Case study - Identification of significant escosystem services' synergies, trade-offs and bundles

Urban ecosystems

12.2022

Services provided by main types of ecosystems in Poland

- an applied approach

The project 'Services provided by main types of ecosystems in Poland - an applied approach' received funding from Iceland, Liechtenstein and Norway within the EEA Financial Mechanism 2014-2021 in the amount of 1,489,999 EUR, and from budget of Poland in the amount of 262,941 EUR. The aims of the project are transferring of scientific knowledge on ecosystem services which exists in Europe to the process of mapping and assessment of ecosystem services in Poland, as well as increasing the scientific potential and the ability of administration and interested social groups to implement this approach in environmental management.

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Summary Report

Identification of significant interactions of ecosystem services and relevant bundles of services on the example of Warsaw's urban ecosystem subtypes

Report prepared for the Project Coordinator - Adam Mickiewicz University in Poznań

Usługi świadczone przez główne typy ekosystemów w Polsce – Podejście Stosowane
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1. INTRODUCTION

In a rapidly urbanising world, the concentration of population in cities has made them the main centres of demand for ecosystem services. They therefore represent places of strong human impact on the environment (Degórski et al., 2022). In future, both the demand for ecosystem services and the pressure on urban ecosystems will intensify as cities grow spatially and demographically (Berry, 1990; Degórska, 2017). Urbanisation is therefore a fundamental challenge for sustainable development. It requires innovative forms of design and management of urban ecosystems in order to secure their capacity to maintain ecosystem services and to be resilient to change. Green and blue infrastructure is increasingly recognised as a component of urban space that plays a key role in ensuring the well-being of citizens and in mitigating and adapting cities to climate change, as well as in coping with other global changes and threats (Depietri et al., 2012). Urban ecosystems can simultaneously generate multiple ecosystem services, synergistically enhancing human well-being, making investment in green infrastructure very important (Elmqvist et al., 2013, 2016).

For the average city resident, especially the elderly and children, it is very important to feel comfortable in the place of residence, taking advantage of the potential of local ecosystems. Access to the ecosystem services provided by blue-green infrastructure is one of the elements that contribute to the well-being of residents, e.g. the possibility of recreation in green spaces or observing them from the window, breathing air purified by vegetation and cooled on hot days. Urban ecosystems, perform many functions and provide bundles of services by combining regulating functions (e.g. air and water purification, cooling) with cultural functions (e.g. recreation and education).

The aim of the fifth stage of the ongoing task on urban ecosystems was to identify significant interactions of ecosystem services and relevant bundles of services on the example of Warsaw's urban ecosystem subtypes. The research at this stage was conducted on a local scale, corresponding to the needs of local planning. It was carried out as part of the project 'Services provided by main ecosystem types in Poland - an applied approach'.

Ten study areas located in Warsaw were selected for the local scale analysis. They represent five types/subtypes of urban ecosystems, more precisely, the five functional-morphological categories:

1. tenement housing,
2. large-scale housing estates,
3. area with single-family housing, single-family housing
4. city park, and
5. industrial area.

Each of the types/subtypes is represented by two areas characterised by extreme values regarding tree canopy density and impervious areas. Our research focused on 6 groups of ecosystem services that are crucial for the well-being of city residents. Four of them belong to the regulating services section:

- preservation of breeding sites and ecological connectivity between populations and habitats,

- mediation of nuisances of anthropogenic origin, including smell reduction, noise attenuation and visual screening,
- purification of the air from particulate matter generated by humans,
- regulation of air temperature and humidity.

Two ecosystem services belong to the cultural services section:

- characteristics of living systems that enable aesthetic experiences and activities promoting health, recuperation or enjoyment,
- recreation and recuperation in nature.

The social method was used to estimate the potential of city parks to provide services related to recreation and recuperation in nature, while the expert method was used to calculate their use.

Services, depending on their nature, were estimated within the test areas or in their nearest vicinity. As in the earlier stages of the project, the subject of measurement was the potential, use or unmet demand for a particular service.

The report focuses on the presentation of methods and analytical procedures that can be implemented in many Polish cities at the local planning level. By understanding the interactions between different ecosystem services, it is possible to optimise urban development solutions to improve the living conditions and well-being of residents. During the work on the presented stage of the project, we used the database of types/subtypes of the functional and morphological areas of Warsaw, provided by the Architecture and Spatial Planning Office of the Warsaw City Hall.

