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Ecosystem benefits of urban woody plants for sustainable green space planning: a case study from Wroclaw

Oleksandra Strashok[1,2]✉, Dmytro Bidolakh[3] & Monika Ziemiańska[1]

City residents benefit daily of urban green spaces, often unaware of their true value. We transformed biometric indicators of woody plants into ecosystem equivalents for evaluating ecosystem services (ES) by the I-tree eco tool estimate of boulevards with a different ratio of bushes, trees, and urban canopy cover (UCC). The results showed that the studied green spaces annually retain 111.24 metric tonnes of carbon in their biomass, estimated at 17,846 thousand €, and are capable of producing 1928 thousand € by different ES. It includes 4.01 metric tonnes/year of gross carbon sequestration worth €636.15, 76.01 m^3/year of avoided runoff worth €139.28, and 60.95 metric tonnes/year of pollution removal (ozone, carbon monoxide, nitrogen dioxide, and particulate matter) worth €1152.16. For objects where shrubs are the primary producers of ES, it is important to model crown development along the horizontal axis. Quantitative and qualitative assessment of different types of woody plants of different ages allows for effective selection of urban plants to create a well-being environment for citizens. The practical value of the results can improve the spatial planning of urban green infrastructure by considering the ES indices of trees and shrubs and expanding opportunities to inform the public about their value.

Keywords Biomass, Carbon sequestration, Pollution removal, Spatial planning, Well-being

As a key link between humans and nature, cities are increasingly becoming centres of demand for ES[1,2]. The millennium ecosystem assessment report categorizes ES into 4 main groups and 30 categories, each providing various types of benefits to people, including provisioning, regulating, cultural, and supporting services[3]. Urban green infrastructure is an essential component of residents' well-being, delivering various ES depending on its type[4]. For instance, recent research focusing on the ES provided by grassy lawns and urban forests highlights the complexity and ambiguity of their benefits[5–7]. Additionally, scientists are discussing the ES of green-blue infrastructure, noting the insufficiently studied potential benefits and the lack of comprehensive research[8]. The ES provided by urban trees[9,10], as components of green infrastructure and blue-green infrastructure[11], significantly contribute to the well-being of urban ecosystem inhabitants while delivering a wide range of environmental, social, and economic benefits[12]. In particular, it is done through their ability to produce such benefits as[13]: air pollutant removal, carbon storage and sequestration, urban heat island reduction, stormwater runoff reduction as well as other socio-economic benefits. In addition, actions to preserve and restore ES can improve the well-being and resilience of urban residents and reduce the ecological footprint and environmental debt in urban areas[14].

At the same time, global digitalisation with information and transformation processes that are constantly taking place in the process of human development[15,16] are changing its digital health[17] and require the improvement of appropriate sources of valuable, vital, relevant, and accessible information for many users[18,19]. The ecological status and ecosystem benefits of the human environment are increasingly recognized, drawing more attention from various groups, particularly urban residents, as evidenced by studies[20–23]. Moreover, for managers, professionals, and others whose activities or interests are related to urban landscapes and who do not

[1]Department of Landscape Architecture, Wroclaw University of Environmental and Life Sciences, Grunwaldzka St. 55, Wroclaw 50-357, Poland. [2]Department of Landscape Architecture and Phytodesign, National University of Life and Environmental Sciences of Ukraine, Heroyiv Oborony St. 15, Kyiv 03041, Ukraine. [3]Department of Forestry and Landscape-Park Management, Separated subdivision of the National University of Life and Environmental Sciences of Ukraine «Berezhany Agrotechnical Institute», St. Academichna 20, Berezhany 47-500, Ukraine. ✉email: oleksandra.strashok@upwr.edu.pl

have the appropriate environmental or specialised education, the results of such research are often difficult to access[24], incomprehensible, and of little use[25]. Overall, this greatly diminishes the effectiveness of research results. These findings should not only be accessible to scientists but also to other stakeholders. It is essential to present the information in a clear and accessible format for everyone[26]. On the other hand, the rapid development of information systems and technologies opens up wide opportunities for achieving a qualitative breakthrough in improving information management systems in various industries[18], including the environment. For example, modern approaches in ecosystem research today include geographic information systems, remote sensing methods, GPS technologies, interactive mapping, modern tools for biometric measurements, etc., which not only optimise the research process but also expand opportunities for monitoring ecosystems and facilitate the assessment of damage[27–30].

The i-Tree Eco tool, a state-of-the-art tool that includes software designed to process inventory results together with local air pollution and meteorological data to quantify urban tree structure, environmental impacts, and community value, is increasingly being used by scientists to assess ES[27,31–34]. Researchers conducted studies of quantitative and cost parameters of ES of green spaces in Poland, in particular in Warsaw[6,33,34], Poznan[31], Racibórz[27] using I-Tree eco. However, the functionality of this tool has not been fully implemented, and there is no study of the possibility of its integration into the national green space inventory methodology. It has been used primarily to obtain information on the quantity and monetised value of ecoservices based on tree inventories. Meanwhile, the international scientific community is constantly expanding the research areas utilizing I-Tree eco, exploring its potential for a wider range of studies and incorporating additional methods. Some researchers have used the capabilities of I-Tree eco to model and predict the growth of young plantations[35]. Others have employed it to identify the optimal locations for planting trees using the Planting Priority Index[36], taking into account air quality measurement results[37]. It has been used to justify the selection of the most suitable tree and shrub species in terms of ecosystems[38]. A significant advantage of using these tools to evaluate the damage caused to urban ecosystems by tree destruction is the ability to calculate financial losses, estimated at millions of euros[27]. In addition, the strategy's effectiveness for the spatial placement of green areas is significantly increased by the sound planning of the urban green space system, which is proposed based on the research on ES[14,39]. Furthermore, according to British researchers[40], i-Tree Eco reports help to shift the local authorities' focus from the costs and obligations of creating and maintaining urban trees to their overriding environmental and economic values. In fact, municipal authorities and residents of urban areas often do not realise the threats to green spaces and the possible losses due to their deterioration or loss, not only in the economic context of restoring lost plants but also in the ecosystem context, due to the loss of benefits created by urban plants. Consequently, various studies on the environmental benefits of green spaces and the monetisation of the values of individual ES can raise environmental awareness and help policymakers better manage urban vegetation to achieve desired environmental improvements[40]. Research findings should be presented in a way that is understandable and useful for a wide range of users through accessible formats[24–26].

Our research aimed to assess how effectively urban woody plants provide ES in riverside boulevards with different ratios of shrubs and trees and, accordingly, different levels of UCC. Urban green spaces are characterized by imbalance and heterogeneity of woody plants mainly due to the aesthetic or ecological values of species, design solutions and socio-economic factors[41–44]. The objective of our study was to conduct a quantitative and cost assessment of the ES of trees and shrubs in research objects aimed at facilitating effective spatial planning of urban green spaces in the future. The interim goal was also to assess the potential economic damage in areas with high flooding risk in September 2024. We also aimed to find a way to interpret and present the results in a manner that is understandable and accessible to a wide range of users.

Materials and methods

The methods described in this study aim to set up a toolkit for assessing of ES of urban woody plants and them representing in the form of an interactive map, emphasising the value of each plant for the urban ecosystem.

Study area

We selected three study sites located in the central-eastern part of Wrocław (Poland) near the Oder River. These areas are ecologically important and serve as recreational and tourist destinations. They were also at risk of flooding in September 2024 (Fig. 1; Table 1). The sites vary in terms of land use and their historical backgrounds.

