sciendo

Environmental & Socio-economic Studies

environ

DOI: 10.2478/environ-2022-0012

Environ. Socio.-econ. Stud., **2022, 10, 3: 1-11**

Original article

The value of air purification and carbon storage ecosystem services of park trees in Warsaw, Poland

Zbigniew Szkop

Faculty of Economic Sciences, University of Warsaw, Długa Street 44/50, 00-241 Warsaw, Poland
E–mail address: zszkop@wne.uw.edu.pl
ORCID iD: https://orcid.org/0000-0002-4102-4119

ABSTRACT

This study assessed, in monetary terms, the ecosystem services provided by trees growing in public parks and garden squares in Warsaw, Poland. It focused on the valuation of two services: air purification (measured as an annual benefit stream in EUR/year) and carbon storage (measured as a fixed value at a given point in time in EUR). The study was conducted using the Avoided Cost Method with i-Tree Eco software. The initial calculations were based on data obtained from 41 selected green spaces in Warsaw. Subsequently, the results were extrapolated to all public parks and garden squares. The findings indicate that the average economic value of the NO_2, SO_2 and $PM_{2.5}$ pollution removal ecosystem service provided by trees in Warsaw is around 3 EUR/tree/year. On average, one hectare of a public park in Warsaw provides this service at a value of 408 EUR/ha/year, while one hectare of a garden square provides this service at a value of 347 EUR/ha/year. With regards to the carbon storage ecosystem service, the results showed that the average economic value of this service is around 170 EUR/tree. On average, one hectare of a public park provides this service at a value of 22.4 thousand EUR/ha, and one hectare of a garden square provides this service at an average value of 18.9 thousand EUR/ha. By extrapolating these results, the total value of the air pollution removal ecosystem service provided by trees growing in all public parks and garden squares in Warsaw was estimated to range from 393 to 560 thousand EUR/year. The value of the carbon storage service ranges from 23.3 to 30.2 million EUR.

KEY WORDS: urban greenery, Avoided Cost Method, i-Tree Eco

ARTICLE HISTORY: received 1 May 2022; received in revised form 16 August 2022; accepted 19 August 2022

1. Introduction

The valuation of ecosystem services has a history dating back over a quarter of a century. The origin of this concept is usually associated with a paper by Robert Costanza and his team (Costanza et al., 1997), in which the term *ecosystem service* was defined as "the benefits people derive from an ecosystem". What the paper is arguably most famous for is the authors' attempt to assess, in monetary terms, the ecosystem services provided by nature worldwide. They estimated the value of the world's ecosystem services to be around 33 trillion USD per year – which was more than the global GDP at the time. The results of the study have been cited in some of the most prestigious scientific journals, such as Science (Roush, 1997). Likewise, it has been quoted by many renowned media outlets including the New York Times, Newsweek, Science News, National Public Radio, and the BBC (Costanza et al., 2017). The vast popularity of this paper contributed to an explosion of research and debates on valuing ecosystem services, that continues to this day.

Besides highlighting the importance of studying the monetary value of ecosystem services, Costanza and his team also made a first attempt at classifying ecosystem services – an important step in facilitating the comparison of results from different valuation studies. Their paper identified 17 types of ecosystem services. In subsequent research projects focusing on assessing ecosystem services (e.g., MEA, 2005; TEEB, 2010; CICES, 2013), the list proposed by

Costanza and his team has been expanded upon and made more specific. Nowadays, the CICES list (*Common International Classification of Ecosystem Services*) is the reference list used in many studies (HAINES-YOUNG & POTSCHIN, 2018). This is also the list officially recommended by institutions in the European Union for research purposes.

The current version of the CICES list (v5.1) includes 90 ecosystem services. Of course, not all these services can be provided by all types of ecosystems. For instance, the service "*provision of wild animals used as a source of energy*" could perhaps be provided by woodlands or oceans, but not urban trees. Nevertheless, the value provided by urban trees can easily be assigned to other services included in the CICES. Studies assessing the monetary value of these services found, among others:

- Trees provide raw materials such as fruits (CICES: 1.1.1.1) or wood fuels such as pellets or briquettes (CICES: 1.1.1.3) (e.g., VELÁZQUEZ-MARTÍ ET AL., 2013; VON HOFFEN & SÄUMEL, 2014);
- Trees supply transpiration and shading (CICES 2.2.6.2) (e.g., PAULEIT & DUHME, 2000; SHASHUA-BAR ET AL., 2009; BOWLER ET AL., 2010; TSIROS, 2010).
- Trees act as windbreaks (CICES 2.2.1.4) (e.g., HEISLER, 1986; DEWALLE & HEISLER, 1988; PEPER ET AL., 2007).
- Trees sequester and store carbon (CICES: 2.1.1.2) (e.g., MOULTON & RICHARDS, 1990; PEPER ET AL., 2007; SZKOP, 2019, 2021a).
- Trees control runoff (CICES 2.2.1.3) (e.g., XIAO ET AL., 1998; ROGERS ET AL., 2015; BERLAND ET AL., 2017; MOFFAT ET AL., 2017).
- Trees purify the air (CICES 2.1.1.2) (e.g., NOWAK ET AL., 2007; NOWAK ET AL., 2014; PEPER ET AL., 2007; SZKOP, 2016, 2020; ZAWOJSKA ET AL., 2016).
- Trees reduce noise pollution (CICES 2.1.2.2) and mask noise (CICES 2.1.2.3) (e.g., TAMURA, 1997).
- Trees have aesthetic (CICES 3.1.12) and recreational benefits (CICES 3.1.1.1) (e.g., BERTRAM ET AL., 2017; CHIESURA, 2004; ANDERSON & CORDELL, 1988; SUMMIT & SOMMER, 1999; BORKOWSKA ET AL., 2001; DONOVAN & BUTRY, 2010; GIERGICZNY & KRONENBERG, 2012; DIMKE ET AL., 2013; CZEMBROWSKI ET AL., 2016).

Evidently, trees provide a range of ecosystem services and many of them are of high economic value. It is important to conduct valuation studies, as quantification can raise environmental awareness and help policymakers to better manage urban greenery and achieve desired environmental improvements (RAUM ET AL., 2019). The study presented in this paper aimed to assess the value of the air purification and carbon storage ecosystem services provided by urban trees growing in Warsaw's public parks and garden squares.

