

UDC 630*1:630*181.351:581.5:528.946
DOI: 10.31548/forest/1.2023.08

Assessment of ecosystem functions of green spaces as an important component of their inventory in the context of sustainable development of urban landscapes

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Abstract. An important area of research in the context of ensuring the sustainable development of urban ecosystems is the development of theoretical and applied aspects of the possibilities of obtaining information about the ecosystem usefulness of green spaces. The concept of evaluating and paying for eco-services that produce trees and shrubs for the environment and society is characterised by substantial international interest. In this context, it is important to analyse modern tools and techniques that can adequately determine and evaluate the amount of ecosystem services, which was the main goal of the study. In this paper, the possibility of using the i-Tree Eco tools for quantitative and cost determination of the volume of ecosystem services created by park spaces in the green space inventory process is tested. For this purpose, on the example of the prefix part of the Rayivskyy landscape park of the Ternopil region, the measurement of biometric and sanitary indicators of trees during their inventory was conducted, a number of ecosystem services of plants were determined (reduction of pollutants, absorption and sequestration of carbon, oxygen production, and regulation of avoided runoff), the replacement cost of trees was established, the data obtained were analysed, the interpretation of the information received in the form of an interactive electronic map was performed, and the advantages and disadvantages of this process were determined. The study showed that the cost of ecosystem services (in the context of the indicators under study) for the attached part of the Rayivskyy landscape park is 81894 UAH (€3044) per year, and the total replacement cost of the examined plantings is 4486,464 thousand UAH (€166,783). The monetised expression of the ecosystem utility of this plantation creates conditions for improving the understanding of the value of the phytocenosis for urban landscapes. The practical value of the study is the possibility of using its results to improve and

Suggested Citation:

Bidolakh, D. (2023). Assessment of ecosystem functions of green spaces as an important component of their inventory in the context of sustainable development of urban landscapes. *Ukrainian Journal of Forest and Wood Science*, 14(1), 8-26 . doi: 10.31548/forest/1.2023.8.

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increase the information content of the green space inventory process, by obtaining information about ecosystem services of trees in quantitative and cost terms to increase the validity of decisions in the field of nature management

Keywords: utility monetisation; replacement cost of trees and shrubs; i-tree Eco, environmental improvement; century-old trees

Introduction

Green spaces are important for ensuring the sustainable development of urban landscapes due to the fact that they can mitigate the negative effects of anthropogenic activities in urban ecosystems by improving the ecological, sanitary, climatic, and aesthetic state of the environment. Tree and shrub stands in the city need regular examinations to ensure proper care, protection from adverse factors and protection to fulfil their important role in optimising the oxygen-carbon balance of the ecosystem, cleaning and improving the biosphere, improving the local microclimate, avoiding runoff, and other ecosystem functions. For this purpose, the inventory of green spaces defined by the Order of the State Committee for Construction, Architecture and Housing Policy of Ukraine No. 134 “On the Approval of the Instructions on the Inventory of Green Spaces in Populated Areas of Ukraine” (2014) should be conducted regularly, once every five years. However, in practice, according to the findings of researchers Y.A. Melnyk *et al.* (2019), D.I. Bidolakh & P.I. Lakyda (2019), in Ukraine, such inventory for urban plantings is performed much less often. In addition, according to D.I. Bidolakh (2020), S.V. Rohovskyi *et al.* (2021) it is conducted in accordance with an outdated methodology and requires updating approaches.

The latest trends in the development of modern technologies, according to many researchers (Lin *et al.*, 2020; Bidolakh, 2020; Croci, Lucchitta & Penati, 2022), open up new opportunities for collecting, analysing, and

interpreting information obtained during the inventory of green spaces. One of the important areas of this process is the assessment of the quantitative and cost parameters of ecosystem services of trees and shrubs, which allows for a better understanding of the usefulness and value of green spaces in urban landscapes. Therefore, the combination of processes for obtaining standard information based on the results of inventory on the main quantitative and qualitative indicators of phytolandscapes, the sanitary condition of plants with their biometric data, which are used to determine ecosystem benefits, creates conditions for expanding the scope of application of the obtained materials and increases their value. Therewith, according to the results obtained by N. Stoeckl *et al.* (2023) almost 90% of these utilities are ecosystem services related to natural capital, and more than half are services that are still difficult to monetise.

Along with this, some researchers (Steenberg *et al.*, 2017) recommend considering the vulnerability of green spaces in urban landscapes, which, in the absence of preventive measures, can lead to a decrease in the volume of ecosystem functions performed with a corresponding loss of benefits for residents, urban infrastructure, and natural biodiversity. These volumes also require quantitative and monetised expression to understand the losses that the ecosystem and society will suffer from the misuse of natural resources. Under such conditions, a logical conclusion arises, formulated in the studies of researchers T.P. Ly & H. Xiao

(2016), C.-S. Chan *et al.* (2018), on the importance of establishing a balance between the norms of recreation and the use of useful functions of green spaces, on the one hand, and environmental measures and economic investments in the development of green infrastructure, on the other hand, in the context of the need to ensure sustainable ecosystem development. In general, the critical state of ecosystems at the planetary level, according to the authors (Gaglio *et al.*, 2023), requires, in the light of the Sustainable Development Goal of cities and communities, the immediate adoption of measures aimed at achieving an impact in the environmental field and economic development.

Therefore, the relevance of the paper follows from the need to examine the theoretical and practical foundations of the possibilities of obtaining information about ecosystem services of green spaces and their assessment, considering the benefits that they create for the environment and society.

The purpose of this study was to develop approaches to involve tools for assessing the cost of ecosystem services in the process of inventory of green spaces to obtain, interpret and further present information about the environmental and cost value of green spaces. The task of measuring biometric and sanitary indicators of plants during their inventory is set to determine the amount and cost of individual ecosystem services (reducing the volume of pollutants, carbon uptake and sequestration, oxygen production, and regulation of surface water runoff), determining the replacement cost of plants, analysing and interpreting the information obtained, and determining the advantages and disadvantages of this process.

The scientific originality of the study is the first analysis for Ukraine of the possibility and prospects of integrating advanced international tools for evaluating ecosystem services of green spaces in the process of their inventory.