Site A's greenery consists mainly of grassed areas and mature trees, evenly distributed throughout the historic boulevard, in alley and lanes. The entire boulevard area underwent a revitalisation process as a result of which, in November 2015, 94 trees were planted, mainly of the species *Tilia tomentosa* Moench. and *Acer pseudoplatanus* L. The nursery stock consists of avenue trees planted with their root ball enclosed, with a total height of 3.5[m] and a trunk circumference of 16–18[cm].

Site B's vegetation also includes grassed areas with freely spaced trees. Mature trees individually complement the composition of young trees planted as part of the implementation of the new landscaping in 2020/2021. A total of 55 trees mainly of the species *Betula papyrifera* Marsh. and *Tilia tomentosa* Moench. were planted as part of the project. The layout of the greenery composition of the Sloneczny Boulevard is complemented by multi-species flower beds composed mainly of perennials. In this case, trees with a root ball included in the boulevard were also planted, with a total height of 5.5[m] and a trunk circumference of 30–35 [cm]. The Sloneczny Boulevard, like the Boulevard named X. Dunikowskiego has great panoramic and landscape qualities.

Site C comprises mainly open grassy space, which is saturated with group plantings of trees and shrubs especially next to buildings. The mature tree composition is complemented by ornamental shrubs and trees introduced spontaneously over the last decade from planting material of various ages. Recent landscaping changes in 2016 resulted in new tree plantings mainly of the species *Acer platanoides* L. and *B. papyrifera*.

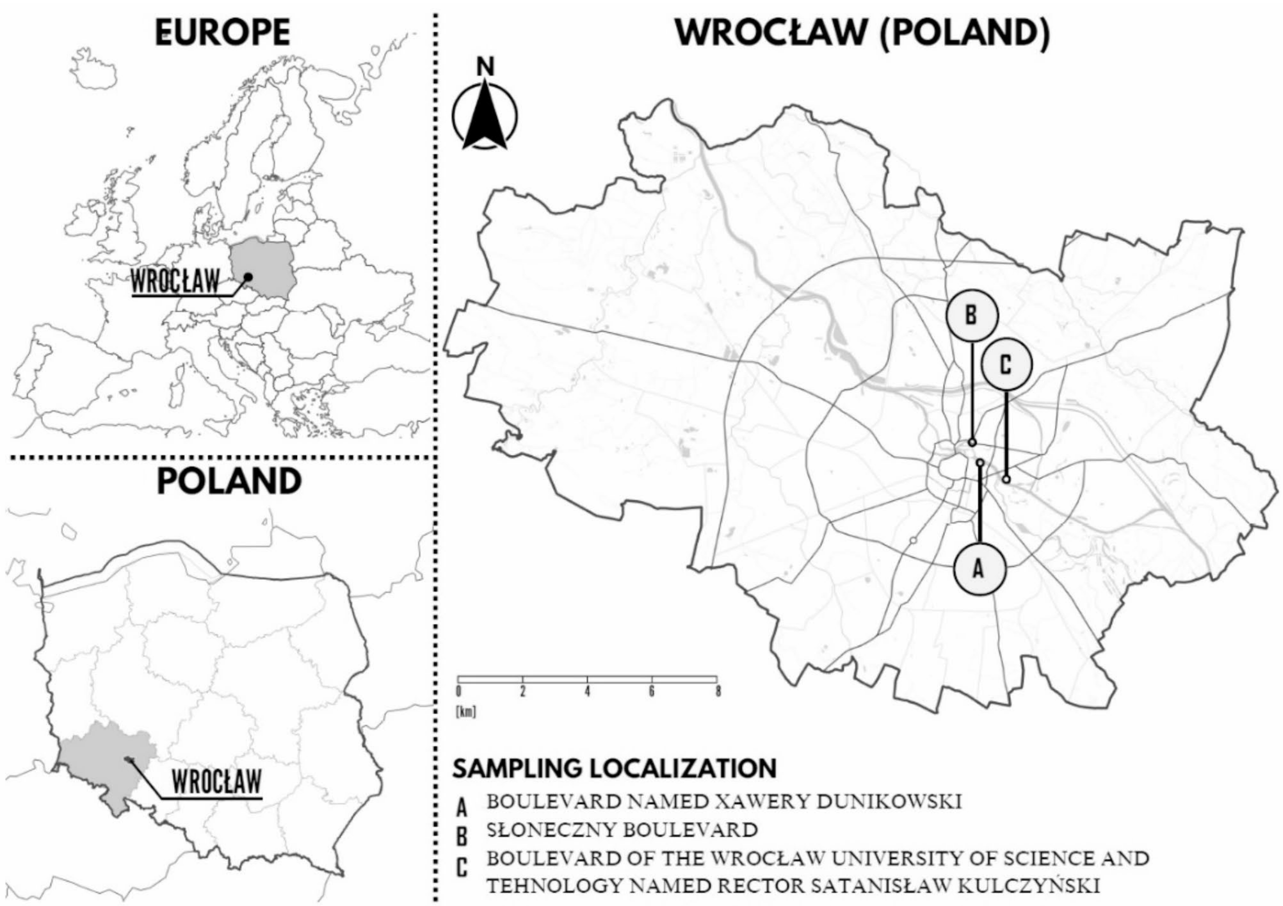

Fig. 1. Localisation of research objects.

Object	Official name of the boulevard	Latitude/longitude	Research area, ha	Coverage, %			Quantity	
				Tree and shrub crowns	Lawn	Paved surfaces (walkways, paving)	Trees	Shrubs
A	Xawerego Dunikowskiego	51.112284° N/17.042736° E	2.27	19.6	23.8	56.6	190	0
B	Sloneczny	51.117984° N/17.038796° E	1.52	6.8	40.5	52.7	126	1270
C	Wrocław University of Science and Technology Rector Stanisław Kulczyński's	51.106582° N/17.059540° E	1.35	8.8	30.1	61.1	99	68
Total				11.7	31.5	56.8	415	1338

Table 1. Detailed characteristics of the research objects.

Field work and inventory

Trees and shrubs of boulevards were inventoried during the growing season (September-October 2024). The first step was to identify the tree or shrub species, locate it on the map, then take the necessary measurements of dendrometric parameters, such as total height (m), crown diameter (m), trunk circumference measured at 1.3 (m) given in (cm) and, in the case of shrubs, crown projection in (m^2)[45]. The final stage of the inventory work was to establish and record comments on the sanitary condition of the surveyed units. In addition to the indicators defined by the inventory methodology, additional plant parameters were measured simultaneously, in accordance with the recommendations for assessing their ES using the i-Tree Eco toolkit[46]. These parameters include the height of the tree to the base of the crown and from this border to the top of the plant; the width of the crown projection in two mutually perpendicular directions; the proportion of lost and dieback crown (%), plant illumination in five categories, distance to the nearest building, and geographical coordinates of the location of each tree.

We identified tree and shrub species according to "Klucz do oznaczania roślin naczyniowych Polski niżowej"[Key to the Identification of Vascular Plants of Lowland Poland][47]. The age of the trees was determined visually by morphological features. Diameter at breast height (DBH) was measured with a measuring fork in two mutually perpendicular directions and a tape measure at a height of 1.3 m. A PM-5 Suunto optical altimeter was used to measure tree height. The values of geographic longitude and latitude were determined using a Garmin GPSMap64s receiver. The USDA Forest Service (2021) recommendations were used to determine the proportion of missing (percent of the crown volume that is not occupied by branches and leaves) and dieback crown (estimate of the percent of the crown that is composed of dead branches) and crown plant light exposure (Number of sides of the tree receiving sunlight from above, maximum of 5). The distances to buildings were measured with a measuring tape for trees and shrubs that may affect them, and the width of the crown projection was determined with the same measuring tool in two mutually perpendicular directions (north-south; west-east).