2. State-of-the-art

The first step in the valuation of air purification and carbon storage ecosystem services is to estimate the amount of air pollutants removed by trees per year (g/year), as well as the total amount of carbon stored (kg). The second step is to estimate the costs that would have been incurred in the absence of these ecosystem services, i.e., how much more money would have to be spent on healthcare or fighting the harmful effects of climate change. This *Avoided Cost Method* is a well-established technique used to value ecosystem services by researchers across the globe.

An *in situ* study that aims to calculate the exact annual amount of pollutants absorbed by an individual tree growing in the city would be a very methodically complicated and capital-intensive process. The same is true for the carbon storage ecosystem service. When estimating the amount of carbon stored in tree tissues, it is found that about half of the dry mass of wood is made up of atmospheric carbon (NOWAK, 1994). However, when this is calculated for an individual tree, the tree is not removed, dried, and weighed to estimate how much carbon it has stored. Instead, models which were developed during studies under laboratory conditions are used to estimate these quantities (SZKOP, 2020a). The software tool i-Tree Eco can be used to estimate the amount of carbon stored in tree tissues (kg) and the annual amount of pollutants removed (kg/year) by an individual tree. By linking this data with the information about avoided costs due to the provision of ecosystem services, researchers can successfully estimate the economic value of such services.

The i-Tree Eco software was developed in the United States and has gained popularity abroad in recent years. Studies using this software have been performed in Canada (LEFRANÇOIS, 2015), Colombia (BAUTISTA & PEÑA-GUZMÁN, 2019), Mexico (DE LA CONCHA, 2017), Puerto Rico (MELÉNDEZ-ACKERMAN ET AL., 2018), the Dominican Republic (BAUER ET AL., 2016), Germany (SCHOLZ ET AL., 2018), Spain (CHAPARRO & TERRADAS, 2009; BARÓ ET AL., 2014), France (NOWAK, 2018), the Netherlands (MEDRANO, 2019), Portugal (GRAÇA ET AL., 2017), the United Kingdom (HUTCHINGS ET AL., 2012; ROGERS ET AL., 2015; DOICK ET AL., 2017; RAUM ET AL., 2019), Australia (BLAIR ET AL., 2017; GARDNER ET AL., 2017) and China (WU ET AL., 2019).

In addition to the countries listed above, this software has also been used to perform several studies in Poland. Among others, it has been used to estimate the value of air purification and carbon storage ecosystem services provided by trees growing in Krasińskich Garden in Warsaw (Szkop, 2016), trees growing in the Palace Park in Wilanow (Zawojska et al., 2016) and selected urban treen in the Wola district of Warsaw (Szkop, 2021a). However, these were rather small-scale studies and did not allow for the verification of obtained values being either significantly higher, or lower, than the average in the region.

To date, no studies to assess the economic value of air purification and carbon storage ecosystem services across all the public parks and garden squares of a large city have been conducted in central and eastern Europe – including Poland. Moreover, the results of the studies conducted in other regions of the world may not be valid for central and eastern Europe's spatial context, e.g., due to a difference in tree species composition. The presented study aims to fill this knowledge gap.

3. Study area

The i-Tree Eco software requires field data to estimate the amount of air pollutants absorbed by trees per year (g/year) and the amount of carbon they store (kg). Data that relate to the size, species, health condition and location of the analyzed trees were obtained from the Greenery Office of the Capital City of Warsaw (ZZW) (ZZW, 2021).

Data from 29,165 trees growing in 41 selected urban green spaces (14 public parks and 27 garden squares) in central Warsaw were used in the analysis. This covers an area of approximately 234 ha. The location of the individual analyzed trees within the city boundary (zoomed-out view) (Fig. 1), the location of the public parks/garden squares (zoomed-in view) (Fig. 2), and the names and sizes of these areas (Table 1) are shown below.

Table 1. Urban green areas included in the analysis

Location name	Area (ha)	Number of trees
Krasinski Garden	9.57	606
Agrykola Park	4.71	810
J. Porazinska Park	4.12	564
K. Beyer Park	2.28	270
Casimir Park	4.29	436
Marshal E. Rydz-Śmigły Park	32.85	5 518
Soviet Military Cemetery - Mausoleum Park	15.63	2 110
Mirowski Park	4.84	678
Morskie Oko Park	17.61	1 365
Praga Park	17.67	2 237
R. Traugutt Park	13.05	2 219
S. Żeromski Park	4.74	834
T. Mazowiecki Park	5.42	841
Mokotów Field	73.36	7 937
A. M. Bocheński garden square	0.75	87
Batalion AK "Miłosz" garden square	0.36	66
Batalion AK "Ruczaj" garden square	0.23	28
F. Mitterrand garden square	0.09	9
Fijewscy garden square	1.19	93
H. Hoovera garden square	0.21	15
J. Janicki garden square	0.93	163
J. Twardowski garden square	0.87	69
B. Kontrym "Żmudzina" garden square	0.41	35
R. Reagan garden square	0.42	45
Radio Matysiak Family garden square	0.82	102
S. Jankowski "Agatona" garden square	2.17	319
S. Orgelbrand garden square	1.36	194
W. Stus garden square	0.82	114
Zgrupowanie AK "Róg" garden square	0.45	52
B. Wodiczko garden square	2.51	199
Swiss Valley garden square	0.83	43
L. Strehl garden square	0.55	69
Grzybowski square	0.55	40
Piaseczyński canal garden square	2.67	476
Gnojną Górą garden square	2.51	182
Dąbrowski square	0.47	22
Nike monument garden square	1.02	75
Kawaleria street garden square	0.24	5
Kozia street garden square	0.59	61
Szara street garden square	0.16	36
Vistula Escarpment garden square	1.00	141
TOTAL	234.32	29 165