Literature Review

A characteristic feature of the development of the economy of states that pay considerable attention to the implementation of the principles of sustainable development is a substantial change in the approach to financing environmental protection measures. One of the most advanced approaches in this area can be considered the introduction of special payments for the use of services created by ecosystems. This approach to financing eco-balanced development, according to C. Sattler *et al.* (2013), is defined by different terminology but corresponds to the same content subject, and is usually generalised under the brand name PES (Payments for Environmental Services). The concept of PES has recently attracted considerable international interest (Sattler *et al.*, 2013; Schomers *et al.*, 2021; Croci *et al.*, 2022). Ultimately, this approach is considered a very effective economic means of improving environmental management due to the possibility of introducing financial incentives for measures aimed at improving ecosystem services, including those provided by green spaces. According to H. Yan *et al.* (2022), a separate prospect of such financial incentives is the possibility of justifying the feasibility of allocating funds for environmental protection measures based on economic calculations of ecosystem benefits that the state receives from nature (in this case, trees and shrubs).

Awareness of the important role of green spaces in creating a comfortable and safe living spaces for residents of settlements encourages the development of regular measures for careful treatment, protection, high-quality reproduction, and increasing the area of vegetation in urban landscapes. This direction, in terms of the importance of improving the quality of green spaces while simultaneously meeting the public's demand for environmental services, is also effectively consistent with the requirements of the current legislation in Ukraine. Thus, Law of

Ukraine No. 2059-VIII “On Environmental Impact Assessment” (2017) defines that activities and objects that have or may have a substantial impact on the environment should be analysed in relation to their impact on the environment.

However, green spaces, which have one of the greatest impacts on urban landscapes, as of 2023 do not have a well-defined methodology for assessing their value and the amount of the ecosystem functions they create. For this reason, quite often, when withdrawing green areas for construction, only the cost of a land plot is taken into account without considering an important indicator of assessing the utilities created by green spaces that grew in this territory (Derkulsky, 2016). In this context, there are separate findings regarding the assessment of certain components of the cost of green spaces and the services they perform, according to which researchers use various well-known approaches based on:

- ◆ the cost of restoring plantings to the state of their functional purpose (Rogovsky, 2016) using the recommendations of the methodology for determining the replacement cost of green spaces;

- ◆ the cost of compensatory landscaping for the purpose of restoring green spaces to replace destroyed or damaged ones (Draft Law ..., 2015);

- ◆ accounting for tangible and intangible benefits produced by green spaces (Pryshchepa, 2019; Velasco-Muñoz *et al.*, 2022);

- ◆ application of payments for ecosystem services provided, which are created by green spaces in the course of their life (Yan *et al.*, 2022; Gaglio *et al.*, 2023);

- ◆ use of information systems, computer modelling, and other tools to automate the determination of the amount and cost of ecosystem services for plantings or individual plants (Nowak *et al.*, 2018; Babí Almenar *et al.*, 2023).

Some Ukrainian researchers are also developing new methods and means for combining

the above approaches to consider the advantages and features of each of the methods mentioned (Rogovskiy, 2016; Bidolakh & Lakyda, 2019; Havrylenko & Tsyhanok, 2019). The presence of different approaches and the lack of a unified methodology for estimating the cost of green spaces, the quantitative and monetised expression of their services in Ukraine indicates the need to continue searching for an effective, accessible, and recognised international scientific community methodology for solving this issue.

One of the areas that has international recognition, which is confirmed by a fairly substantial number of publications in the international literature (Nowak *et al.*, 2018; Lin *et al.*, 2020; Mosyftiani *et al.*, 2022) is the application of the i-Tree Eco special tool for the need to determine individual ecosystem services of trees and shrubs and their replacement cost. However, this approach is poorly tested in Ukraine and requires a more detailed study of its effectiveness, suitability for adaptation to the conditions of the state, and the possibility of integration into the national methodology for the inventory of green spaces.

Materials and Methods

As an experimental base of the study, green spaces of the prefix part of Rayivskyy landscape park were used, which is located near the city of Berezhany, Ternopil region. The geographical location of the experimental base of the study, which covers an area of 1.71 hectares, is described by the following geographical coordinates: north latitude in the range from 49.427485° to 49.428758° and east longitude from 24.938052° to 24.907597°. The height of plant placement above sea level ranges from 322.7 to 339.6 m. In total, the inventory at this facility covers 109 trees.

For trees and shrubs of the attached part of the park, an inventory was conducted during the growing season (July-August 2022) in

accordance with the Order of the State Committee for Construction, Architecture and Housing Policy of Ukraine No. 134 "On the Approval of the Instructions on the Inventory of Green Spaces in Populated Areas of Ukraine" (2014). During the implementation of the recommendations of this instruction, additional measurements of plant parameters that are necessary to determine their ecosystem services in accordance with the recommendations of the USDA Forest Service (2021) were simultaneously conducted to evaluate them using the i-Tree Eco toolkit. These parameters include: geographical coordinates of the location of each tree; land use category from a list of 12; the height of the tree from the soil surface to the base of the crown and from this border to the top of the plant; the width of the crown projection in two directions; the proportion of the lost and dead part of the crown (percentage value), and the light exposure of the plant in five categories. The following methods and tools were used to conduct the above-mentioned studies.

Types of woody and shrubby plants were determined by the determinant under the authorship of D.N. Dobrochaeva & Yu.N. Prokudin (1999). The eye estimation of the tree age by morphological features was conducted. Tree diameters were measured with a measuring fork in two mutually perpendicular directions at a height of 1.3 m (Diameter at breast height – DBH), and a measuring tape was used for individual trees of large diameter and with a complex trunk circumference configuration. An Anuchin altimeter was used to measure the height of trees. The geographical longitude and latitude were determined using Garmin GPS-Map64s receivers (USA). The USDA Forest Service (2021) guidelines were used to determine the land use category, the proportion of lost and dead crown parts and plant light exposure in five categories. The width of the crown projection was measured with a measuring tape in

two mutually perpendicular directions (north-south; west-east).