2. RESEARCH AREAS

Ten selected study areas are located in 7 districts of Warsaw and represent:
– three types of residential areas: tenement housing (2 sites), large-scale housing estate (2 sites) and single-family housing (2 site), two areas of specialised services (industrial areas): sewage treatment plant and combined heat and power plant,
– two city parks (Tab. 1, Fig. 1).

Table 1. Study areas – location, type/subtype, area and population

Name of the study area	Code in Figure 1	District	Municipal Information System unit (MIS)	Type/subtype	Area [ha]	Number of inhabitants
Nowa Praga	A. 1	Praga Północ	Nowa Praga	tenement housing	6.1	2411
Śródmieście Północne	A. 2	Śródmieście	Śródmieście Północne	tenement housing	11.0	1766
Chomiczówka	B. 3	Żoliborz	Chomiczówka	large-scale housing estates	22.0	4009
Bemowo-Lotnisko	B. 4	Bemowo	Bemowo Lotnisko	large-scale housing estates	17.9	8095
Zacisze	C. 5	Targówek	Zacisze	single-family housing	30.4	2497
Anin	C. 6	Wawer	Anin	single-family housing	21.5	377
Praski Park	D. 7	Praga Północ	Nowa Praga	city park	17.6	n.a.
Górczewska Park	D. 8	Bemowo	Jelonki Północne	city park	21.4	n.a.
Żerań (combined heat and power plant)	E. 9	Białołęka	Żerań	industrial area	32.5	n.a.
Czajka (sewage treatment plant)	E. 10	Białołęka	Choszczówka	industrial area	52.7	n.a.