To get an up-to-date mapping base, a DJI Phantom4 quadcopter flew over the territory to obtain an orthophotoplan in accordance with the methodology using Agisoft PhotoScan software for orthotransformation of images and mounting the mapping base[48]. This approach allowed the open-source GIS QGIS 3.38.3 to refine and adjust the locations of plants obtained from GPS receivers, which made it possible to increase the accuracy of the geolocation data of trees and shrubs in the research object.

I-tree eco tool

After completing the fieldwork to collect the data mentioned above, the processed information was interpreted and entered into the i-Tree Eco software[46]. After processing the data entered into the I-Tree Eco tools, information was obtained on the results of the assessment of individual ES (reduction of pollutants, carbon sequestration and sequestration, oxygen production and regulation of surface water flow, energy conservation) and the restoration value for the plantation as a whole and for each tree, in particular, in quantitative, qualitative and cost terms, and displayed in the form of tables, reports and graphs. A comprehensive explanation of the assessment and valuation of ES is provided in the i-tree eco users manual (see pp. 50–51; 63–87)[46]. The same program also determined the future value and scale of ES to be provided by young trees planted in the study areas.

In addition, the I-Tree Eco tools allowed us to export the geographic information database in common .CSV or .KML formats, which enabled the creation of electronic interactive maps of ES for the study sites. This map is publicly available and can be used by anyone interested in obtaining information about the ES of each plant.

Results

Findings of the study of green spaces on three riverside boulevards showed that the observed phytolandscapes are represented by 54 tree and shrub species with a total number of 1753 inventoried plants, among which the most numerous are shrubs (*Rosa* spp. with a share in the total composition of woody plants of 21.4%, *Pinus mugo* Turra. 18.7% and *Ligustrum vulgare* L. 11.6%). Among the woody tree plants, *Tilia cordata* Mill. has the largest share (5.1%) in the total composition of research plants, *Taxus baccata* L. 3.3% and *Acer platanoides* L. 2.5%. Large-sized plants with high indicators of vital status and viability make the most impact on the functioning of the studied landscapes. Most of the plants are representatives of the green spaces from Object A due to the highest biometric indicators in the plantations (Table 2). The comparison of the annual benefits of monetized ecosystem productivity of the trees relative to shrubs (average values) shows a significant (two or even three orders of magnitude higher) advantage of woody plants (207, 11634, and 637 times higher efficiency for Objects A, B, and C, respectively) (see Table 2). Of course, this is explained by the significant predominance of biomass, particularly the ability of trees to produce ES compared to shrubs.

Calculations of such indices as «Tree cover», «Leaf Area», «Leaf Biomass», and «Tree Dry Weight Biomass» per unit area for the three sites demonstrate that they are not so much related to the number of plants per unit area (Table 3). Thus, the presence of large-sized trees in combination with their close placement on the territory of Object A contributes to an increase in the values of «Tree Cover» and «Tree Dry Weight Biomass» by more than 3 times and more than 5 times for the other above-mentioned indicators per unit area compared to Object C, even if they are adjusted for «Average Condition». It is important to highlight that the chosen Object C is a riverside boulevard, with space organized and limited on both sides by planting trees and shrubs. A study of the ecosystem utility of such an object showed that the addition of tree and shrub plants, even along the perimeter of landscaping areas, not only protects them from external factors (pollution, noise, etc.) but also significantly enhances their ecosystem functions.

On average, the calculated area of tree and shrub crown coverage per hectare (according to I-Tree Eco tools) is 37.8% of the total study area. However, the total leaf area of all the plantations in the research exceeds the total area of the studied plots, measuring 115.5%. This is mainly due to the larger area of Object A and its higher leaf biomass volumes. This information makes it possible to determine that under the given experimental conditions the leaf area of Object A exceeds their area by two times, and for object b and object C it is smaller and amounts 59 and 36%, respectively. This information may reflect the effectiveness of space utilization by green spaces, considering the development of their crowns in both horizontal and vertical planes. Thus, the phytolandscapes of Object A, when covering the horizontal plane of the area with their crowns by 33.5%, are able to form a leaf area corresponding to 201% of the total area of the site due to the use of the vertical plane (see Table 3).

The impact on the production of ES of individual species growing in the research areas significantly depends on their leaf area. Therefore, to determine the weight of the influence of individual species on the production of ecosystem functions of the researched plants, we calculated the «Importance Value» indicator. It was calculated as the product of the percentage of plant participation in the green space and the area of their leaf surface (Fig. 2). Of course, this distribution can demonstrate only the theoretical impact of the studied vegetation on the ES of urban landscapes through the area of their leaf surface. Its high values do not indicate a greater value of these species for the ecosystem, but only reflect their dominance in the structure of plantations due to their predominance in the composition or higher leaf biomass parameters.

The data showed that even plants with small leaf area (and also leaf biomass) have a significant impact on the production of ES of the sites due to their large number of species present in the urban landscapes (Fig. 2). This is

Object	ID	Species name	DBH	Replacement value	Carbon storage		Gross carbon sequestration		Avoided runoff		Carbon avoided		Pollution removal		Energy savings	Total annual benefits
			(cm)	(€)	(kg)	(€)	(kg/yr)	(€/yr)	(m^3/yr)	(€/yr)	(kg/yr)	(€/yr)	(g/yr)	(€/yr)	(€/yr)	(€/yr)
Species with maximum impact on ecosystem productivity																
A	187	*Platanus acerifolia L.*	125.0	19760.21	4006.9	642.83	27.10	4.35	2.90	5.32	0.00	0.00	3713.8	44.93	0.00	54.61
	186	*Platanus acerifolia L.*	148.0	22412.28	5766.2	925.07	27.70	0.28	2.90	5.25	0.00	0.00	3661.5	44.30	0.00	49.82
	161	*Acer platanoides* L.	65.0	6318.50	1682.6	269.94	34.00	6.14	1.20	2.25	14.9	2.40	1 543.4	19.19	7.94	37.91
B	156	*Fraxinus excelsior* L.	100.3	12350.99	2 844.4	456.33	67.60	10.84	2.00	3.69	0.00	0.00	2 500.1	28.39	0.00	42.92
	34	*Acer pseudoplatanus* L.	63.4	5773.44	1 142.1	183.23	42.40	6.80	0.50	1.00	6.60	1.06	675.90	7.67	3.51	20.04
	108	*Acer platanoides* L.	55.4	4688.01	819.30	131.44	46.10	7.40	0.70	1.20	0.00	0.00	813.40	9.24	0.00	17.84
C	10	*Fraxinus excelsior* L.	56.1	4150.47	693.30	111.23	34.20	5.49	0.60	1.06	0.00	0.00	775.00	8.41	0.00	14.96
	47	*Populus tremula* L.	59.7	2841.63	868.00	139.25	45.70	7.34	0.50	0.84		0.00	611.30	6.63	0.00	14.81
	126	*Populus tremula* L.	65.3	2745.90	1 081.8	173.56	43.00	6.90	0.40	0.78	0.90	0.15	571.90	6.21	0.42	14.46
Species with the least impact on ecosystem productivity																
A	56	*Tilia tomentosa* Moench.	6.70	172.69	4.40	0.71	0.80	0.13	0.00	0.01	0.00	0.00	8.90	0.11	0.00	0.25
	41	*Tilia americana* L.	2.90	65.54	0.50	0.08	0.60	0.09	0.00	0.00	0.00	0.00	3.40	0.04	0.00	0.13
	79	*Picea pungens* Engelm.	4.00	62.93	3.50	0.56	0.30	0.06	0.00	0.01	0.00	0.00	4.70	0.06	0.00	0.12
B	563	*Pinus mugo* Turra	0.60	56.13	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.002
	564	*Pinus mugo* Turra	0.60	56.13	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.002
	565	*Pinus mugo* Turra	0.60	56.13	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.002
C	165	*Cornus alba* L.	1.00	54.82	0.10	0.01	0.10	0.01	0.00	0.00	0.00	0.00	0.80	0.01	0.00	0.02
	166	*Cornus alba* L.	1.00	54.82	0.10	0.01	0.10	0.01	0.00	0.00	0.00	0.00	0.80	0.01	0.00	0.02
	167	*Cornus alba* L.	1.00	54.82	0.10	0.01	0.10	0.01	0.00	0.00	0.00	0.00	0.80	0.01	0.00	0.02