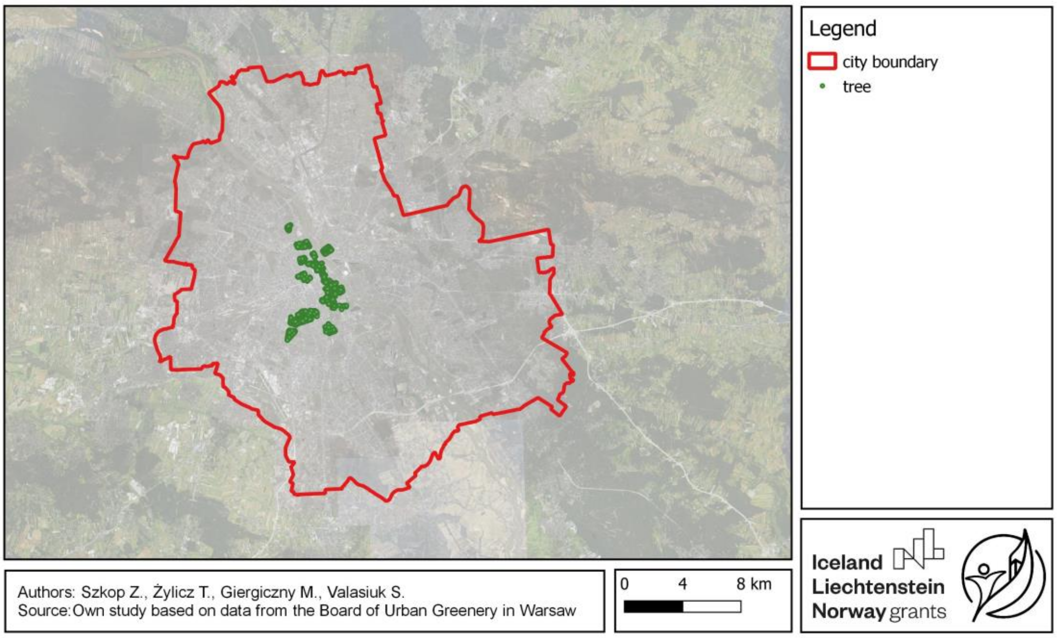

Fig. 1. Location of trees included in the analysis

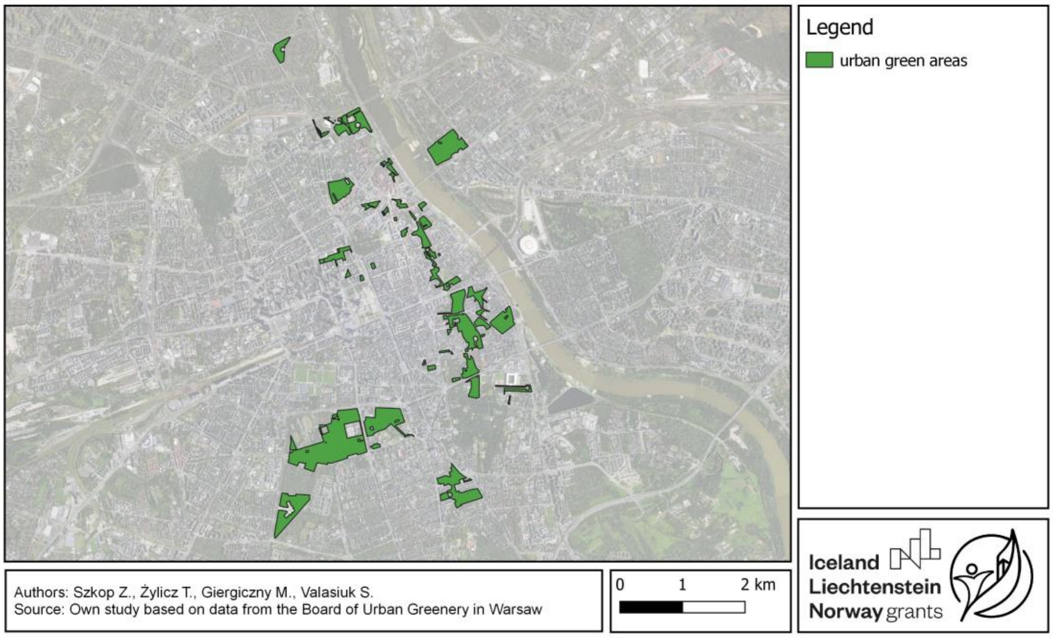

Fig. 2. Analyzed urban green areas

4. Method

The amount of air pollutants absorbed by the analyzed trees per year (g/year) and the amount of carbon they store (kg) were estimated using the i-Tree Eco software. The analysis focused on three air pollutants: SO_2, NO_2 and $PM_{2.5}$, as the software provides reliable estimates for these compounds. Once the air pollution removal and carbon storage ecosystem services were estimated in physical terms (units of mass), the ecosystem services were valuated (expressed in monetary terms). This was performed by evaluating the social costs that would have been incurred in the absence of these ecosystem services, i.e., the *Avoided Cost Method* approach.

The value of an ecosystem service is calculated by multiplying the obtained physical value of the service with the unit social cost. The unit social cost is an estimate of the economic costs, or damages, that would result when reducing the ecosystem service by one unit. For example, the unit social cost of a certain air pollutant, or CO_2, is equal to the cost of emitting one additional kg, or ton, of that substance into the atmosphere, indicating the potential benefit of reducing emissions by the same amount. These unit social costs depend on many factors and are therefore not easy to calculate. Fortunately, many long-term research projects have already determined such values for the substances included in the presented study.

In this study, the benefits of improving air quality by removing SO_2, NO_2 and $PM_{2.5}$ were calculated based on the unit social costs of these pollutants, which were estimated for various European research projects and summarized in the ExternE database (2005). ExternE's methodology determines the unit social costs using an "impact pathway" approach. This means analyzing a series of events linking each activity under consideration (e.g., the emission of an additional ton of SO_2) to its "effects" (e.g., impacts on human health, plants, physical assets, etc.) and then determining the monetary value of those impacts (e.g., the cost of treating diseases or renovation of building facades). The value of the unit social costs of air pollutants strongly depends, among other things, on how much of the population is exposed to the concentration of a given pollutant or what the costs of treating air pollution-related diseases are in a specific country. To take these factors into account, the ExternE project values calculated for urbanized areas in Poland were used in this study. These were: 18.26 EUR/kg of NO_2, 12.05 EUR/kg of SO_2, and 56.70 EUR/kg of $PM_{2.5}$ (at 2021 prices)[1].