A flyby was conducted with photographing the territory using a DJI Phantom4 quadcopter (China) to obtain an orthophotoplane in accordance with the methodology (Bidolakh & Lakyda, 2019) using the Agisoft PhotoScan programme for orthotransformation of images and mounting the cartographic basis to obtain an up-to-date cartographic basis. This approach allowed for refining and adjusting the locations of plants obtained from GPS receivers in GIS QGIS 3.16 in accordance with the methodology (Bidolakh & Lakyda, 2019), which, in turn, created conditions for improving the accuracy of the obtained geolocation data of park trees.

Upon completion of the field work to collect the above data, the information processed in accordance with the recommendations of the USDA Forest Service (2021) and interpreted was entered into the i-Tree Eco software. This programme is an adaptation model of Urban Forest Effects, which was developed jointly by individual programmes, public and private companies under the coordination of the US Forest Service.

After processing the data entered in I-Tree Eco tools, information was obtained on the results of evaluating individual ecosystem services (reducing pollutants, carbon uptake and sequestration, oxygen production, and avoided surface runoff) and the replacement cost for both plantings in general and for each tree in particular, in quantitative, qualitative, and cost terms in the form of reports, diagrams, and tables. In addition, I-Tree Eco tools allow exporting geographic information databases in commonly used formats .CSV or .KML, which opens up the possibility of further use of this information for the creation of electronic maps of ecosystem planting services. This feature was used to visualise the results obtained by exporting the geographic information database to the My-Maps (2023) application and presenting it as an

interactive plant map (MyMaps..., 2023). This map is publicly available and can be used by all interested parties to obtain information about the ecosystem services of each individual plant.

Results

According to the results of the survey, it was identified that the examined phytolandscapes are represented by 15 tree species, among which the most numerous are *Thuja occidentalis* L. (22.0% of the total population); *Larix decidua*

Mill. (19.3%), and *Betula pendula* Roth. (15,6%). The listed species together make up more than half of the plant in terms of quantity, and the remaining tree species are represented in the plantings by a share of no more than 8 per cent. Therewith, it should be noted the presence of individual specimens of large-sized plants, which, even with a small number in the composition of plantings, have a substantial impact on the functioning of the local ecosystem due to their biometric indicators (Table 1).

Table 1. Summary information about plant specimens with the highest biometric indicators

ID	Botanical name	Latitude, degrees	Longitude, degrees	Elevation, m	Landuse	DBH, cm	Crown Dieback, %	Height, m	Base height, m	Top height, m	Crown (NS), m	Crown (EW), m	Missing crown, %	Light exposure, category
18	<i>Populus Tremula</i>	49.428263	24.907438	338.3	park	143	38	37.2	6.5	30.7	15.3	17.3	48	3
16	<i>Fagus sylvatica</i>	49.428355	24.907541	337.6	park	121	28	37.2	3	34	17.6	15.7	18	3
87	<i>Fraxinus excelsior</i>	49.427987	24.90735	339.4	park	102	23	24	9	15	14.2	15.5	38	3
89	<i>Fraxinus excelsior</i>	49.427894	24.907109	338.9	park	92	43	26	8	18	12.8	14	28	5
76	<i>Acer negundo</i>	49.428224	24.906233	332.5	park	60	18	21	7	14	12.5	14.5	28	4

Notes: Light exposure is evaluated in five categories. Number of sides of the tree receiving sunlight from above (maximum of five). Top of tree is counted as one side

Source: compiled by the author

The area of the calculated (according to I-Tree Eco tools) projection cover of plant crowns is 0.5261 ha, which is 30.1% of the total area of the experimental base of the study and corresponds to 3.765 hectares of leaf area. These data allow concluding that under these experimental conditions, the leaf area of a park with an approximate tent closure of 0.3 exceeds the area of such an object by 2.2 times and the area of the projection cover of plant crowns by 7.2 times.

The results of processing the data entered in I-Tree Eco tools for evaluating individual

ecosystem services allowed for analysing of the amount of these utilities in both quantitative and monetised terms. In particular, analysing *the ability of green spaces to reduce the amount of harmful substances* in the biosphere, according to researchers D.J. Nowak *et al.* (2018), trees and shrubs can reduce the concentration of gaseous pollutants in the air by absorbing them with their leaves and needles. The experimental data obtained showed the ability of the examined park stands to extract 355.8 kilograms of pollutant gaseous substances from the air annually.

The monetised expression of this ecosystem green space service is estimated at the equivalent of UAH 66.08 thousand (€2,457). Notably, the calculations of this ecosystem service consider the current indicators of pollution in the study region and the specific features of local climatic conditions, which allows for increasing the accuracy of the results and adapting them to local conditions.

Analysis of annual dynamics (Fig. 1) and the total annual absorption of harmful gaseous substances by the examined park plantings showed that the highest value of pollutant extraction is characteristic of solid particles with a size of 2.5-10 microns (PM10) and sulfur di-

oxide (SO₂). This process was quite intense during the months of March and May, which is explained by the increased concentration of pollutants in the air according to local air pollution data and the intensive process of building up leaf biomass. In general, according to I-Tree Eco Tools, it was identified that the examined trees and shrubs are able to reduce air pollution with harmful compounds (ozone O₃, carbon monoxide CO, and nitrogen dioxide NO₂), and particles of substance size less than 2.5 microns (PM2.5) and 2.5-10 microns (PM10) per 355.8 kilograms of air pollution annually, which in monetised terms is 66.08 thousand UAH (2456.5€) annually.