Table 2. Summary information on plant specimens with maximum and minimum ecosystem productivity (based on the results of processing inventory data in I-tree eco).

Object	Woody plants	Area	Cover		Leaf area		Leaf biomass		Tree dry weight biomass		Average condition
	Number	(ha)	(ha)	Per unit area	(ha)	Per unit area	(Metric ton)	Per unit area	(Metric ton)	Per unit area	(%)
A	190	2.265	0.7583	0.3348	4.55	2.01	3.31	1.46	133.81	59.08	95.11
B	1396	1.521	0.2436	0.1602	0.89	0.59	0.66	0.43	40.16	26.40	92.46
C	167	1.345	0.1334	0.0992	0.48	0.36	0.36	0.27	21.21	15.77	86.96
Total	1753	5.131	1.135		5.924		4.335		195.18		
Average			0.378	0.198	1.975	0.984	1.445	0.722	65.060	33.750	91.510

Table 3. Summary data of biomass volumes for green spaces of riverside boulevards in Wroclaw.

especially evident in such species as *Rosa* sp., *Ligustrum vulgarea* L., and *Buxus sempervirens* L. in Object B and *T. baccata*, *Cornus alba* L., and *Euonymus fortunei* (Turcz.) Hand.-Maz. for Object C.

The analysis of the ecosystem productivity of woody plants of the studied objects according to the relevant reports of I-Tree Eco made it possible to identify the species with the greatest and least ecological benefits in terms of the sum of the monetization results of the studied indicators («Gross Carbon Sequestration», «Avoided Runoff», «Carbon Avoided», «Pollution Removal» and «Energy Savings»), the top 3 values of which are listed in (Table 2). The data suggests that compensating for the eco-productivity of one tree from the Top 3 on Object A requires approximately 280 young linden or spruce trees growing on this site.At the same time, at Object B, such compensation requires approx. 11.5 thousand bushes with the lowest productivity in the given conditions are *P. mugo*, and at Object C, respectively, there are more than 630 bushes of *C. alba*.

In this context, we conducted a study of the effectiveness of planting new trees and bushes in the research areas and modeled their growth in terms of their production of ecosystem functions.

During the inventory at Object A 62 young plants were identified with a diameter of 3 to 16 cm with a predominance of *T. tomentosa* (61.3%), *Tilia cordata* L. (8.1%) and *Gleditsia triacanthos* L. (8.1%). A total annual ecosystem productivity in terms of the investigated indicators is 81.11 euros (that is, the average value of each young plant is only 1.31 euros). However, this indicator should increase annually along with the increase in plant biomass. In this context, we modeled the growth of these young plants up to 30 years of age. The simulation results (Fig. 3) showed that the current leaf biomass of young plants (3.67 metric tons) will double in 15 years (7.37 metric tons) and reach a value of 16.87 metric tons (increase 4.6 times) in 30 years at current rates (mortality rates and extreme events). Under such conditions, these 62 plants will be able to absorb carbon (total gross carbon sequestration) from 2.27 metric tons (as of today) to 4.68 and 9.78 metric tons in 15 and 30 years, respectively. For comparison, it should be noted that the largest plant on the site, *Platanus acerifolia L.*, with a diameter of 148 cm, during its existence achieved a carbon storage index of 5.766 metric tons, and the average value of carbon storage for all plants on this site is 0.424 tons. The vitality of 62 young plants in this area currently allows them to absorb as much carbon as would be sequestered by 5 average plants. In 15 years, this capacity will increase to the equivalent of 11 average plants, and in 30 years, these same plants will be able to absorb an amount of carbon equivalent to what 23 average plants sequester today.

Modeling of the amount of absorption of harmful substances also showed a gradual increase in its monetized value every year (see Fig. 3). The current value of the monetized value of the investigated young plants in Object A should double already in 14 years, and increase by 4.3 times at the age of 30. Today, the woody plants of Object A are able to produce annual ES in terms of absorption of harmful substances in the amount of 16,713 Euros. The studied 62 young plants, which today in this monetized volume of production occupy only 5.2%, in 30 years will make up 22.5%, which is quite a significant indicator.

Evaluating the ecosystem functions of trees and shrubs of the three studied objects, it should be noted that these plants are able to absorb and retain carbon in their biomass, which is becoming relevant in the face of global climate change, creating conditions for their mitigation (Table 4). The research phytolandscapes retain 111.24 metric tons of carbon in their biomass, which is estimated at €17,846,000. The largest share (72.4%) in this eco-service is played by plants from the Object A due to the significant volume of adult tree trunks.

At the same time, the annual volumes of carbon sequestration by the studied objects do not differ so dramatically. The data obtained indicate that the studied plantations are capable of providing 4.01 metric tons of gross carbon sequestration annually, with a monetized value of this service of € 636.15, which, in terms of one plant, represents 4 kg of annual carbon sequestration with an associated utility of € 0.55. The analysis of the scope of provision of this ES in the section of different objects also proved the predominance in this regard of the plantations of object A by the larger amount of biomass of woody plants. (Fig. 4).

The next ecosystem function studied was the ability of green spaces to regulate water flow. This service is valuable to the urban environment due to the ability of trees and shrubs to reduce and improve surface water runoff. It became especially relevant in the conditions of the threat of flooding of the embankments of the city of Wroclaw during the flood in September 2024. The obtained results proved that the trees and bushes of the studied objects can reduce the water flow by 76 cubic meters annually, and with an increase in the amount of precipitation, this indicator will, of course, increase (see Table 2; Fig. 4). Such an ecosystem service corresponds to a monetized value of €139.3 of annual utility. According to the results, landscapes with a preference for mature trees, which are characterized by developed root systems and larger crowns, have the highest productivity for regulating water flow.