The benefit of the carbon storage ecosystem service, as presented in the study, was calculated based on the unit social cost of carbon (SCC). This SCC value was determined by the Interagency Working Group on Social Cost of Greenhouse Gases, United States Government (IWG) (IWG, 2021). It shows the marginal cost of the impact caused by emitting one extra ton of CO_2 and is equal to 51.00 EUR/ton of CO_2 (162.22 EUR/ton of C)[2,3].

In this study, the air purification service is estimated as a stream of benefits (EUR/year or EUR/ha/year) and the carbon storage service as a fixed value (EUR or EUR/ha). This is a deliberate decision by the authors, as trees remove air pollution each year and these pollutants will never return to the atmosphere in the same form. Therefore, presenting this value as a stream of benefits is justified.

The matter is more complex when it comes to the carbon storage ecosystem service. Trees sequester carbon every year, but all, or most, of that carbon will return to the atmosphere when they die and decompose. Thus, how much carbon a tree has sequestered in a given year is less important than the total amount of carbon stored in its tissues. The carbon storage social cost is estimated for the removal of the tree and therefore the release of all the carbon it has stored. For that reason, presenting this service as a fixed value is justified.

After estimating the value of the ecosystem services provided by the 29,165 trees, for which the necessary parameters were available, the results were extrapolated to all public parks and garden squares in Warsaw. According to the information obtained from ZZW (ZZW, 2021), Warsaw is covered by 1013.7 ha of public parks and 207 ha of garden squares. Based on the analysis carried out for the trees growing in the selected 14 public parks and 27 garden squares, the lower (first quartile) and upper (third quartile) estimates per hectare were calculated for each of the two area types. These values were then multiplied by the total area of public parks and garden squares in Warsaw to estimate the total value of air purification and carbon storage ecosystem services provided by all its urban trees.

5. Results

The study showed that the 29,165 examined trees remove an estimated 3,503 kg of NO_2, 504 kg of $PM_{2.5}$, and 375 kg of SO_2 from the air each year. This service can be valued at approximately 91 thousand EUR/year. The average value of this service per tree is slightly more than 3 EUR/year. These urban trees store about 30 thousand tons of carbon in their tissues. If all the trees were cut down and the carbon stored in their tissues returned to the atmosphere as CO_2, it would result in a social cost estimated at approximately 5 million EUR. The average value of this service per tree is around 170 EUR. It should be noted that, unlike the pollution removal ecosystem service, this is not the value of an annual stream of avoided costs (or benefits), but rather a fixed benefit of avoiding the cost of tree removal at a given point in time. Detailed valuation results are presented in Table 2.

The value of ecosystem services such as air purification and carbon storage is related to the size of a tree, which is related to the age of a tree. As a rule, the age of trees in urban areas does not have a normal distribution. Warsaw is no exception, as there are a lot more younger trees than old ones. This is because many newly planted trees do not survive to maturity, due to harsh urban conditions. Therefore, presenting the data by referring to the median, first and third quartiles (Q1 and Q3) may be more informative. This information is presented in Table 3.

---

[1] The costs, originally estimated at 2010 rates, were recalculated in 2021 using the consumer price index (CPI). If the producer price index (PPI) was used, values would be 1.2% lower.

[2] The conversion factor used is: EUR 1 = USD 1.125

[3] After taking the atomic mass proportions of C and CO_2 into account

Table 2. Total and average economic values of the analyzed ecosystem services for the n=29,165 trees included in the analysis

Total				Average			
C (thous. of EUR)	NO_2 (thous. of EUR /year)	SO_2 (thous. of EUR /year)	$PM_{2.5}$ (thous. of EUR /year)	C (EUR/tree)	NO_2 (EUR/tree/ year)	SO_2 (EUR/tree/ year)	$PM_{2.5}$ (EUR/tree/ year)
4 964.3	64.0	6.1	21.3	170.2	2.2	0.2	0.7

Table 3. Economic value of the analyzed ecosystem services for the trees included in the n=29,165 analysis, expressed by quartiles

	C (EUR/tree)	NO_2 (EUR/tree/year)	SO_2 (EUR/tree/year)	$PM_{2.5}$ (EUR/tree/year)
Q1	27.1	0.6	0.1	0.2
Median	96.8	2.1	0.2	0.7
Q3	213.5	3.2	0.3	1.1

The median value of the air purification ecosystem service provided by the analyzed trees is very similar to the average value of 3 EUR/year. The value of this ecosystem service for half of the analyzed trees ranged from 0.9 to 4.6 EUR/year.

The median value of the carbon storage service provided by the analyzed trees is almost 97 EUR, therefore it is different from the average value. The value of this service for half of the analyzed trees ranged from 27.1 to 213.5 EUR.

These ecosystem service results were also investigated by type of area, and this is shown in Table 4 (public parks) and Table 5 (garden squares).

The study showed that the total value of the NO_2, SO_2 and $PM_{2.5}$ pollution removal ecosystem service provided by all trees growing in the analyzed public park areas in Warsaw, is around 83 thousand EUR/year. On average, one hectare of the public park areas in Warsaw provides an air purification service to the estimated value of 408 EUR/ha/year. The median value is 392 EUR/ha/year. The value for half of the analyzed public parks ranged between 340 (Q1) and 489 EUR/ha/year (Q3).

The carbon storage ecosystem service provided by the trees growing in these parks has a total estimated value of around 4.5 million EUR. On average, one hectare of public park area in Warsaw provides this service to the estimated value of 22.4 thousand EUR/ha. The median value is 22.2 thousand EUR/ha. The value for half of the analyzed public parks ranged between 20.3 (Q1) and 25.9 thousand EUR/ha (Q3).