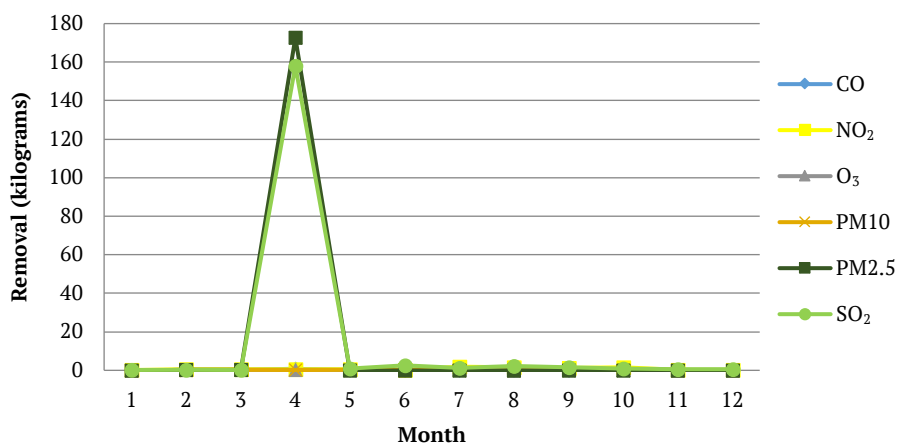


Figure 1. Dynamics of absorption of harmful substances by trees of the attached part of Rayivsky landscape park

Notes: CO – carbon monoxide; NO₂ – nitrogen dioxide; O₃ – ozone; PM10 – solid particles with a size of 2.5-10 microns; PM2.5 – particles with a substance size of less than 2.5 microns; SO₂ – sulfur dioxide

Source: compiled by the author

In addition, in 2022, the trees of the attached part of the Rayivsky landscape park provided the release of about 19.27 kilograms of volatile organic compounds (VOC) (5,881 kilograms of isoprene and 13.39 kg of monoterpenes). This ecosystem function is still difficult to express in a monetised form, but they play an important sanitary and hygienic role

due to their ability to destroy and suppress the spread and development of harmful microscopic fungi, pathogenic bacteria, and other forms of negative microorganisms. These compounds are also precursor chemicals for ozone formation. Notably, the release of VOCs into the atmosphere depends on the species composition of the plantation (the number

of phytoncidal species) and leaf biomass. According to i-Tree Eco Tools, more than 55% of volatile organic compound emissions are provided by the *Larix decidua* Mill. and *Populus Tremula* L. plants.

Another ecosystem service evaluated in this study was *the properties of green spaces for carbon storage and sequestration*. This function is particularly useful in the context of global climate change when phytolandscapes create

conditions to mitigate this change by sequestering carbon from carbon dioxide in their tissues. This property depends on the size and sanitary condition of trees and increases with the growth and development of plants. The gross annual volume of sequestration of trees in the attached part of Rayivskyy landscape park is about 1012 metric tonnes of carbon per year (Fig. 2), with the associated cost of 5.59 thousand UAH (€207.8).

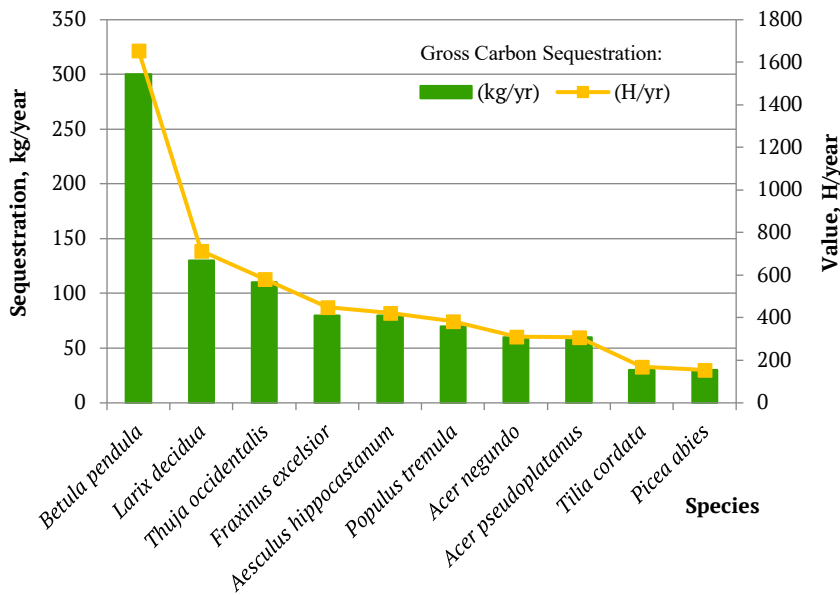


Figure 2. Estimated carbon sequestration and cost of this ecosystem service by main tree species for the attached part of Rayivskyy landscape park

Notes: the sequestration values in the chart are shown in columns, and the cost of ecosystem services is indicated by symbols

Source: compiled by the author

Another part of this ecosystem service for tree stands growing in the adjacent part of Rayivskyy landscape park is the ability to store carbon and its tissues throughout its life cycle. According to I-Tree Eco Tools, the examined plantings are able to store 48.3 metric tonnes of carbon in their tissues (Fig. 3). This ecosystem service is estimated by the programme at

267 thousand hryvnias (€9926). In the context of the experimental base of the study, it was identified that among all species, *Populus Tremula* L. stores the most carbon in its tissues (19.3% of total stored carbon), and *Betula pendula* Roth. is capable of the largest volumes of its sequestration (approximately 29.6% of the total carbon absorbed).

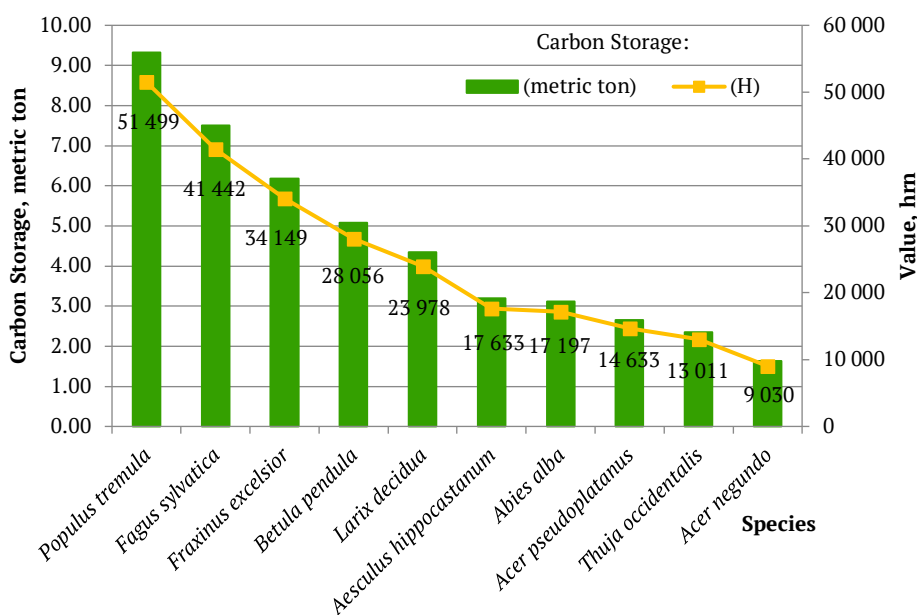


Figure 3. Carbon accumulation in tree tissues and the cost of this ecosystem service in the context of the main tree species for the attached part of Rayivskyy landscape park