The ES «Pollution Removal» is characterized by the highest value parameters of monetization of ES for the studied objects (Fig. 3). Processing the results of the plant inventory based on data on environmental pollution in the city of Wroclaw in the i-Tree Eco program made it possible to obtain information on the absorption of

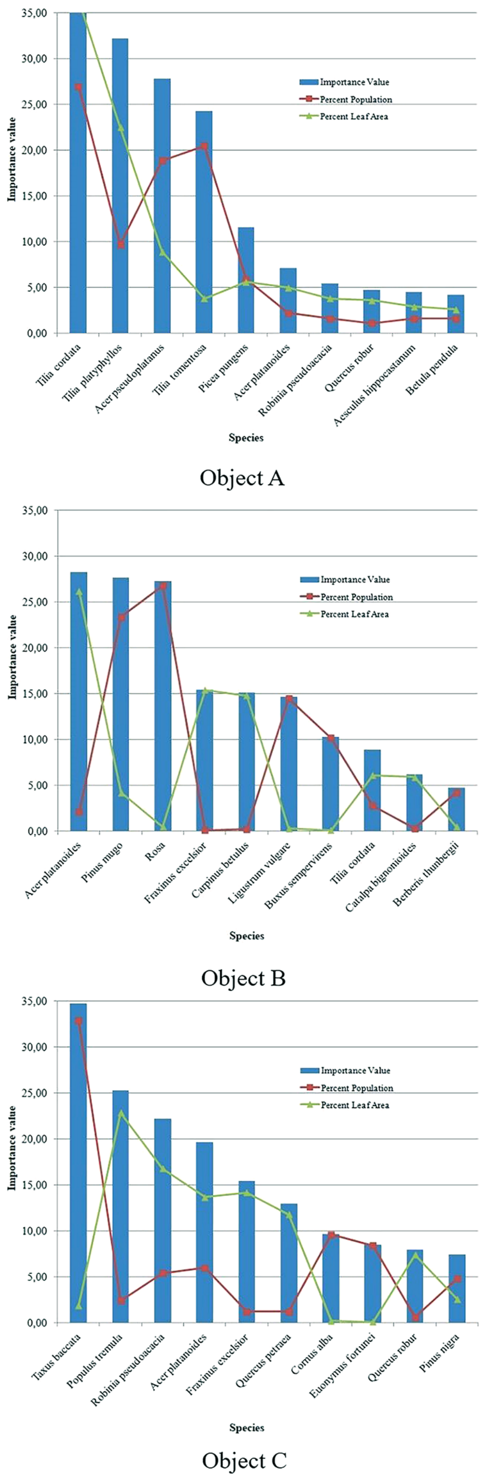

Fig. 2. Importance of the top 10 species on the biomass production. The "importance value" is calculated as the product of the percentage values of "population" and "leaf area".

sulfur dioxide (SO_2), ozone (O_3), carbon dioxide (CO), nitrogen dioxide (NO_2) by trees and bushes, as well as particles with a size of less than 2.5 microns ($PM_{2.5}$) and 2.5–10 microns (PM_{10}). The total volume of air pollution absorption by trees and bushes of harmful compounds is 60.95 metric tons per year, which in monetized terms is €1,152,000 annually. In the ability to produce this ES the woody plants of Object A are also of the greatest importance due to the greater biometric parameters. Data distribution analysis reveals that ozone (O^3) has the largest absorption volumes, whereas sulfur dioxide, carbon monoxide, and particles smaller than 2.5 microns exhibit the smallest absorption volumes. (Fig. 5). The average volumes of absorption per 1 plant are also higher for objects with a predominance of woody vegetation.

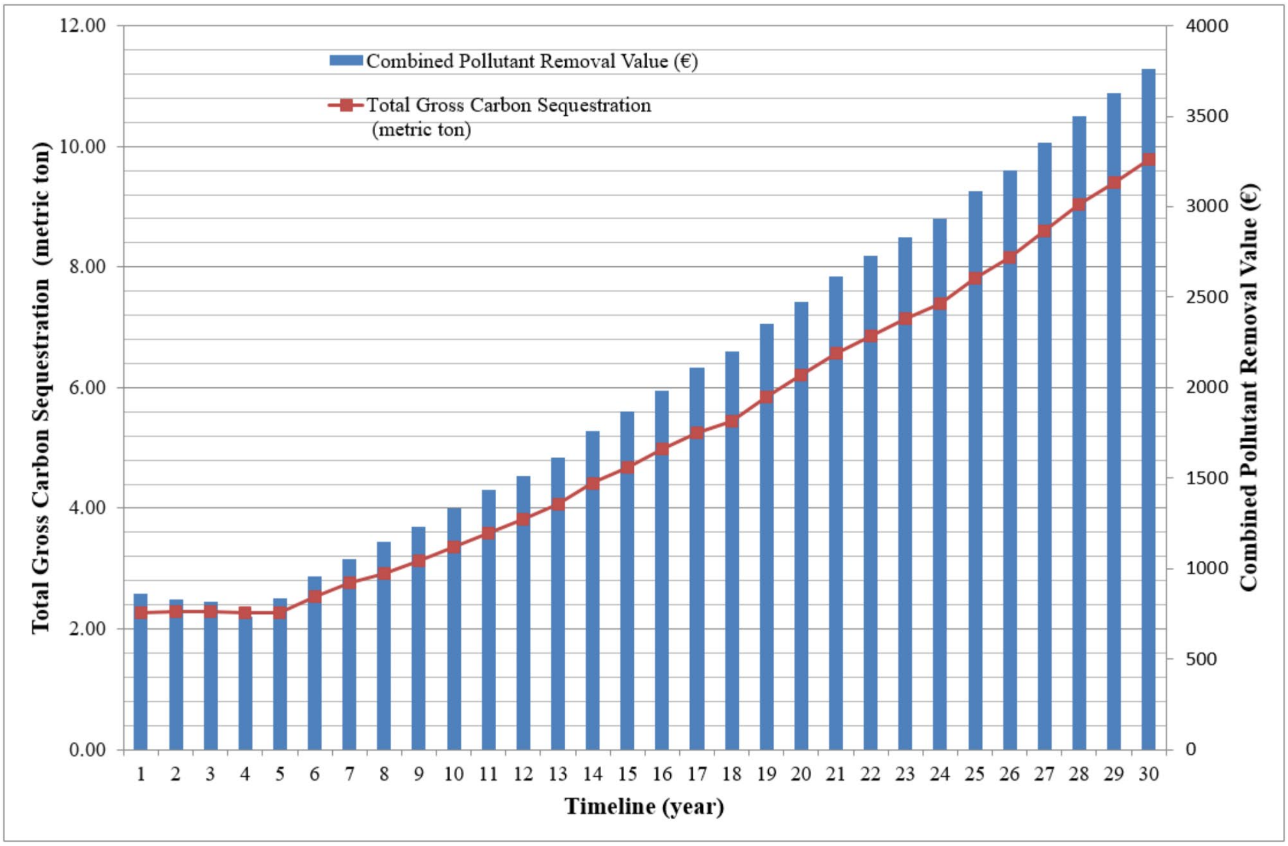

Fig. 3. Results of modeling of the volumes of carbon absorption by young plants in Object A. Modelling was done using I-Tree Eco tools. Pollution removal value is calculated based on the prices of z dashed l4.53 per kilogram (CO), z dashed l30.45 per kilogram (O_3), z dashed l4.55 per kilogram (NO_2), z dashed l1.66 per kilogram (SO2), z dashed l1 057.13 per kilogram ($PM_{2.5}$), z dashed l25.69 per kilogram (PM_{10}*). PM_{10}* is particulate matter less than 10 microns and greater than 2.5 microns. $PM_{2.5}$ is particulate matter less than 2.5 microns. If $PM_{2.5}$ is not monitored, PM_{10}* represents particulate matter less than 10 microns.