Table 4. Economic value of the analyzed ecosystem services across 14 public parks in Warsaw

Public park name	C (thous. of EUR)	NO_2 (EUR/ year)	SO_2 (EUR/ year)	$PM_{2.5}$ (EUR/ year)	C (thous. of EUR/ha)	NO_2 (thous. of EUR/ ha/year)	SO_2 (thous. of EUR/ ha/year)	$PM_{2.5}$ (thous. of EUR/ ha/year)
Krasinski Garden	139.6	1 669	158.4	555	14.6	174.4	16.6	58
Agrykola Park	98.4	1 293	122.6	430	20.9	275	26	91.3
J. Porazinska Park	107.9	1 123	106.6	374	26.2	273	25.9	90.7
K. Beyer Park	53.1	626	59.4	208.1	23.3	274	26.1	91.3
Casimir Park	70.4	905	85.9	301	16.4	211	20	70.1
Marshal E. Rydz-Śmigły Park	896.3	11 900	1 129	3 957	27.3	362	34.4	120.5
Soviet Military Cemetery - Mausoleum Park	474.5	6 097	578	2 028	30.4	390	37	129.7
Mirowski Park	107.4	1 803	171.1	600	22.2	373	35.4	123.9
Morskie Oko Park	388.5	4 002	380	1 331	22.1	227	21.6	75.6
Praga Park	439.4	4 768	452	1 586	24.9	270	25.6	89.7
R. Traugutt Park	262.4	4 061	385	1 350	20.1	311	29.5	103.5
S. Żeromski Park	105.1	1 325	125.8	441	22.2	280	26.5	93
T. Mazowiecki Park	146.6	1 914	181.5	636	27.0	353	33.5	117.4
Mokotów Field	1205.6	16 514	1 567	5 491	16.4	225	21.4	74.9
TOTAL	4495.1	58 000	5 503	19 286				

Table 5. Economic value of the studied ecosystem services across 27 garden squares in Warsaw

Garden sqare name	C (thous. of EUR)	NO_2 (EUR/ year)	SO_2 (EUR/ year)	$PM_{2.5}$ (EUR/ year)	C (thous. of EUR/ha)	NO_2 (thous. of EUR/ ha/year)	SO_2 (thous. of EUR/ ha/year)	$PM_{2.5}$ (thous. of EUR/ ha/year)
A. M. Bocheński garden square	14.5	195.6	18.6	65.1	19.4	261	24.8	86.8
Batalion AK "Miłosz" garden square	7.6	132.5	12.6	44	21.1	368	35	122.2
Batalion AK "Ruczaj" garden square	3.7	51.1	4.8	17	15.9	222	20.9	73.9
F. Mitterrand garden square	2.5	36.9	3.5	12.3	27.4	410	38.9	136.7
Fijewscy garden square	8	91.5	8.7	30.4	6.7	76.9	7.3	25.5
H. Hoovera garden square	2.7	36.8	3.5	12.2	13	175.2	16.7	58.1
J. Janicki garden square	18.4	266	25.3	88.5	19.8	286	27.2	95.2
J. Twardowski garden square	19.6	169.3	16.1	56.3	22.5	194.6	18.5	64.7
B. Kontrym "Żmudzina" garden square	5.5	70.9	6.7	23.6	13.3	172.9	16.3	57.6
R. Reagan garden square	13.3	151.5	14.4	50.4	31.6	361	34.3	120
Radio Matysiak Family garden square	16.8	214	20.3	71.1	20.5	261	24.8	86.7
S. Jankowski "Agatona" garden square	57.7	836.5	79.4	278	26.6	386	36.6	128.2
S. Orgelbrand garden square	16.6	168.5	16	56	12.2	123.9	11.8	41.2
W. Stus garden square	25.1	372	35.3	123.7	30.6	454	43	150.9
Zgrupowanie AK "Róg" garden square	13.5	142	13.5	47.2	30.1	316	30	104.9
B. Wodiczko garden square	61.8	528	50.1	175.5	24.6	210.2	20	69.9
Swiss Valley garden square	15.1	163.9	15.5	54.5	18.2	197.5	18.7	65.7
L. Strehl garden square	11.6	155.4	14.7	51.7	21.1	283	26.7	94
Grzybowski square	2.8	48.4	4.6	16.1	5.2	88	8.4	29.3
Piaseczyński canal garden square	68	1 222	115.9	406	25.5	458	43.4	152.2
Gnojną Górą garden square	31.3	299	28.4	99.5	12.5	119.3	11.3	39.6
Dąbrowski square	3.8	52	4.9	17.3	8.1	110.6	10.4	36.8
Nike monument garden square	18.2	162	15.4	53.9	17.8	158.8	15.1	52.8
Kawaleria street garden square	0	0.4	0	0.1	0	1.7	0	0.4
Kozia street garden square	9.8	99.6	9.5	33.1	16.5	168.8	16.1	56.1
Szara street garden square	5.2	76.7	7.3	25.5	32.8	479.4	45.6	159.4
Vistula Escarpment garden square	16.1	217	20.6	72.2	16.1	217	20.6	72.2
TOTAL	469	5 960	566	1 982				

It was found that the total value of the NO_2, SO_2 and $PM_{2.5}$ pollution removal ecosystem service provided by all trees growing on the analyzed garden squares in Warsaw, is around 9.4 thousand EUR/year. On average, one hectare of garden squares in Warsaw provides this service to the estimated value of 347 EUR/ha/year. The median value is 310 EUR/ha/year. The value for half of the analyzed garden squares ranged between 234 (Q1) and 483 EUR/ha/year (Q3).

The carbon storage ecosystem service provided by the trees growing on these squares has a total estimated value of around 0.5 million EUR. On average, one hectare of garden squares in Warsaw provides a carbon storage service to the estimated value of 18.9 thousand EUR/ha. The median value is 19.4 thousand EUR/ha. The value for half of the analyzed public parks ranged between 13.1 (Q1) and 25.1 thousand EUR/ha (Q3).

The study covered an area of 14 public parks and 27 garden squares with a total size of around 234.3 ha. This constitutes less than 20% of the total area of Warsaw's public parks and garden squares, as public parks in Warsaw cover 1013.7 ha and garden squares cover 207.0 ha (ZZW, 2021). The values[4] (EUR/ha or EUR/ha/year) obtained for the selected public parks and garden squares were thus extrapolated to represent the total area of public parks and garden squares in Warsaw, as shown in Table 6.