n.a. – not available

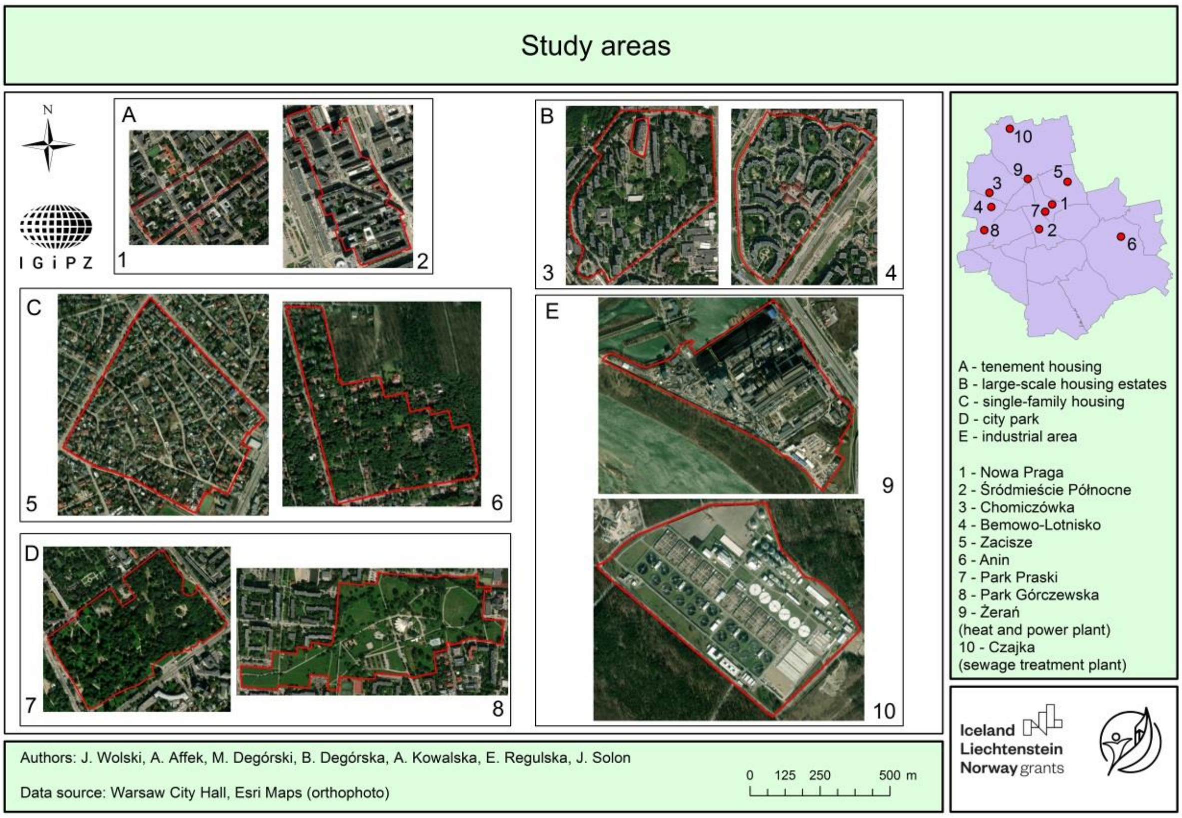

Fig. 1. Location of the study areas

As mentioned above, each urban ecosystem subtype selected for the study is represented by two extremely different sites, mainly due to tree cover density and imperviousness. Selected characteristics of research areas that are important for ecosystem services are listed in Table 2.

Table 2. Selected characteristics of the study areas

Study area	Code on the maps	Type/subtype	Leaf Area Index (LAI) [$m^2 \cdot m^{-2}$] (see: Fig. 2)	Tree Cover Density [%] (see: Fig. 3)	Total productivity (VPP) [PPI x day] (see: Fig. 4)	Imperviousness Density [%] (see: Fig. 5)
Nowa Praga	A. 1	tenement housing	0.70	5.9	456	56.6
Śródmieście Północne	A. 2	tenement housing	0.39	0.4	242	90.6
Chomiczówka	B. 3	large-scale housing estates	1.77	27.6	999	22.3
Bemowo-Lotnisko	B. 4	large-scale housing estates	0.99	6.7	647	50.0
Zacisze	C. 5	single-family housing	1.05	7.7	687	44.8
Anin	C. 6	single-family housing	2.48	51.5	1148	9.3
Park Praski	D. 7	city park	3.38	64.1	1698	1.9
Park Górczewska	D. 8	city park	1.81	8.5	1698	6.1
Żerań (combined heat and power plant)	E. 9	industrial area	1.15	2.4	656	56.3
Czajka (sewage treatment plant)	E. 10	industrial area	1.15	0.6	1003	59.5

The spatial distribution of selected characteristics of the study areas, which indicate the potential of ecosystems to provide ecosystem services, is presented in the maps below: leaf area index (Fig. 2), tree cover density (Fig. 3), total productivity (VPP) (Fig. 4) and imperviousness density (Fig. 5). In contrast to the other characteristics, an increase in the proportion of impervious areas is associated with a decrease in ecosystem potential.