Category	Woody plants quantity	Carbon storage		Gross carbon sequestration		Avoided runoff		Pollution removal		Replacement value
		(Metric ton)	(€)	(Metric ton/yr)	(€/yr)	(m^3/yr)	(€/yr)	(Metric ton/yr)	(€/yr)	(€)
Object A										
Total	190	80,540	12923.03	2.410	383.85	56.410	103.48	0.072	873.46	471164.33
Per 1 plant	1	0.424	68.016	0.013	2.020	0.297	0.545	0.0004	4.597	2479.812
Object B										
Total	1396	20.100	3221.60	1.000	161.20	13.10	24.00	0.016	184.80	189949.40
Per 1 plant	1	0.014	2.308	0.001	0.115	0.009	0.017	0.00001	0.132	136.067
Object C										
Total	167	10.600	1701.50	0.600	91.10	6.500	11.80	0.008	93.90	59085.40
Per 1 plant	1	0.063	10.189	0.004	0.546	0.039	0.071	0.0001	0.562	353.805
Total	**1753**	**111.24**	**17846.13**	**4.01**	**636.15**	**76.01**	**139.28**	**60,95**	**1152.16**	**720199.13**

Table 4. Summary information on the production of ecosystem benefits of green spaces of the investigated embankments of the City of Wroclaw (Poland). The table shows annual utility data for the indicators «Gross Carbon Sequestration», «Avoided Runoff» and «Pollution Removal» and aggregated utility as of 2023 for the indicator «Carbon Storage». Source: developed by the authors based on their own research by processing it in the i-Tree Eco tools program.

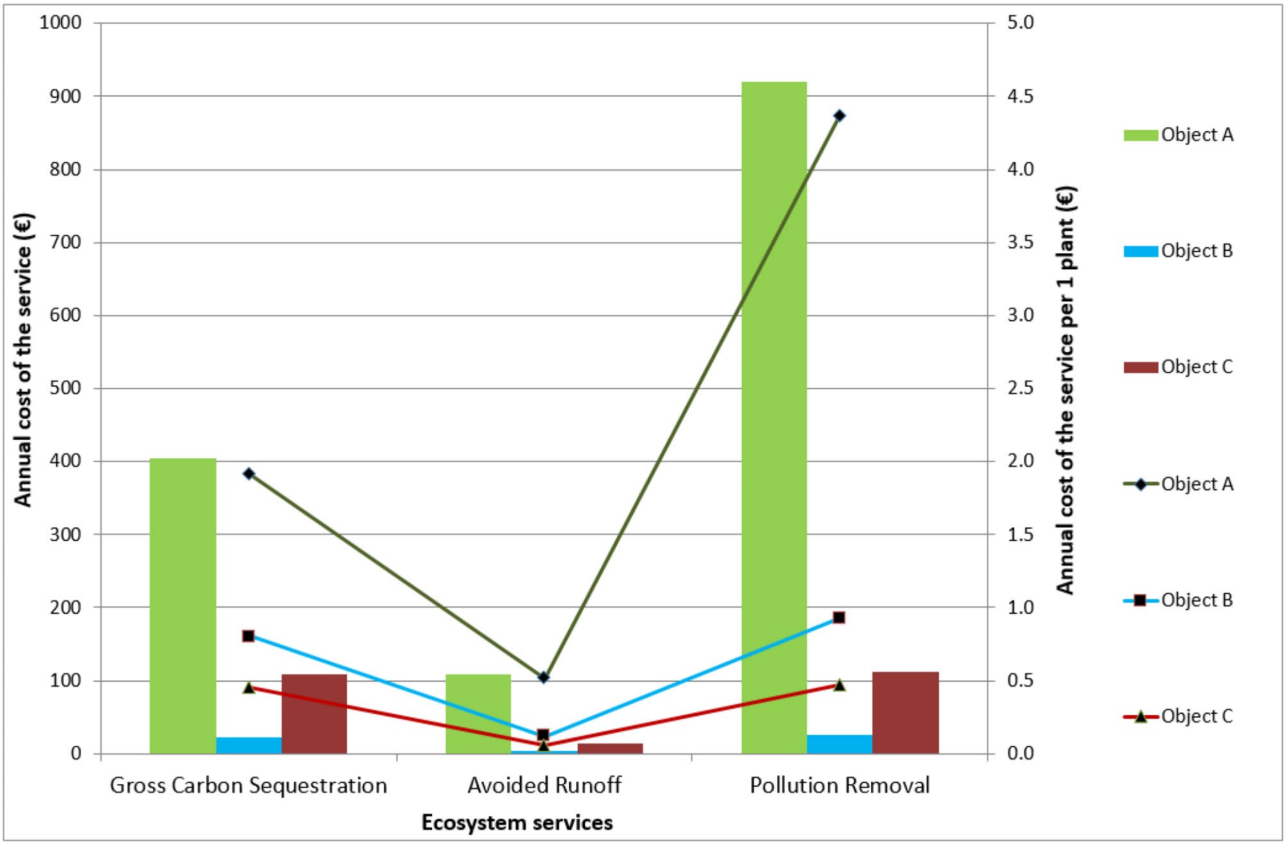

Fig. 4. Summary data on annual ecosystem benefits for all plants of the research objects (graph) and per plant (columns).

The «Replacement Value», the estimated local cost of replacing a tree with a similar tree, is also an important characteristic of the trees and bushes of the studied landscapes. It was determined that the total cost of restoration of all trees and bushes in the studied areas, according to the calculations of i-Tree Eco, is 720.2 thousand euros. The maximum values of «Replacement Value» are typical for the largest trees, particularly for *P. acerifolia* with a diameter of 148 cm, which is 28.31 thousand euros.

Discussion

Quantitative analysis of ES

The originality of this study is based on the comparative analysis of the ecosystem productivity of trees and shrubs growing on the embankments in Wroclaw across different landscape types. This study analyses the characteristics of the influence of trees and shrubs, as well as their biometric parameters, on the magnitude of ES provision. The results revealed that Object A, which predominantly feature mature trees, are the most effective. It is important to evaluate the efficiency of using urban space by woody plants due to the development of their crowns not only in the horizontal but also in the vertical planes, especially for shrubs. Under these conditions, plantations of such a landscape can annually produce ES (in terms of gross carbon sequestration, avoided runoff and pollution removal) worth € 600.8 /1 ha, which is € 7.16 per plant. The reduction in vegetation cover and decrease in tree biomass (typical for semi-open and open landscapes) leads to a decrease in the ecosystem productivity of such communities. The results confirm that good tree viability is important for achieving the maximum level of ES[49]. The analysis of the volume of provision of ES in the section of different objects proved a significant predominance in this regard of the plantations of Object I (closed type landscape) in view of the larger amount of biomass of woody plants. At the same time, the vegetation of other objects produces significantly less annual carbon sequestration due to the smaller amount of leaf biomass. The amount of carbon sequestration depends to a large extent on the biomass and sanitary condition of plants and increases during the growth and development of trees and bushes, which is also confirmed by the results of similar studies[38,49–52]. At the same time, large-sized plants (Table 2) with high indicators of vital status and viability have the greatest impact on the functioning of the studied landscapes.