[4] First and third quartiles (Q1 and Q3) were used to set a range for a lower and upper estimate

Table 6. Results of data extrapolation for the whole of the Warsaw area

	All public parks in Warsaw				All garden squares in Warsaw			
	C (millions of EUR)	NO_2 (thous. of EUR/year)	SO_2 (thous. of EUR/year)	$PM_{2.5}$ (thous. of EUR/year)	C (millions of EUR)	NO_2 (thous. of EUR/year)	SO_2 (thous. of EUR/year)	$PM_{2.5}$ (thous. of EUR/year)
Lower estimate (Q1)	20.6	241.1	22.9	80.2	2.7	33.9	3.2	11.3
Upper estimate (Q2)	26.2	347.2	32.9	115.5	4.0	44.9	4.3	15.0
Average of Q1 and Q2	23.4	294.2	27.9	97.9	3.4	39.4	3.8	13.1

The results suggest that the total value of the NO_2, SO_2 and $PM_{2.5}$ air purification ecosystem service provided by all trees growing in public parks and garden squares in Warsaw, is between 393 and 560 thousand EUR/year. The value of the carbon storage service provided by these trees is between EUR 23.3 million and EUR 30.3 million.

6. Conclusions and recommendations

This study assessed the monetary value of ecosystem services provided by trees growing in public parks and garden squares in Warsaw. It focused on two ecosystem services: carbon storage and air purification. To conduct the valuation, the *Avoided Cost Method* together with i-Tree Eco software was used. This approach to valuation has been used in many studies across the globe, as well as in Poland. Among others, it has been used to estimate the value of air purification and carbon storage ecosystem services provided by trees growing in: the Krasińskich Garden in Warsaw (Szkop, 2016), the Palace Park in Wilanów (Zawojska et al., 2016) and selected urban trees in the Wola district of Warsaw (Szkop, 2021a). The results obtained in this study are consistent, in order of magnitude, with these previous studies. Unfortunately, the previous studies were small-scale and did not allow for the verification of values being either significantly higher, or lower, than the average for the region. The presented study improves on this, by conducting valuations on a much larger sample of 41 areas with trees (14 public parks and 27 garden squares) in Warsaw.

The findings presented here showed that, on average, one hectare of the public park in Warsaw provides an air purification ecosystem service to the value of 408 EUR/ha/year, while one hectare of garden square provides this service to the value of 347 EUR/ha/year. Regarding the carbon storage ecosystem service, it was found that one hectare of public park provides this service at an average value of 22.4 thousand EUR/ha and one hectare of garden square provides this service at an average value of 18.9 thousand EUR/ha. By extrapolating these results to represent the entire city, it was estimated that the total monetary value of the air purification ecosystem service provided by trees growing in all public parks and garden squares in Warsaw, ranges from 393 to 560 thousand EUR/year. The value of the carbon storage service ranges from 23.3 to 30.2 million EUR.

To date, no previous studies have estimated the economic value of air purification and carbon storage ecosystem services for such a large urban area. This applies not only to Poland, but also to the entire region of central and eastern Europe. This knowledge gap was identified and filled by the results of the presented study. Other researchers and decision-makers can now successfully use these findings to estimate the approximate monetary value of selected ecosystem services provided by public parks and garden squares in other central and eastern European cities. To facilitate this application, the results presented in this study were given values in units per hectare (EUR/ha or EUR/ha/year) and lower and upper estimates (Q1 and Q3) were also shown.

When interpreting the results of the conducted monetary valuation, one should bear in mind the study's main limitation. Though it is the largest of its kind to be conducted in Poland and in central and eastern Europe, the results provide only fragmentary information on the value of ecosystem services provided by urban trees in a large city. This is because:

1) The study did not cover the air purification ecosystem service fully. It focused on NO_2, SO_2 and $PM_{2.5}$ pollutant removal, while the removal of other pollutants such as O_3 or PM_{10} was not investigated. This is due to the methodological issues of such an investigation, i.e., the lack of reliable pollutant removal models and information on the pollutants' unit social costs – both of which are needed to perform the *Avoided Cost Method* valuation process.

2) The study focused only on public parks and garden squares, when many other urban green spaces were omitted. These include street trees, housing estate greenery, urban forests, cemeteries,

allotment gardens and private gardens, to name a few. This means that the total value of air purification and carbon storage ecosystem services would be much higher if calculated for all green spaces in the city.

3) The study focused only on two ecosystem services, while trees provide a range of ecosystem services. Services that were not investigated include supplying raw materials, transpiration and shading, windbreak, runoff control, the reduction of noise pollution and noise masking, as well as aesthetic and recreational benefits. The latter service should especially be investigated, as existing international studies (BERTRAM ET AL., 2017; CHIESURA, 2004) indicate that recreation benefits could be much higher than the benefits from other ecosystem services provided by urban trees.

Notwithstanding the above-mentioned limitations, it should be noted that the presented study is an essential first step towards estimating the broadest possible range of ecosystem services provided by urban ecosystems in central and eastern European cities, but the topic requires further investigation. Future studies should aim to cover the air purification ecosystem service fully, by taking into account more pollutants. Other than just public parks and garden squares, a broader focus on more urban green spaces is also necessary. Finally, ecosystem services other than the air purification and carbon storage provided by urban trees, should also be assessed.

Acknowledgments

This research was funded by a grant from the EEA Grants (ZP/2235/U/20). The author would like to express his appreciation and gratitude to Prof. Tomasz Żylicz and Prof. Marek Giergiczny from the Faculty of Economic Sciences at the University of Warsaw, who helped him during this study.

References

Anderson L.M., Cordell H.K. 1988. Influence of trees on residential property values in Athens. Gerogia (U.S.A.): a survey based on actual sales prices. *Landscape and Urban Planning*, 15: 153–164.

Baldocchi D.D., Hicks B.B., Camara P. 1987. A canopy stomatal resistance model for gaseous deposition to vegetated surfaces. *Atmospheric Environment*, 21: 91–101.

Bauer J., Pérez M.E., Olivero S. 2016. *i-Tree urban forest assessment in Santo Domingo's Colonial City*. Technical Report. Santo Domingo.

Bautista D., Peña-Guzmán C. 2019. Simulating the hydrological impact of green roof use and an increase in green areas in an urban catchment with i-tree: A case study with the town of Fontibón in Bogotá. *Colombia Resources*, 8: 68.

Berland A., Shiflett S., Shuster W., Garmestani A., Goddard H., Herrmann D., Hopton M. 2017. The role of trees in urban stormwater managemant. *Landscape and Urban Planning*, 162: 167–177.