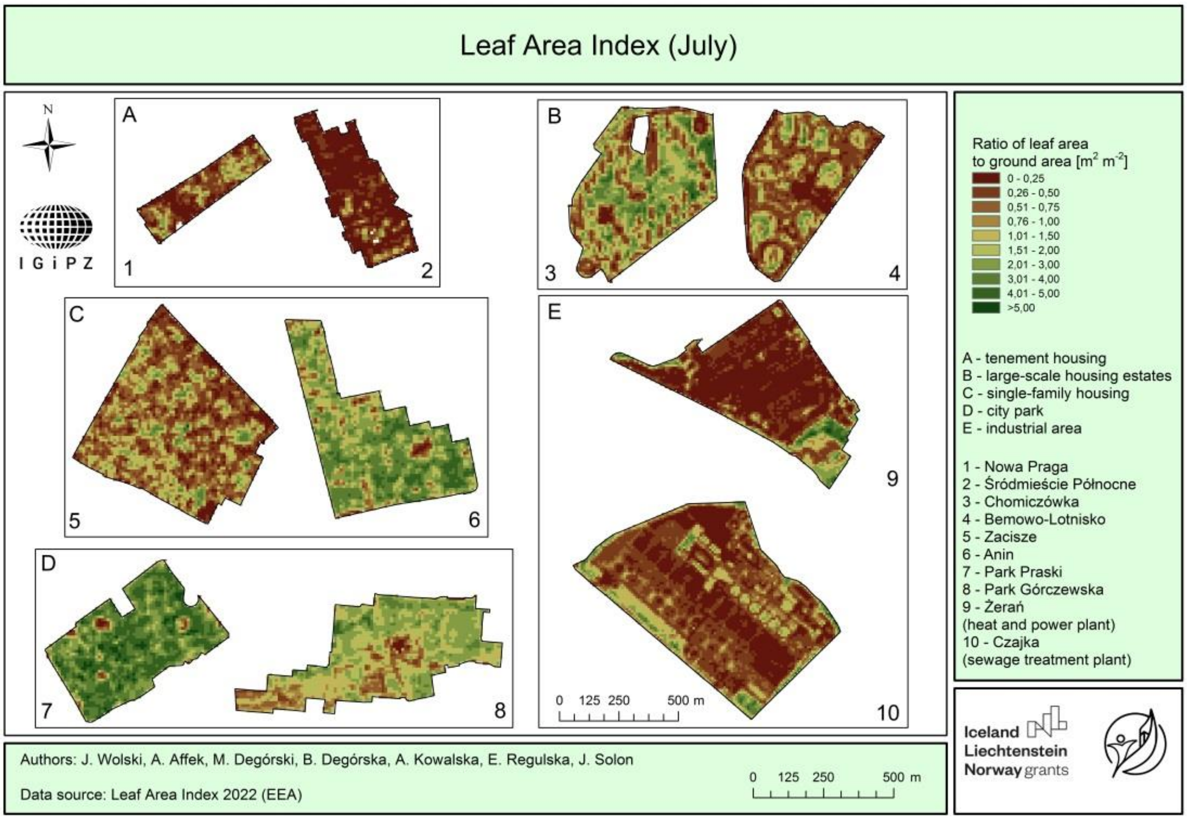

Fig. 2. Leaf Area Index (LAI) of the ten study areas

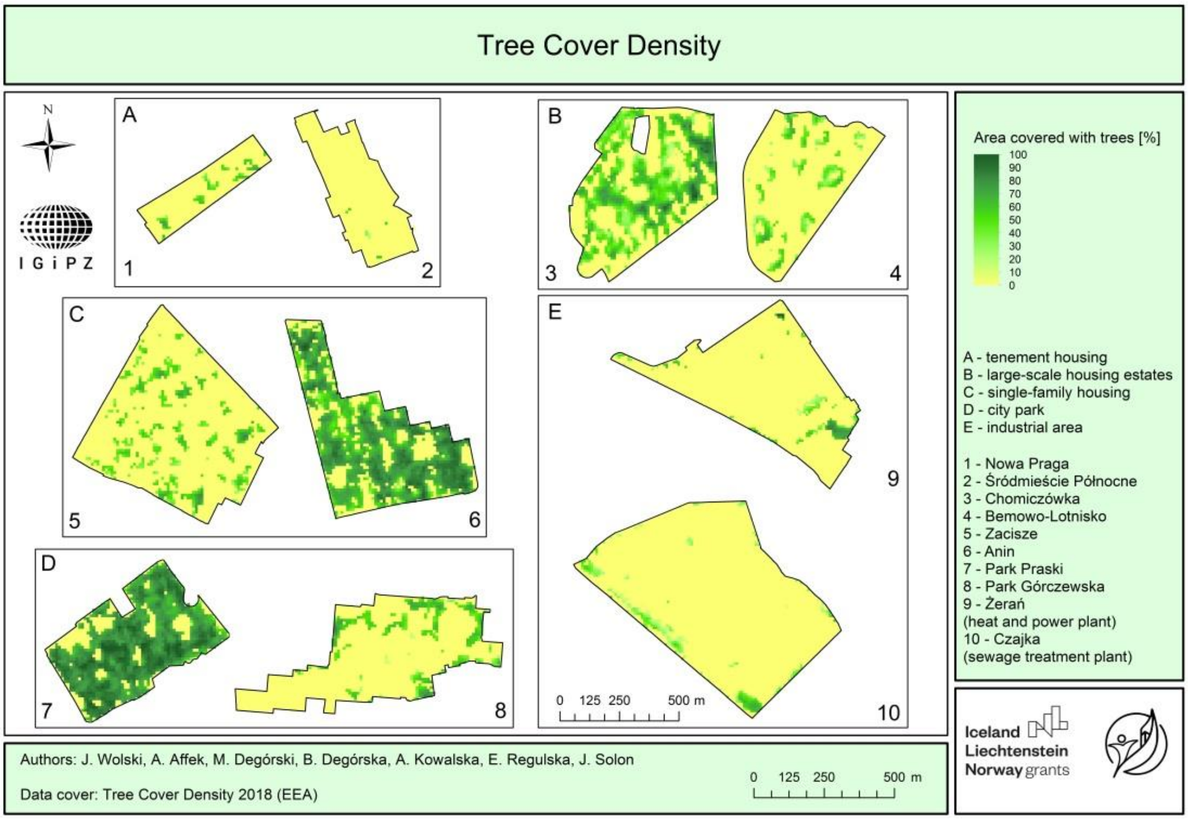

Fig. 3. Tree cover density of the ten study areas

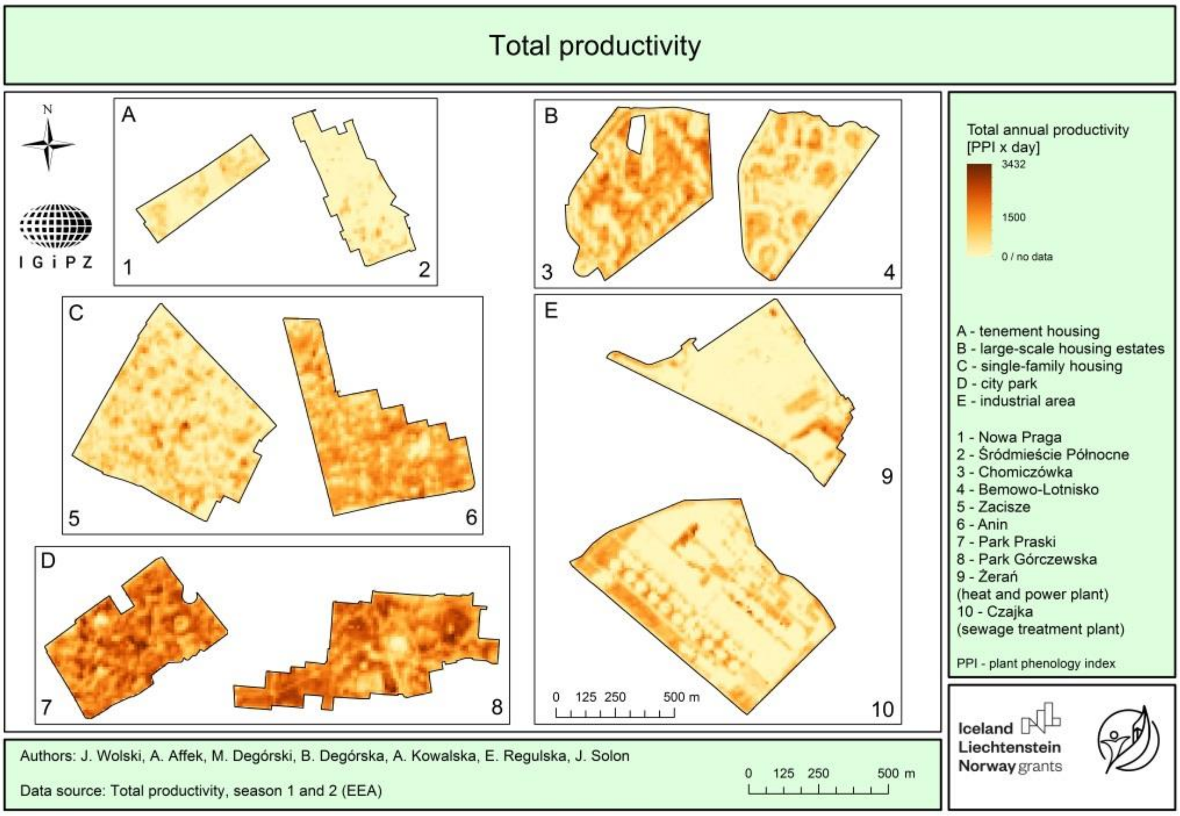

Fig. 4. Total productivity (VPP) of the ten study areas

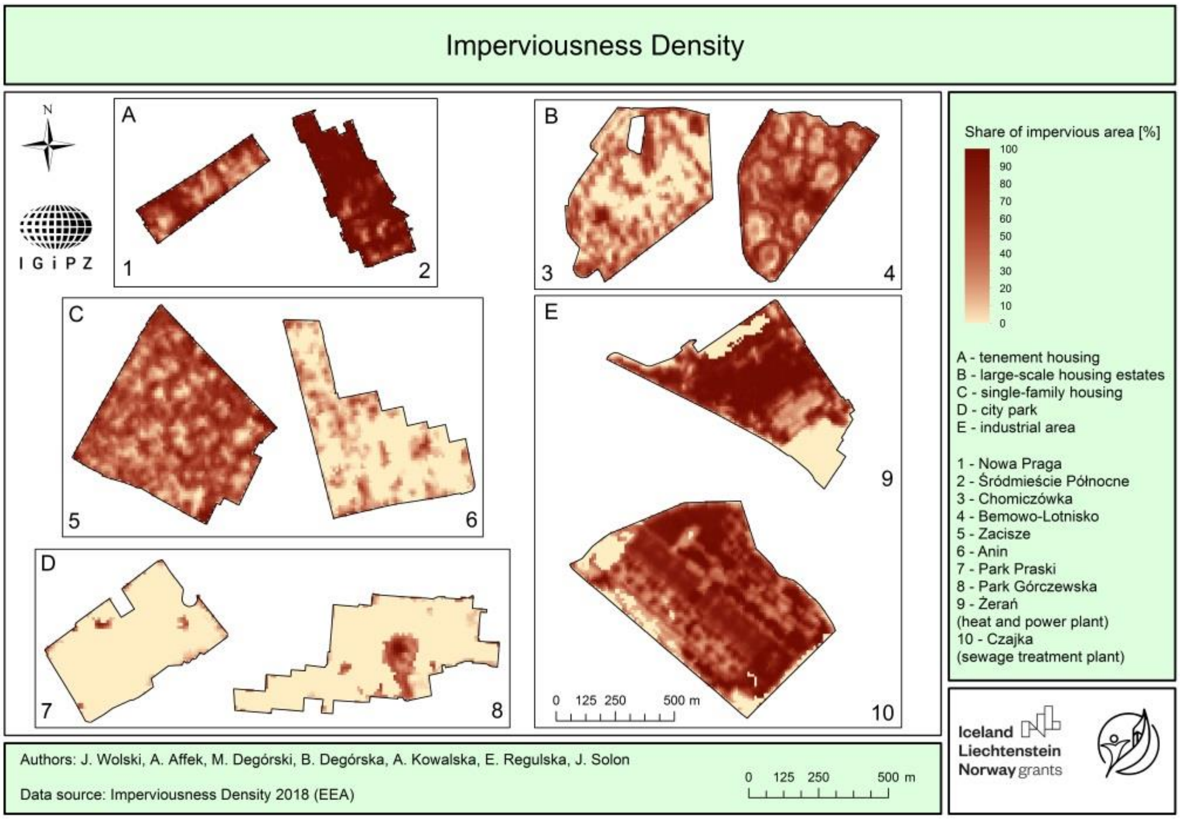

Fig. 5. Imperviousness density of the ten study areas

Among the case studies analysed, Praski Park (Photo 1) stands out as an area with the highest potential to provide ecosystem services (Tab. 2). This is the oldest public park in Warsaw. Praski Park is characterised by significant tree species diversity, a large number of old trees, a high tree cover density and multi-storey vegetation. The park is a habitat of valuable animal species. It has been classified as a biodiversity hotspot of Warsaw (Ecophysiographic Atlas of Warsaw, 2018). Górczewska Park (Photo 2) is also characterised by high potential, but slightly lower than Praski Park. This relatively young Park differs from Praski Park due to the large number of unsealed sport fields and other areas with grassy vegetation, and low tree cover density. The young age of most trees and the relatively low tree cover mean that it has a slightly lower potential to provide some ecosystem services.


Photo. 1. Praski Park (photo: A. Kowalska)


Photo. 2. Górczewska Park (photo: J. Wolski)

Among the residential areas, the single-family housing Anin (Photo 3) stands out positively, followed by the large-scale housing estate Chomiczówka, due to the development conducive to the generation of ecosystem services. Anin is characterised by very large forest areas, with a significant share of old trees. While Chomiczówka (Photo 5) is characterised by a high proportion of publicly available recreational, sport and leisure areas with attractively designed greenery with a high proportion of various tree and shrub species of different age. Both sites have an exceptionally low proportion of impervious areas (Tab. 2).

