.1002/pan3.10428>
- Scharenbroch, B. C., Carter, D., Bialecki, M., Fahey, R., Scheberl, L., Catania, M., Roman, L. A., Bassuk, N., Harper, R. W., Werner, L. P., Siewert, A., Miller, S., Huyler, L., & Raciti, S. (2017). A rapid urban site index for assessing the quality of street tree planting sites. *Urban Forestry & Urban Greening*, 27, 279–286. <https://doi.org/10.1016/j.ufug.2017.08.010>
- Scholz, T., Hof, A., & Schmitt, T. (2018). Cooling effects and regulating ecosystem services provided by urban trees – Novel analysis approaches using urban tree cadastre data. *Sustainability*, 10(3), 712. <https://doi.org/10.3390/su10030712>
- Schunko, C., & Brandner, A. (2022). Urban nature at the fingertips: Investigating wild food foraging to enable nature interactions of urban dwellers. *Ambio*, 51(5), 1168–1178. <https://doi.org/10.1007/s13280-021-01648-1>
- Selbig, W. R. (2022). *Loss of street-tree canopy increases storm-water runoff* (Fact Sheet 2022-3074). U.S. Geological Survey. <https://doi.org/10.3133/fs20223074>
- Sharma, G., Morgenroth, J., Richards, D., & Ye, N. (2025). Advancing urban forest and ecosystem service assessment through the integration of remote sensing and i-Tree Eco: A systematic review. *Urban Forestry & Urban Greening*, 104, 128659. <https://doi.org/10.1016/j.ufug.2024.128659>
- Sjöman, J. D., Tuhkanen, E.-M., Mänttari, M., Čepić, Ž., Randrup, T. B., & Deak Sjöman, J. (2024). Expectations of i-Tree Eco as a tool for urban tree management in Nordic cities. *Frontiers in Sustainable Cities*, 5, 1325039. <https://doi.org/10.3389/frsc.2023.1325039>
- Szkop, Z. (2016). An evaluation of the ecosystem services provided by urban trees: The role of Krasiński Gardens in air quality and human health in Warsaw (Poland). *Environmental & Socio-economic Studies*, 4(4), 41–50. <https://doi.org/10.1515/environ-2016-0023>
- Szkop, Z. (2020). Evaluating the sensitivity of the i-Tree Eco pollution model to different pollution data inputs: A case study from Warsaw, Poland. *Urban Forestry & Urban Greening*, 55, 126859. <https://doi.org/10.1016/j.ufug.2020.126859>
- Szkop, Z. (2022). The value of air purification and carbon storage ecosystem services of park trees in Warsaw, Poland. *Environmental & Socio-economic Studies*, 10(3), 1–11. <https://doi.org/10.2478/environ-2022-0012>
- Szkop, Z. (2023). *Materials prepared under the “Nauka jest dla ludzi” project*. University of Warsaw. [Unpublished project material]. (in Polish).
- Tan, X., & Shibata, S. (2022). Factors influencing street tree health in constrained planting spaces: Evidence from Kyoto City, Japan. *Urban Forestry & Urban Greening*, 67, 127416. <https://doi.org/10.1016/j.ufug.2021.127416>
- U.S. Forest Service. (2013). *A guide to assessing urban forests (NRS-INF-24-13)*. USDA Forest Service, Northern Research Station. https://www.itreetools.org/resources/content/guide_to_assessing_urban_forests_nrs_inf_24_13.pdf
- Van Renterghem, T. (2019). Towards explaining the positive effect of vegetation on the perception of environmental noise. *Urban Forestry & Urban Greening*, 40, 133–144. <https://doi.org/10.1016/j.ufug.2018.03.007>

- Velasquez-Camacho, L., Cardil, A., Mohan, M., Etxegarai, M., Anzaldi, G., & de-Miguel, S. (2021). Remotely sensed tree characterization in urban areas: A review. *Remote Sensing*, 13(23), 4889. <https://doi.org/10.3390/rs13234889>
- Wang, Y., Niemelä, J., & Kotze, D. J. (2022). The delivery of cultural ecosystem services in urban forests of different landscape features and land use contexts. *People and Nature*, 4(5), 1369–1386. <https://doi.org/10.1002/pan3.10394>
- Wang, R., Zhao, J., Meitner, M. J., Hu, Y., & Xu, X. (2019). Characteristics of urban green spaces in relation to aesthetic preference and stress recovery. *Urban Forestry & Urban Greening*, 41, 6–13. <https://doi.org/10.1016/j.ufug.2019.03.005>
- Wong, C., Li, T., & Rahman, M. (2025). Differing perceptions on cultural ecosystem service values of urban forests: Recreational, aesthetic, and social benefits. *Urban Forestry & Urban Greening*. Advance online publication. <https://doi.org/10.1016/j.ufug.2025.129005>
- Zhang, H., Yu, J., Dong, X., Zhai, X., & Shen, J. (2024). Rethinking cultural ecosystem services in urban forest parks: An analysis of citizens' physical activities based on social media data. *Forests*, 15(9), 1633. <https://doi.org/10.3390/f15091633>
- Zheng, S., He, C., Guldmann, J.-M., Xu, H., & Liu, X. (2023). Heat mitigation benefits of urban trees: A review of mechanisms, modeling, validation and simulation. *Forests*, 14(12), 2280. <https://doi.org/10.3390/f14122280>

Zbigniew SZKOP

INTEGRACJA TELEDETEKCJI I DANYCH TERENOWYCH W EKONOMICZNEJ WYCENIE USŁUG EKOSYSTEMOWYCH ŚWIADCZONYCH PRZEZ KLONY ZWYCZAJNE W WARSZAWIE

STRESZCZENIE: Drzewa miejskie dostarczają wielu istotnych usług ekosystemowych, a ich ilościowa ocena jest kluczowa dla zrównoważonego zarządzania przestrzenią miejską. Narzędzie i-Tree Eco jest szeroko stosowane do takich analiz, jednak jego zależność od szczegółowych inwentaryzacji terenowych ogranicza zastosowanie w skali całego miasta. Teledetekcja dostarcza kompleksowych danych przestrzennych, lecz nie pozwala bezpośrednio uzyskać wszystkich parametrów wymaganych przez ten model. W badaniu opracowano zintegrowane podejście łączące dane teledetekcyjne i modelowanie terenowe, umożliwiające prowadzenie analiz i-Tree Eco w skali miasta. Metodę przetestowano na *Acer platanoides* (klonie zwyczajnym) w Warszawie. Dane terenowe z 529 drzew posłużyły do budowy modeli ekonometrycznych przewidujących cechy strukturalne na podstawie danych teledetekcyjnych. Wykorzystując te modele i inne atrybuty drzew pozyskane z teledetekcji, przeprowadzono analizę i-Tree Eco dla całego miasta. Oceniono, że ok. 122 tys. drzew rocznie usuwa 46 t zanieczyszczeń, sekwestruje 2 440 t węgla i ogranicza spływ wód opadowych o 38 100 m³, generując korzyści o wartości 787 tys. euro.

SŁOWA KLUCZOWE: drzewa miejskie, wartość ekonomiczna, teledetekcja, i-Tree Eco, zrównoważony rozwój miasta