Bertram C., Meyerhoff J., Rehdanz K., Wüstemann H. 2017. Differences in the recreational value of urban parks between weekdays and weekends: A discrete choice analysis. *Landscape and Urban Planning*, 159: 5–14.

Blair J., Roldan C., Ghosh S., Yung S.H. 2017. Greening Rail Infrastructure for Carbon Benefits. *Procedia Engineering*, 180: 1716–1724.

Borkowska M., Rozwadowska M., Śleszyński J., Żylicz T. 2001. Environmental Amenities on Housing Market in Warsaw: Hedonic Price Method Research. *Ekonomia* 3: 70–82.

Bowler D., Buyung-Ali L., Knight T., Pullin A. 2010. Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landscape and Urban Planning*, 97: 147–155.

Chaparro L., Terradas J. 2009. *Ecological services of urban forest in Barcelona*. Technical Report. Ballaterra.

Chiesura A. 2004. The role of urban parks for the sustainable city. *Landscape and Urban Planning*, 68: 129–138.

CICES (Common International Classification of Ecosystem Services). 2013. *Towards a common classification of ecosystem services*.

Costanza R., D'Arge R., Groot R.D., Faber S., Grasso M., Hannon B., Limburg K., Naeem S., O'Neill RV., Paruelo J., Raskin RG., Sutton P., Van den Belt M. 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387: 253–260.

Costanza R., Groot R.D., Braat L., Kubiszewski I., Fioramonti L., Sutton P., Farber S., Grasso M. 2017. Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosystem Services*, 28: 1–16.

Costanza R., Groot R.D., Sutton P., Ploeg S., Anderson S.J., Kubiszewski I., Farber S., Turner R.K. 2014. Changes in the global value of ecosystem services. *Global Environmental Change*, 26: 152–158.

Czembrowski P., Kronenberg J., Czepkiewicz M. 2016. Integrating non-monetary and monetary valuation methods - SoftGIS and hedonic pricing. *Ecological Economics*, 130: 166–175.

De la Concha H. 2017. *Inventario del Arbolado Urbano de la ciudad de Mérida*. Technical Report. Mérida.

Dewalle D., Heisler G. 1988. Use of Windbreaks for Home Energy Conservation. *Agriculture Ecosystems and Environment*, 22: 243–260.

Dimke K.C., Sydnor T.D., Gardner D.S. 2013. The effect of landscape trees on residential property values of six communities in Cincinnati. Ohio. *Arboriculture and Urban Forestry*, 39: 49–55.

Doick K., Handley P., Ashwood F., Vaz Monteiro M., Frediani K., Rogers K. 2017. *Valuing Edinburgh's Urban Trees. An update to the 2017 i-Tree Eco survey – a report of Edinburgh City Council and Forestry Commission Scotland*. Technical Report. Farnham.

Donovan G.H., Butry D.T. 2010. Trees in the city: valuing street trees in Portland. Oregon. *Landscape Urban Planning*, 94: 77–83.

ExternE (External Costs of Energy). 2005. ExternE - Externalities of Energy Methodology. Available at http://www.externe.info/externe_d7/

Gardner J., McDuie M., Boyle E. 2017. *Valuing the Waite Arboretum. South Australia*. Technical Report. Adelaide.

Giergiczny M., Kronenberg J. 2012. Jak wycenić wartość przyrody w mieście? Wycena drzew przyulicznych w centrum Łodzi. [in:] T. Bergier. J. Kronenberg (ed.) *Przyroda w mieście. Usługi ekosystemów - niewykorzystany potencjał miast.* Polish TEEB guide for cities. Sendzimir Foundation. Cracow.

Graça M.S., Gonçalves J.F., Alves P.J.M., Nowak D.J., Hoehn R., Ellis A., Farinha-Marques P., Cunha M. 2017. Assessing mismatches in ecosystem services proficiency across the urban fabric of Porto (Portugal): The influence of structural and socioeconomic variables. *Ecosystem Services*, 23: 82–93.

Heisler O.M. 1986. Effects of individual trees on the solar radiation climate of small buildings. *Urban Ecology*, 9: 337–359.

Hutchings T., Lawrence V., Brunt A. 2012. *Estimating the Ecosystem Services Value of Edinburgh's Trees*. Technical Report. Farnham

IWG (Interagency Working Group). 2021. *Technical Support Document: Social Cost of Carbon. Methane. and Nitrous Oxide Interim Estimates under Executive Order 13990.* United States Government. Available at https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

Kiss M., Takács Á., Pogácsás R., Gulyás Á. 2015. The role of ecosystem services in climate and air quality in urban areas: Evaluating carbon sequestration and air pollution removal by street and park trees in Szeged (Hungary). *Moravian Geographical Reports*, 23: 36–46.

Lefrançois C.B. 2015. *Designing effective stormwater management policies : The role of the urban forest and impervious cover in Vancouver* (B.C. Master Thesis). The UBC School of Community and Regional Planning. Vancouver.

MEA (Millennium Ecosystem Assessment). 2005. Ecosystems and Human Wellbeing: Synthesis. Island Press.

Medrano O.A. 2019. *Measuring the benefits of urban nature-based solutions through quantitative assessment tools* (Master Thesis). Universiteit Utrecht, Utrecht.

Meléndez-Ackerman E., Trujillo A., Nytch C., Ramse M., Branoff B., Olivero-Lora S. 2018. *Ecological vulnerability of urban green infrastructure to Hurricanes Irma and Maria in Puerto Rico*. Technical Report. Puerto Rico.

Moffat A.J., Doick K.J., Handley P. 2017. *Petersfield's trees - their importance and value. Results of the i-Tree Eco survey. Technical Report. Report to East Hampshire District Council. South Downs National Park Authority and Petersfield Town Council*. The Petersfield Society. Petersfield.

Moulton R., Richards K. 1990. *Costs of Sequestering Carbon through Tree Planting and Forest Management in the United States*. General Technical Report WO-58. U.S. Department of Agriculture. Washington. D.C.

Na H.R., Heisler G.M., Nowak D.J., Grant R.H. 2014. Modeling of urban trees' effects on reducing human exposure to UV radiation in Seoul. Korea. *Urban Forestry and Urban Greening*, 13, 4: 785–792.