Notes: the carbon storage values in the chart are shown in columns, and the cost of ecosystem services is indicated by symbols

Source: compiled by the author

The next important ecosystem service evaluated in this study was *the ability of green spaces to produce oxygen*. Although this service is most often mentioned in the context of useful functions of woody plants, this ecosystem function on a global scale is not so substantial compared to the production of oxygen by aquatic ecosystems (Liqoarobby *et al.*, 2021). However, at the local level, it requires research and evaluation to regulate the oxygen-carbon balance of urban ecosystems. According to i-Tree Eco Tools, the trees of the attached part of Rayivskyy land-

scape park produce 2,699 metric tonnes of oxygen per year for the plant under study. The highest amount of oxygen production among the trees of the experimental base of the study are achieved by the species prevailing in the park space: *Betula pendula* Roth., *Larix decidua* Mill., and *Thuja occidentalis* L. due to their substantial number (Table 2). Therewith, trees with the highest biometric indicators and a large leaf area are characterised by maximum individual oxygen productivity: *Fraxinus excelsior* L., *Aesculus hippocastanum* L., and *Populus Tremula* L.

Table 2. List of species with the highest oxygen productivity in 2022 (on the territory of the attached part of Rayivskyy landscape park)

No.	Species	Oxygen production, kg	Annual gross carbon uptake, kg	Number of trees	Leaf area, ha
1	<i>Betula pendula</i>	799.46	299.80	17	0.63
2	<i>Larix decidua</i>	345.09	129.41	21	0.44
3	<i>Thuja occidentalis</i>	280.73	105.27	24	0.33

Table 1, Continued

No.	Species	Oxygen production, kg	Annual gross carbon uptake, kg	Number of trees	Leaf area, ha
4	<i>Fraxinus excelsior</i>	216.24	81.09	2	0.21
5	<i>Aesculus hippocastanum</i>	203.63	76.36	6	0.50
6	<i>Populus tremula</i>	185.69	69.64	6	0.44
7	<i>Acer negundo</i>	149.77	56.16	2	0.13
8	<i>Acer pseudoplatanus</i>	149.39	56.02	3	0.09
9	<i>Tilia cordata</i>	81.33	30.50	3	0.09
10	<i>Abies alba</i>	74.61	27.98	8	0.09

Source: compiled by the author based on USDA Forest Service (2021)

Another ecosystem service that was evaluated in this paper was *the avoided runoff by green spaces*.

This ecosystem function is quite important for urban landscapes due to the ability of trees to reduce and regulate surface runoff by trapping some of the precipitation with their crowns, creating a mechanical barrier to water movement on the soil surface, and transferring external water movement into intra-soil runoff. Therewith, trees perform important

anti-erosion, protective, and water-regulating functions. The study allowed establishing that the trees of the attached part of the Rayivskyy landscape park annually help to avoid about 149 cubic meters of runoff, which is estimated by the i-Tree Eco Tools (Fig. 4) programme in the amount of 10 thousand UAH (€372) annually. These indicators are calculated based on local meteorological data (with annual precipitation of 91.9 centimetres) and biometric parameters of the park's trees.

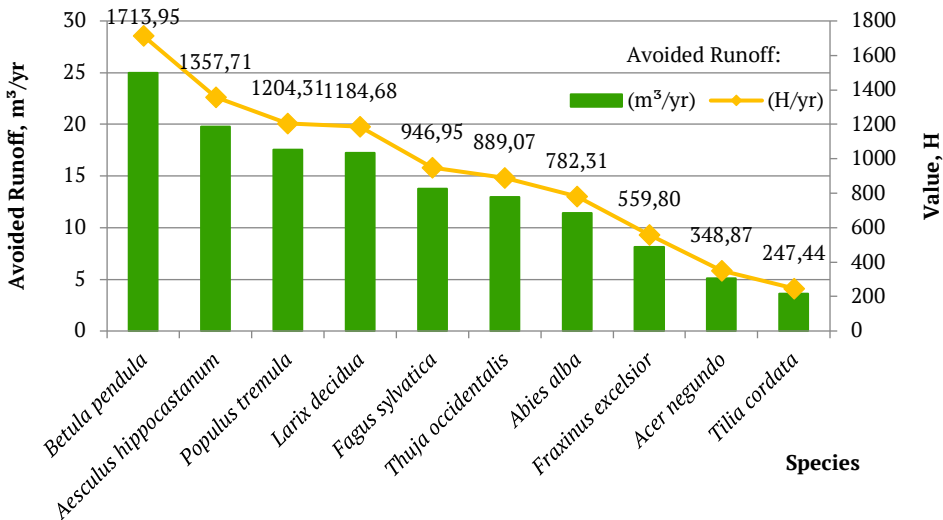


Figure 4. The amount of avoided runoff by tree species of the attached part of Rayivskyy landscape park and the cost of this ecosystem service

Notes: the values of the volume of surface runoff regulation in the chart are shown in columns, and the cost of ecosystem services is indicated by symbols

Source: compiled by the author based on USDA Forest Service (2021)

The replacement cost of green spaces is also an important indicator in the context of assessing the importance of plants for urban landscapes, because, according to the methodology (Order of the Ministry..., 2018), it should provide for the cost of creating and maintaining similar phytolandscapes, considering the characteristics that determine their value. In this case, the USDA Forest Service (2021) methodology has its advantages in the context of considering biometric indicators of

plantings, land use category, plant life status and ecosystem value, and local conditions. Therewith, the essence of the approach used in I-Tree Eco Tools is similar, and consists in calculating the potential cost of replacing a plant with a similar one, considering their functional importance. Plantings of the attached part of Rayivskyy landscape park, according to the i-Tree Eco Tool (Fig. 5), are estimated at 4486,464 thousand UAH (€166,783) of the total replacement cost of trees.