In contrast, both Zacisze (a single-family housing on small plots – Photo 5) and Bemowo-Lotnisko (i.e. a large-scale housing estate with high blocks of flats, built on a horseshoe plan with fenced green areas – Photo 6) are characterised by worse conditions to provide ecosystem services than in Anin and Chomiczówka, but better than in both tenement housings. This is particularly true for the Śródmieście Północne (Photo 7), i.e. the area with the worst parameters (Tab. 2), located in the very centre of Warsaw. Among the downtown tenement housings, the greenery consists mainly of small green areas, fragmented street greenery and green parts of some courtyards. Trees are usually single objects accompanying some streets and passages. All the studied characteristics have the poor parameters in this area (Tab. 2). The second studied tenement housing, Nowa Praga (Photo 8), is characterised by a slightly higher potential of ecosystem services, although also low. This area stands out due to high share of biologically active areas and trees, especially within the courtyards and greenery along some larger streets.

Photo 3. Anin (photo: B. Degórska)

Photo 4. Zacisze (photo: A. Affek)

Photo. 5. Chomiczówka (photo: J. Wolski)

Photo 6. Bemowo-Lotnisko (photo: J. Wolski)

Photo 7. Śródmieście Płn. (photo: M. Degórski)

Photo 8. Nowa Praga (photo: A. Affek)

The two industrial areas, i.e. the Czajka sewage treatment plant (photo 9) and the Żerań heat and power plant (Photo 10), have relatively low potential to provide ecosystem services. Nevertheless, it should be emphasised that both facilities are characterised by a significant share of unsealed areas. In the case of recently modernized sewage treatment plant Czajka, the unsealed areas are mainly covered with grassy vegetation, favouring a relatively high primary production.

Photo 9. Czajka (photo: A. Affek)

Photo 10. Żerań (photo: J. Wolski)

Summing up, among the studied areas, the best conditions for providing ecosystem services are found in the oldest city park in Warsaw (Praski Park). This is followed by the Anin forest single-family housing and Górczewska Park. It is worth noting that the studied single-family housing sites as well as large-scale housing estates can have both good (Anin and Chomiczówka) and poor conditions (Zacisze, Bemowo-Lotnisko) to provide ecosystem services , depending on their development, area and location. The most unfavourable conditions for ecosystem services are those of the tenement housing located in the very centre of Warsaw (Śródmieście Północne) and industrial areas (Żerań and Czajka).

3. URBAN ECOSYSTEM SERVICES IMPORTANT FOR THE LIFE QUALITY OF LOCAL COMMUNITIES ON THE EXAMPLE OF WARSAW

3.1. Preservation of breeding sites and ecological connectivity between populations and habitats

The service defined as "Preservation of breeding sites and ecological connectivity between populations and habitats" is a service adapted to the type of study area and scale of analysis, known from CICES V5.1 as "Maintenance of maternal populations of organisms and habitats (including protection of the gene pool)". It is about ensuring conditions for the sustainable occurrence and reproduction of species populations while maintaining an adequate level of their genetic diversity. The object of measurement is the presence and distribution of potential habitat and breeding sites of native species in urban semi-natural, transformed and heterogenous ecosystems. The composite indicator of the potential of this service comprises measures of the composition and configuration of woody vegetation and characteristics of grass-and-herb vegetation.

For the purposes of this study, the substantive scope of the service includes two main components: (a) habitat value, i.e. maintaining of breeding and foraging sites for plant and animal species whose optimum occurrence is outside urban areas; (b) corridor value. i.e.

maintaining the possibility of movement of these organisms within and through the adopted spatial core units.