Nowak D., Hoehn R., Crane D., Stevens J., Walton J. 2007. *Philadelphia's Urban Forest. Assessing Urban Forest Effects and Values*. Technical Report. USDA Forest Service. Northern Research Station. Philadelphia.

Nowak D.J. 1994. Atmospheric carbon dioxide reduction by Chicago's urban forest. [in:] E.G. McPherson, D.J Nowak; R.A. Rowntree (eds.) *Chicago's urban forest ecosystem: results of the Chicago Urban Forest Climate Project. General Technical Report. NE-186*. Radnor. PA: U.S. Department of Agriculture. Forest Service. Northeastern Forest Experiment Station: 83–94.

Nowak D.J. 1996. Estimating leaf area and leaf biomass of open-grown deciduous urban trees. *Forest Science*, 42, 4: 504–507.

Nowak D.J. 2018. Améliorer les forêts citadines à travers l'évaluation. la modélisation et le suivi. *Unasylva*, 69: 30–36.

Nowak D.J., McHale P.J., Ibarra M., Crane D., Stevens J., Luley C. 1998. Modeling the effects of urban vegetation on air pollution. [in:] S.E. Gryning, N. Chaumerliac (ed.) *Air pollution modeling and its application*. Plenum Press. New York.

Pauleit S., Duhme F. 2000. Assessing the Environmental Performance of Land Cover Types for Urban Planning. *Landscape and Urban Planning*, 52, 1: 1–20.

Peper P.J., McPherson E.G., Simpson J.R., Gardner S.L., Vargsas K.E., Xiao Q. 2007. *Municipal Forest Resource Analysis. Technical Report*. USDA Forest Service. Pacific Southwest Research Station, New York City.

Raum S., Hand K., Hall C., Edwards D., O'Brien L., Doick K. 2019. Achieving impact from ecosystem assessment and valuation of urban greenspace: The case of i-Tree Eco in Great Britain. *Landscape and Urban Planning*, 190: 1–17.

Rogers K., Sacre K., Goodenough J., Doick K. 2015. *Valuing London's Urban Forest - Results of the London i-Tree Eco Project. Technical Report*. Treeconomics, London.

Roush W. 1997. Putting a price tag on nature's bounty. *Science*, 276(5315): 1029.

Scholz T., Hof A., Schmitt T. 2018. Cooling effects and regulating ecosystem services provided by urban trees - Novel analysis approaches using urban tree cadastre data. *Sustainability*, 10: 712.

Shashua-Bar L., Erell E., Pearlmutter D. 2009. The cooling efficiency of urban landscape strategies in a hot dry climate. *Landscape and Urban Planning*, 92: 179–186.

Summit J., Sommer R. 1999. Further studiem of preferred tree shapes. *Environmental Behavior*, 31: 550–576.

Szkop Z. 2016. An evaluation of the ecosystem services provided by urban trees: The role of Krasiński Gardens in air quality and human health in Warsaw (Poland). *Environmental and Socio-economic Studies*, 4, 4: 41–50.

Szkop Z. 2019. *Wycena usług ekosystemowych świadczonych przez wybrane drzewa miejskie w Rzeszowie*. Technical report prepared for the "EKOSKOP" association for the needs of an educational campaign carried out by the Marshal's Office of the Podkarpackie Voivodeship, Rzeszów.

Szkop Z. 2020a. Evaluating the sensitivity of the i-Tree Eco pollution model to different pollution data inputs: a case study from Warsaw. *Poland. Urban Forestry & Urban Greening*, 55: 126859.

Szkop Z. 2020b. *Wartość ekonomiczna usług świadczonych przez drzewa miejskie. Problem optymalnego zarządzania zielenią miejską (PhD thesis)*. Faculty of Economic Sciences of the University of Warsaw, Warsaw.

Szkop Z. 2021a. *Ocena i wycena usług ekosystemowych w wybranym obszarze miasta stołecznego Warszawy na podstawie danych dostarczonych przez zleceniodawcę*. Technical Report prepared by dr. Zbigniew Szkop at the request of the Warsaw University of Life Sciences, Warsaw.

Szkop Z. 2021b. The problem of suboptimal composition of urban trees in Warsaw. *Urban Forestry & Urban Greening*, 62: 127127.

Tamura A. 1997. Effects of landscaping on the feeling of annoyance of a space. [in:] A. Schick, M. Klatte (eds.) *Contributions to psychological acoustics: Results of the seventh Oldenburg symposium on psychological acoustics*. Universität Oldenbulg, Oldenbulg.

TEEB (Economics of Ecosystems and Biodiversity). 2010. *Mainstreaming the Economics of Nature: A Synthesis of the Approach. Conclusions and Recommendations of TEEB*.

Tsiros I. 2010. Assessment and energy implications of street air temperature cooling by shade trees in Athens (Greece) under extremely hot weather conditions. *Renuable Energy*, 35, 8: 1866–1869.

Velazquez-Marti B., Sajdak M., Lopez-Cortes I. 2013. Available residual biomass obtained from pruning Morus alba L. trees cultivated in urban forest. *Renuable Energy*, 60: 27–33.

Von Hoffen L.P., Samuel I. 2014. Orchards for edible cities: cadmium and lead content in nuts. berries. pome and stone fruits harvested within the inner city neighbourhoods in Berlin. Germany. *Ecotoxicology and Environmental Safety*, 101: 233–239.

Wu. J., Wang Y., Qiu S., Peng J. 2019. Using the modified i-Tree Eco model to quantify air pollution removal by urban vegetation. *Science of the Total Environment*, 688: 673–683.
Xiao. Q., McPherson E.G., Simpson J.R., Ustin S.L. 1998. Rainfall interception by Sacramento's urban forest. *Journal of Arboriculture*, 24, 4: 235–244.
Zawojska E., Szkop Z., Czajkowski. M., Żylicz. T. 2016. Economic valuation of ecosystem services provided by the Palace Park in Wilanow. A benefit transfer study. *Economics and Environment*, 59: 143–153.
Żylicz T. 2017. Wycena drzew miejskich. *Aura*, 11: 16–17.
Żylicz T. 2018. Czy ekosystemy świadczą usługi. *Aura*, 1:19–20.
ZZW (Zarząd Zieleni Warszawy). 2021. *Data provided by the Warsaw City Hall* – Urban Greenery Office. Warsaw.