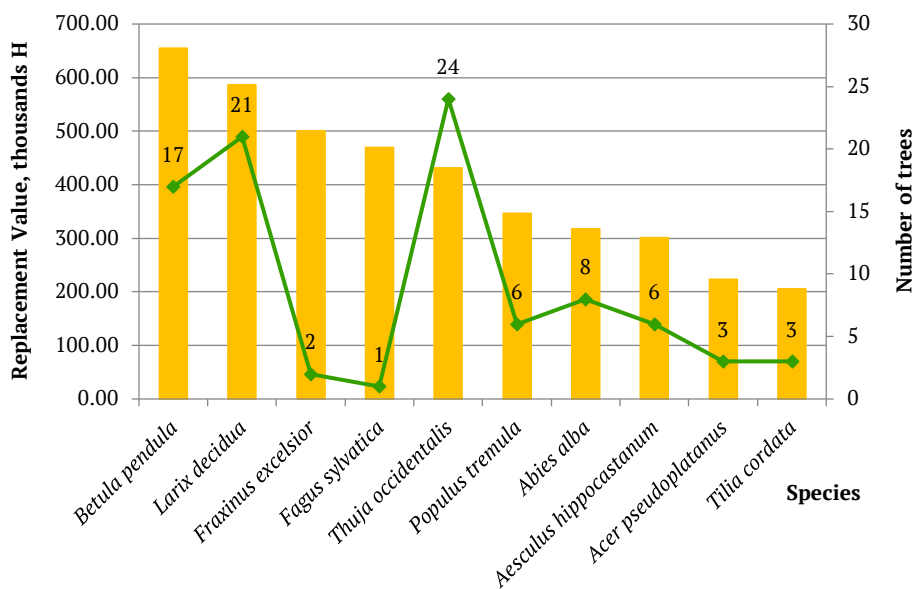


Figure 5. Tree species with the highest replacement cost of the attached part of Rayivskyy landscape park

Notes: the replacement cost values in the chart are shown in columns, and the number of trees of this type is indicated by symbols

Source: compiled by the author based on USDA Forest Service (2021)

Evaluating the entire list of ecosystem services examined in this paper and their replacement cost (Table. 3), the annual cost of the examined ecosystem services (Gross Carbon Sequestration, Avoided Runoff, and Pollution Removal) for the attached part of the Rayivskyy landscape park, in general, is 81894 UAH (€3044). That is, each tree in this park

annually produces an average of UAH 751.32 (€27.93) in the context of the examined three ecosystem services. In addition, the park space contains 48.26 carbon atoms in its tissues, which can be estimated at 266,662 thousand UAH (€9913.09). The total replacement cost of the examined plantings is 4486,464 thousand UAH (€166,783).

Table 3. Consolidated volumes and cost of ecosystem services for trees growing on the territory of the attached part of Rayivskyy landscape park

No.	Species	Trees Number	Carbon Storage		Gross Carbon Sequestration		Avoided Runoff		Pollution Removal		Replacement Value, H
			Metric ton	H	Metric ton/yr	H/yr	m ³ /yr	H/yr	Metric ton/yr	H/yr	
1	<i>Abies alba</i>	8	3.11	17197.36	0.02	133.90	11.39	782.31	0.03	5506.64	317060.27
2	<i>Acer negundo</i>	2	1.63	9029.90	0.06	310.34	5.08	348.87	0.01	1835.55	121792.24
3	<i>Acer pseudoplatanus</i>	3	2.65	14633.06	0.06	309.54	3.39	232.70	0.01	1835.55	223467.39
4	<i>Aesculus hippocastanum</i>	6	3.19	17632.75	0.08	421.95	19.77	1357.71	0.05	9177.74	301295.69
5	<i>Betula pendula</i>	17	5.08	28056.28	0.30	1656.57	24.95	1713.95	0.06	11013.29	654105.52
6	<i>Fagus sylvatica</i>	1	7.50	41442.15	0.00	1.37	13.79	946.95	0.03	5506.64	469030.21
7	<i>Fraxinus excelsior</i>	2	6.18	34148.54	0.08	448.07	8.15	559.80	0.02	3671.10	499858.47
8	<i>Larix decidua</i>	21	4.34	23978.28	0.13	715.07	17.25	1184.68	0.04	7342.19	586001.33
9	<i>Picea abies</i>	8	1.30	7178.70	0.03	154.60	3.47	238.02	0.01	1835.55	161943.25
10	<i>Pinus sylvestris</i>	2	0.19	1053.39	0.02	105.29	2.46	168.80	0.01	1835.55	66331.15
11	<i>Populus tremula</i>	6	9.32	51499.26	0.07	384.78	17.53	1204.31	0.04	7342.19	345879.45
12	<i>Quercus rubra</i>	2	0.45	2494.73	0.02	94.18	3.19	218.97	0.01	1835.55	79165.71
13	<i>Sorbus aucuparia</i>	4	0.08	421.67	0.02	107.74	1.85	127.14	0.00	0.00	24618.18
14	<i>Thuja occidentalis</i>	24	2.35	13011.36	0.11	581.70	12.94	889.07	0.03	5506.64	430959.52
15	<i>Tilia cordata</i>	3	0.88	4884.74	0.03	168.52	3.60	247.44	0.01	1835.55	204955.71
	Total	109	48.26	266662.18	1.01	5593.64	148.81	10220.73	0.36	66079.73	4486464.11

Notes: Tree species are listed in alphabetical order. Values of Carbon Storage and Replacement values are given for all plants of this species at the time of the study (2022). For ecosystem services Gross Carbon Sequestration, Avoided Runoff, and Pollution Removal are given annual data

Source: compiled by the author

Analysing the tree annual utility, its maximum value is characteristic of *Fagus sylvatica* L. (6455 UAH or €240), *Fraxinus excelsior* L. (2339 UAH or €87), and *Aesculus hippocastanum* L. (1826 UAH or €68). The lowest values of annual utility in the context of the examined indicators are typical for plants with low biometric indicators (*Sorbus aucuparia* L. and *Thuja occidentalis* L.). When assessing the sub-tree ecosystem value in terms of carbon storage and replacement cost, its highest indicator is characteristic of *Fagus sylvatica* L. – 510,472 thousand UAH (€18,977), *Fraxinus excelsior* L. 267,004 UAH (€9,926) and *Acer pseudoplatanus* L. – 79,367 UAH (€2,95).