The data presented in Fig. 2 show that for Object A, which is dominated by woody plants, shrub vegetation does not significantly impact the production of ES due to its small biomass. A noteworthy finding of this study is that, for Object B and Object C, shrubs can significantly enhance their ecosystem productivity due to the increased cover vegetation but, as other studies show, in terms of biodiversity, soil, hydrology, nutrient supply, grass growth and soil fertility[53]. Such a feature should be considered in the spatial planning of green

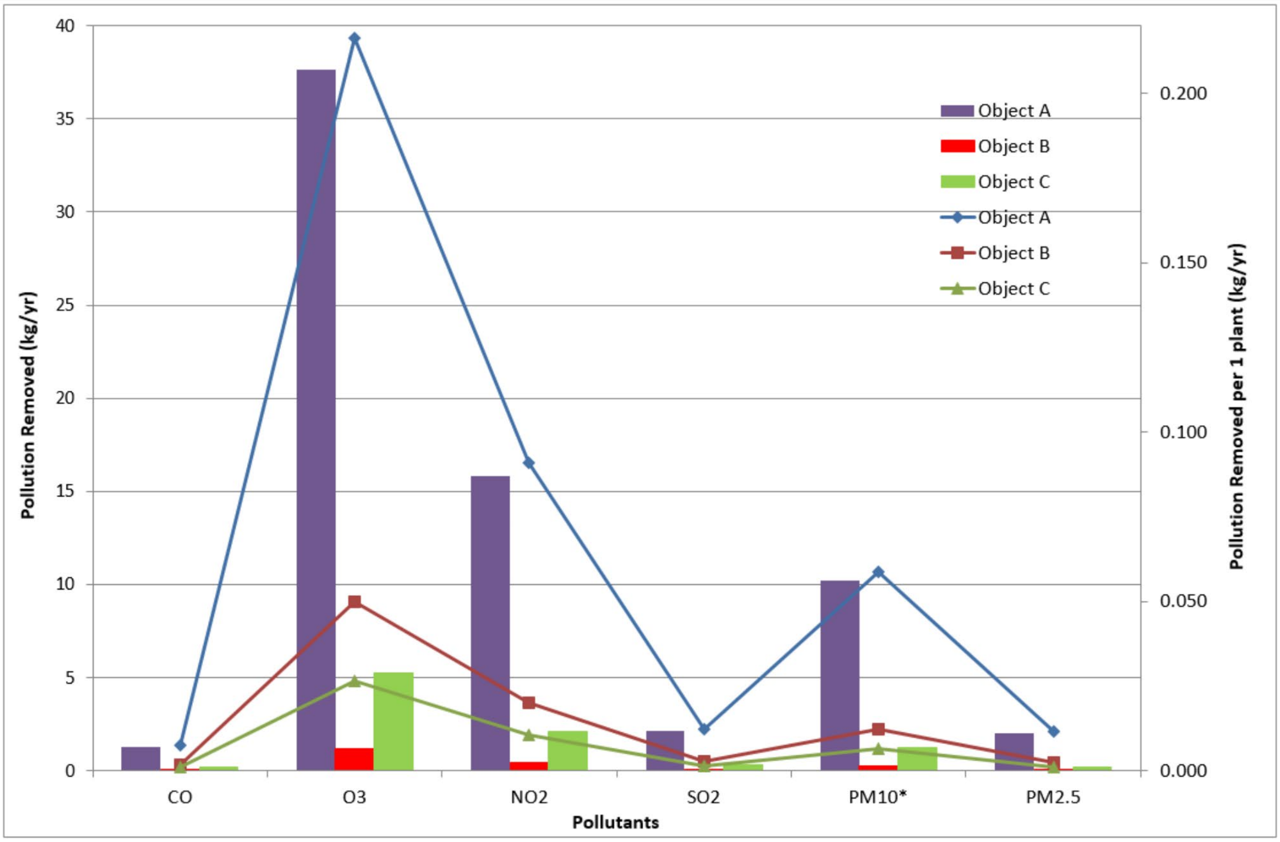

Fig. 5. Quantification of annual absorption of pollutants for all plants in research objects (graph) and per plant (columns).

infrastructure as an opportunity to enhance the ecosystem value of urban landscapes, which is also supported by the results of other researchers[54]. The importance of studying the impact of shrubs on the ES of plantings, in comparison to trees, has already been highlighted by some researchers[55] and the opportunities for enhancing the ecosystem productivity of open spaces in urbanized areas[56]. In this area, we have determined that a study examining the ecological benefits of open space plantings, using trees and shrubs, found that incorporating these plants—even along the edges of landscaped areas—helps protect them from external factors such as pollution and noise. Additionally, this approach significantly enhances their ecosystem functions.

Analyzing the contradictions related to the ecosystem benefits of urban plants, we have determined (see Table 2) that, on the one hand, it demonstrates how difficult it is to compensate for the loss of ES provided by old trees with new plantings of young plants. On the other hand, it should be noted that the processes of biomass reduction and the loss of ecosystem functions of woody plants due to their aging and dying are irreversible, as well as the opposite processes of the annual increase in the biomass of young plants[57]. This obliges landscape designers to plan regular renewal of plant composition by introducing new trees and shrubs to urban landscapes. The information on species selection, tree placement and landscape design provides valuable guidance for urban planners and landscape architects aiming to improve the effectiveness of urban parks as natural solutions for sustainable urban development[38,58]. As a rule, tree planting programs are evaluated only by the number of trees planted, without analysing the condition and growth characteristics of young trees after planting[35]. The economic and non-economic value of urban ES should be taken into account in decision-making and planning in cities[14]. The modelling results (Fig. 2) showed that the current leaf biomass of young plants (and, accordingly, ES) will increase by 4.6 times in 30 years, which will ensure the volume of carbon sequestration at the level of 37.1% of the total volume of its production by the studied closed-type phytolandscapes. In this case, according to the conclusions of scientists who conducted similar studies[51,52], higher biometric parameters have the greatest impact on water flow regulation. Our results support this, as healthier and larger trees with larger canopies are more effective in providing benefits such as pollution removal, runoff reduction and carbon sequestration[38,49].

The analysis of the contribution of individual plants to the generation of ES on the studied sites indicates that the highest share of these services, in monetary terms, is provided by the following species: *A. platanoides* (21.3%), *R. pseudoacacia* (12.8%), *F. excelsior* (12.0%), *P. tremula* (9.3%), and *C. betulus* (5.3%). Together, these five species contribute more than 60% of the total monetary value of ES provided by Wrocław's riverfront landscapes.

Scientists also focus on identifying and correcting inaccuracies in the I-Tree Eco toolkit, particularly in relation to verifying the reliability of the pollution model. This model is used by the program to automatically