Discussion

This analysis shows that typical forest and park tree species that can reach substantial sizes can perform the greatest number of ecosystem functions in the context of carbon storage and sequestration, oxygen production, pollution removal, and avoided runoff. The highest rates of replacement cost also characterise them, because it is extremely difficult to replace the ecosystem services of such large-sized trees, especially in a short period of time. This implies the importance of protecting and carefully caring for century-old trees, given their value for urban ecosystems. Other researchers agree with this conclusion (Piovesan *et al.*, 2022), which,

by investigating the importance of such plants for ecosystem restoration, identify them as an indispensable resource for preserving the forest and park environment.

However, on the other hand, it is necessary not to underestimate the value of small trees and shrubs, which are characterised by a much smaller feeding area and usually have higher decorative qualities, that is, they perform ecosystem functions of a different nature (decorative, aesthetic, cultural, and educational, etc.). Due to the complexity of cost estimation and quantitative expression, these services are often considered when determining the ecosystem value of plantings, but other researchers are already conducting studies in this direction (Vallecillo *et al.*, 2019). Therefore, green spaces are a rather complex biogeocenosis, in which each element performs its own important ecosystem services and requires proper attention and research.

In the course of the study, the feasibility of using one of the tools for assessing the cost of ecosystem functions of i-Tree Eco green spaces in the course of their inventory was tested on the example of the attached part of Rayivskyy landscape park. Based on the results of the study, it was established that the USDA Forest Service (2021) methodology is capable of integration not only into the US green space accounting system, but also into the methods of inventory of plantings in other countries (Raum *et al.*, 2019; Cimburova & Barton, 2020; Gong *et al.*, 2022), including, based on the results of this study, and in the national methodology for inventory of green spaces (Order of..., 2014) by measuring a number of additional biometric indicators of plants. This approach, even if the typical process of performing an inventory of trees and shrubs is slow and complicated, opens up new opportunities for obtaining important information about the ecosystem functions of plantings and the replacement cost of each plant.

When evaluating the possibility of adapting i-Tree Eco tools to local conditions, it is necessary to note that this toolkit uses a number of input national (current exchange rate and cost of basic energy resources) and local parameters (information on sources, volumes, and dynamics of pollution; information from the nearest meteorological stations on climate data of the region; the number of inhabitants of the locality, etc.). This approach creates conditions for assessing the quantitative and cost parameters of ecosystem services and adapting them to local climatic and economic conditions, considering other specific features of the territory for which the study is performed.

The disadvantages of the proposed approach include the need to enter information about the contamination of the study region in a special form and the need to perform additional measurements, which increases the complexity and duration of the examination. Therewith, the advantage of using i-Tree Eco tools when conducting an inventory of green spaces is the substantial volume, informative content and value of materials, various forms of presentation of results and new opportunities for further use. In particular, the possibility of automated preparation of reports, tabular, and graphic material for each plant, and for the species range, or for planting creates conditions for simplifying and improving the quality of further interpretation of the information received. The ability to obtain data on the implementation of ecosystem services in quantitative and monetised terms increases the information content of research results not only for researchers but also for territorial communities, state authorities, public organisations, and residents of localities. This approach, considering the existing experience of other researchers (Ly & Xiao, 2016; Raum *et al.*, 2019; Almenar *et al.*, 2023), should also improve the quality and validity of decision-making in the country regarding the

importance of protecting green spaces and performing regular care for them, the feasibility of replacing individual plants in plantings that cease to perform their ecosystem functions and the list of species that should be used in this case.

Under such conditions, an important area of use of the information obtained in this way is to bring it to a wide range of users. In this direction, according to the studies (Rocha *et al.*,

2015; Bidolakh, 2020; Mosyftiani *et al.*, 2022), visualisation of tree ecosystem services using interactive maps and mapping useful functions of plantings are effective. The use of the Google Mymaps (2023) application, in accordance with the above methodology, created conditions for communicating information about the ecosystem services of each park tree to each interested person in the form of an electronic map (Fig. 6).

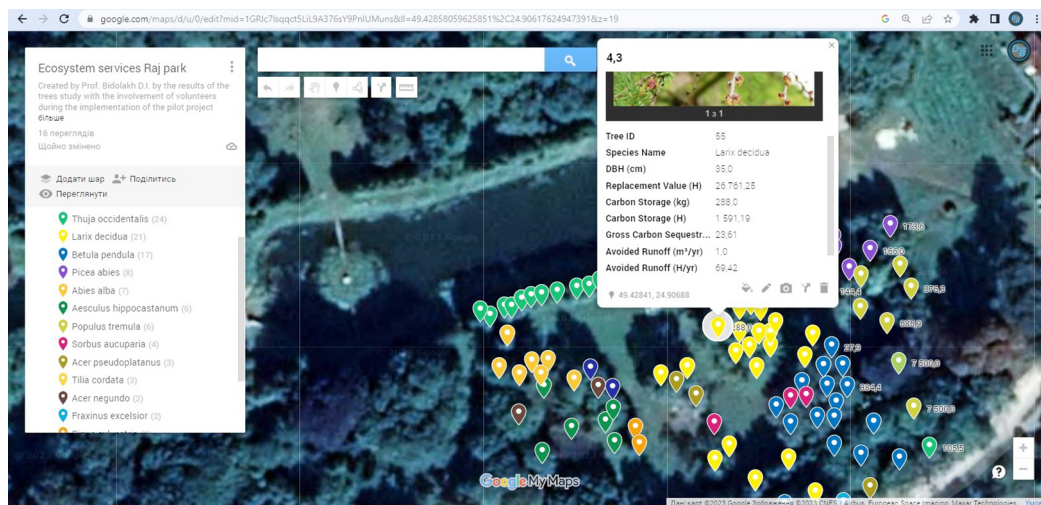


Figure 6. Interactive map of the number and cost of ecosystem services of green spaces on the territory of the attached part of Rayivskyy landscape park, Ternopil region

Source: developed by the author based on USDA Forest Service (2021), Mymaps Google (2023)

In addition, everyone who can be present in Rayivskyy landscape park has the opportunity to work with this application on their smartphone or other gadgets in interactive mode. If geolocation is enabled, the user can get information directly about each tree while being near it. The proposed approach, provided that it is used for other objects of improvement, will also increase the information content of residents of these settlements regarding the useful functions of each individual tree or bush for the urban environment, awareness of the value of green spaces, and increase ecological consciousness. In this context, the general trend of

increasing the number of studies and publications towards the need to ecologise social development is notable (Yang & Khan, 2021; Gaglio *et al.*, 2023; Stoeckl *et al.*, 2023). The researchers agree that the ongoing processes of economic growth, technological development, and urbanisation degrade the ecosystem sustainability of the environment and require the introduction of mechanisms and policies that, on the contrary, will contribute to raising the level of environmental awareness of the population. Under such conditions, the presented results of the study can not only increase the information content of the results of the inventory of

green spaces but also contribute to the process of greening social development in Ukraine.

Conclusions

The study allowed demonstrating the importance of assessing the ecosystem functions of green spaces when performing their inventory to ensure sustainable ecosystem development. One of the most promising tools in this regard is i-Tree Eco, which allows obtaining, interpreting, and further presenting information about the ecological and cost value of green spaces. The approbation performed in this study on the integration of this toolkit into the process of interpreting the results of measuring biometric and sanitary indicators of plants based on the results of their inventory showed the possibility and feasibility of such an approach, considering the value of the information received. The use of i-Tree Eco tools in this direction allows for determining the amount and cost of individual ecosystem services (Pollution removal, carbon storage and sequestration, oxygen production, and avoided runoff), evaluating the replacement cost of plants, analysing, and interpreting the information obtained. This approach improves the quality and validity of decision-making in the protection and use of natural resources.

The disadvantages of this process include the need to perform additional measurements, increase the complexity and duration of the examination. A substantial advantage of using i-Tree Eco tools during inventory management is the substantial volume, informative content, the value of materials, and various forms of presentation and interpretation of results. Creating interactive maps of the ecosystem utility of each tree to visualise information for a wide range of users is proposed, which will increase the ecological consciousness of residents.

The study also allowed establishing the annual cost of ecosystem utilities (in the context of the examined ones) for the attached part of Rayivskyy landscape park in the amount of 81894 UAH (€3044) and the total replacement cost of the examined plantings in the amount of 4486,464 thousand UAH (€166,783). Notably, species that can reach substantial sizes can perform the greatest number of ecosystem functions in the context of the examined indicators. Accordingly, they are characterised by the highest rates of replacement cost, which indicates the importance of their care and protection.

It should also be noted the importance of further research on the possibilities of attracting new tools and expanding the list of ecosystem benefits that will be examined during the inventory of green spaces.

Conflict of Interest

The author declares no conflict of interest.

Acknowledgement

The study was conducted with the involvement of volunteers during the implementation of the pilot project “Transparent and involving system of inventory of the green areas in Ukraine: iTree4UA” under the scientific guidance of the Department of Forestry and Landscape Park Management of the National University of Life and Environmental Sciences of Ukraine “Berezhany Agrotechnical Institute”. The author expresses gratitude to the participants-volunteers (teachers, students, and public figures) of the inventory for assistance in collecting field materials, and to the NGO “Kray” and “Green Wave” for assistance in collecting and entering information about pollution and climate indicators of the study region.

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Оцінка екосистемних функцій зелених насаджень, як важлива складова їх інвентаризації у контексті сталого розвитку урболандшафтів

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Анотація. Важливим напрямком досліджень у контексті забезпечення сталого розвитку урбоекосистем є опрацювання теоретичних та прикладних аспектів можливостей одержання інформації про екосистемну корисність зелених насаджень. Концепція оцінювання та оплати екопослуг, які продукують дерева та кущі для довкілля та суспільства характеризується значним міжнародним інтересом. У цьому контексті важливим є аналіз сучасного інструментарію та методик, які здатні адекватно визначати та оцінювати обсяги екосистемних послуг, що і стало головною метою дослідження. У цій роботі проведено апробацію можливості залучення інструментарію i-Tree Eco для кількісного та вартісного визначення обсягів створюваних парковими насадженнями екосистемних послуг до процесу інвентаризації зелених насаджень. Для цього, на прикладі приставкової частини Раївського парку Тернопільської області, проведено вимірювання біометричних та санітарних показників дерев під час їх інвентаризації, визначено ряд екосистемних послуг рослин (зменшення обсягів забруднюючих речовин, поглинання та секвестрація вуглецю, продукування кисню та регулювання поверхневого водного стоку), встановлено відновну вартість дерев, проаналізовано отримані дані, виконано інтерпретацію отриманої інформації у вигляді інтерактивної електронної карти а також визначено переваги і недоліки цього процесу. Проведене дослідження засвідчило, що вартість екосистемних послуг (у розрізі досліджених показників) для приставкової частини Раївського парку складає 81894 грн (€3044) на рік, а загальну відновну вартість дослідженого насадження становить 4486,464 тис. грн. (€166,783). Монетизований вираз екосистемної корисності цього насадження створює умови для покращення розуміння цінності фітоценозу для урболандшафтів. Практичною цінністю дослідження є можливість використання результатів для удосконалення та підвищення інформативності процесу інвентаризації зелених насаджень, шляхом одержання інформації про екосистемні послуги дерев у кількісному та вартісному виразі з метою підвищення обґрунтованості рішень у сфері природокористування

Ключові слова: монетизація корисності; відновна вартість дерев та кущів; i-Tree Eco; оздоровлення довкілля; вікові дерева