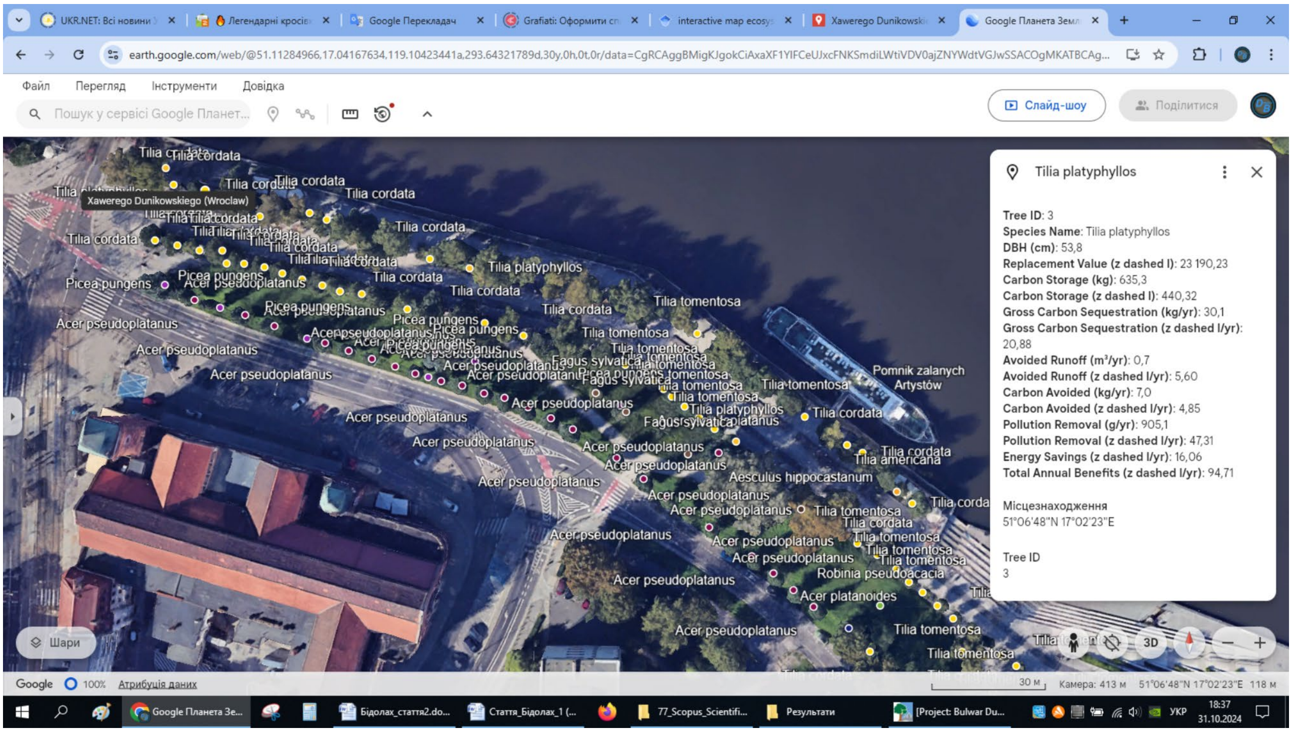

Fig. 6. An interactive map visualizing quantitative and cost parameters of ecosystem services in Wroclaw's green spaces. Link to access the interactive map: https://www.google.com/maps/d/u/0/edit?mid=1iqubQByBqpSJJgb-kbT5tj6MagmTbpI&usp=sharing.

estimate quantitative pollution indicators. The results of other studies proved that the average statistical models of pollution, which are automatically obtained from the relevant pollution stations, can underestimate the obtained utility results for places (highways, areas near industrial enterprises, etc.)[32,59]. At the same time, it should be noted that studies of areas with urban trees, in contrast to the places mentioned above, significantly reduce the concentration of harmful substances (PM 2.5) coming from transport[60]. This once again proves the importance of more detailed research on the variability of the obtained results depending on the characteristics of the research site and the intensity of greening of the territory.

ES costs and financial risks of flood damage in vulnerable areas

We made the first attempt to calculate the potential economic losses of key ES of urban woody plants in Wroclaw from the flood that affected Polish cities in 2024. The conducted research has established that the trees and shrubs on the studied riverfront areas are capable of annually generating ES (in terms of gross carbon sequestration, avoided runoff, and pollution removal) valued at over €375.7 per hectare. Considering that the total area of flood-prone riverfronts within the city of Wrocław exceeds 170 hectares, the potential for prolonged flooding of vegetation in these areas poses a risk of annual ES losses in the studied parameters exceeding €60.000.

Furthermore, the estimated economic loss to Wrocław's riverfront landscapes, in the event of vegetation loss (calculated via interpolation of the replacement cost of plants within the aforementioned area), would amount to over €23.86 million. These findings underscore the value of the studied landscapes and highlight the critical importance of their protection, including against potential damage in areas with high flooding risk.

Dissemination of findings and public outreach

One of the most promising ways to disseminate information to a broad audience is by creating interactive maps. These maps facilitate the mapping of ES and allow users to engage directly with the information in urban environments through their devices, such as smartphones or laptops, in an open-access format[30,61,62]. Therefore, an additional advantage of the obtained data, according to the approaches we proposed, is the possibility and accessibility of visualisation of information on ES of each individual tree and shrub of the studied plantations in the form of an interactive map (for example, using the Google MyMaps application or Google Earth) creates conditions for a better understanding of the ecosystem value of each plant (Fig. 6) and expands the possibilities for stakeholders to access the research results.

To promote the ecosystem services (ES) provided by trees and shrubs at the local level, information stands should be placed at the entrances to green spaces. These stands should feature a QR code linking to an interactive map, as well as general information about the area. Additionally, they should provide quantitative data and the monetary value of plant ecosystem services, details about the most valuable and oldest trees and shrubs, interesting facts, and historical information. Installing signs on some unique plants with information about their name and value for the urban ecosystem is also advisable. This approach, according to the authors, will not only increase the tourist attractiveness of such areas, but will also contribute to improving environmental protection activities and deepening the environmental awareness of the population[63].

The study of the ecological role of urban trees and shrubs is crucial for the overall social and environmental development of cities. It can enhance residents' awareness of their local environment[64,65], and serve as valuable guidance for urban planners and landscape architects. This knowledge aims to improve the effectiveness of urban parks as natural solutions for sustainable urban development[38]. We, and other researchers, believe that integrating ecological and informational perspectives will lead to the development of digital technologies that are crucial for providing the information needed to support sustainable human interactions with nature. This approach applies to ecosystems of various scales and fosters innovation[20–22].

Conclusions

The results of the assessment of ES of woody plants using modern tools, including i-Tree Eco, on the example of riverside boulevards of Wroclaw with different spatial locations have created conditions for demonstrating the value of trees and shrubs for urban ecosystems in both quantitative and monetised terms. The current approaches and findings presented in this article offer a clear understanding of the individual ES that can be evaluated based on inventory results. Additionally, they outline the details of how these services are produced across various types of landscapes. The data obtained made it possible to analyse the extent of ES losses, as well as the features and prospects for their compensation by planting new trees and shrubs. Studying the ES of each individual plant, as well as their collective impact, is crucial for effectively planning green infrastructure. We have shown that this approach enhances the ecosystem value of urban landscapes and ensures the sustainable development of ecosystems. The practical value of this work lies in raising awareness of local authorities, enterprises and organisations involved in municipal and environmental activities, NGOs, activists and other stakeholders about the importance of green spaces. This awareness is crucial for the protection and conservation of these areas. Additionally, it aims to improve management practices and create conditions that facilitate informed decision-making. Ultimately, the goal is to achieve results that support the sustainable development of urban landscapes. Finally, it is worth noting that this research area has prospects for continuing the ES study of other types of urban green spaces, expanding the list of possibilities for assessing new ecosystem functions, finding opportunities to use modern tools to obtain information, and expanding the areas of application and ways to communicate the results to all those interested in promoting the importance of each tree and shrub for the urban ecosystem.

Data availability

All data supporting the findings of this study are available within the paper and its Supplementary Information. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

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Author contributions

The field sampling was conducted by O.S. and D.B. Methodology, software, D.B. and O.S. Formal analysis and investigation, O.S. and D.B. Writing—original draft preparation O.S. and D.B. Data curation, project administration, supervision, M.Z. Writing—review and editing, M.Z and D.B. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to O.S.

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