The suitability of vegetation for maintaining breeding sites and ecological connectivity between populations and habitats (ROŚLINNOŚĆ) is an indicator composed of 6 sub-indicators:

(a) ZIELNA indicator is based on the degree of cover and indirectly species richness of herbaceous vegetation. This is an indicator of the abundance and quality of microhabitats suitable for small vertebrates and for a significant number of invertebrates;

(b) OTOCZENIE indicator describes the connective/barrier function of the analysed area in relation to the surrounding areas;

(c) BARIERY indicator describes the ability of small and medium-sized vertebrates to move across the land surface. It is based on the amount of permanent fences and impervious areas;

(d) DRZEWA10m indicator (number of trees >10 m in height ha^{-1}) describes the size and quality of the area for species that prefer forest habitats, which is one of the main components of vegetation potential for maintaining breeding sites and ecological connectivity between populations and habitats;

(e) NATURALNOŚĆ indicator was defined as a share (in number) of native tree species >10 m in height in the total number of trees >10 m in height in a given area. It is a measure of conditions for the quantitative development of populations of specific groups of organisms;

(f) KORONY indicator (percentage of reference area of the largest dense group of trees) describes the ability to move through the crowns and the size of shaded area under trees, as a condition for the presence of shade-tolerant and shade-preferring species.

The summary indicator of suitability of vegetation for the preservation of breeding sites and ecological connectivity between populations and habitats (ROŚLINNOŚĆ) is calculated as the arithmetic mean of the six sub-indices, rounded up to the nearest integer.

Indicator values

Table 3 shows the values of indicators characterizing the potential for preserving breeding sites and ecological connectivity between populations and habitats for each study area.

Table 3. Actual and rank values of the sub-indices that make up the service indicator "Preservation of breeding sites and ecological connectivity between populations and habitats"

	Study area	Czajka (sewage treatment plant)	Żerań (CHP plant)	Śródmieście Północne	Nowa Praga	Bemowo-Lotnisko	Chomiczówka	Zacisze	Anin	Górczewska Park	Praski Park
	Type	industrial area	industrial area	tenement housing	tenement housing	large scale housing estate	large scale housing estate	single-family housing	single-family housing	city park	city park
Actual values	Area (ha)	53.62	32.53	10.99	6.14	17.93	21.98	30.35	21.54	21.36	17.57
	Impervious areas (%)	59.48	56.28	90.62	56.58	49.96	22.3	44.84	9.52	6.1	1.85
	Ground vegetation type	cultivated lawns	ruderal	traces	ruderal	cultivated lawns	cultivated lawns	ruderal-garden	forest seminatural	cultivated lawns	forest degraded
	OTOCZENIE	one-sided fragmentary	one-sided fragmentary	no	weak	weak	two-sided good	weak	full connectivity with the surroundings	one-sided weak	two-sided with the barrier
	Permanent fences (m ha^{-1})	46.9	60.1	1.3	46.1	59.4	77.5	313.1	174.3	29.6	7.4
	DRZEWA10m	10.85	17.15	6.37	24.41	18.18	45.46	18.65	134.01	37.35	82.87
	NATURALNOŚĆ	0.57	0.44	0.61	0.31	0.61	0.56	0.51	0.96	0.67	0.69
	KORONY	0.62	2.54	0.47	2.08	0.96	5.64	0.85	59.75	3.58	70.49
Rank values	ZIELNA	2	2	1	2	3	3	3	5	3	4
	OTOCZENIE	2	2	1	3	3	4	3	5	2	4
	BARIERY	2	2	1	2	3	4	2	3	5	5
	DRZEWA10m	1	2	1	2	2	3	2	5	2	4
	NATURALNOŚĆ	2	1	3	1	3	2	2	5	4	4
	KORONY	1	2	1	2	1	4	1	5	3	5
Sum of ranks		**10**	**11**	**8**	**12**	**15**	**20**	**13**	**28**	**19**	**26**
Final rank		**very low**	**very low**	**very low**	**very low**	**low**	**high**	**low**	**very high**	**high**	**very high**
		2	**2**	**2**	**2**	**3**	**4**	**3**	**5**	**4**	**5**

The potential of each subtype of urban ecosystem to provide ecosystem service in question is briefly summarized below.

<u>Industrial areas: Czajka (sewage treatment plant) and Żerań (CHP plant)</u>

Both areas are characterized by a very low potential of the service in question, which is mainly due to the low density of trees, found mainly at the edges of the area. The small clumps of trees have a crown projection area usually below 1.000 m^2, with a maximum area of just over 3300 m^2 (Czajka) and 8200 m^2 (Żerań), giving 0.62% and 2.54% of the study area, respectively (Fig. 6).

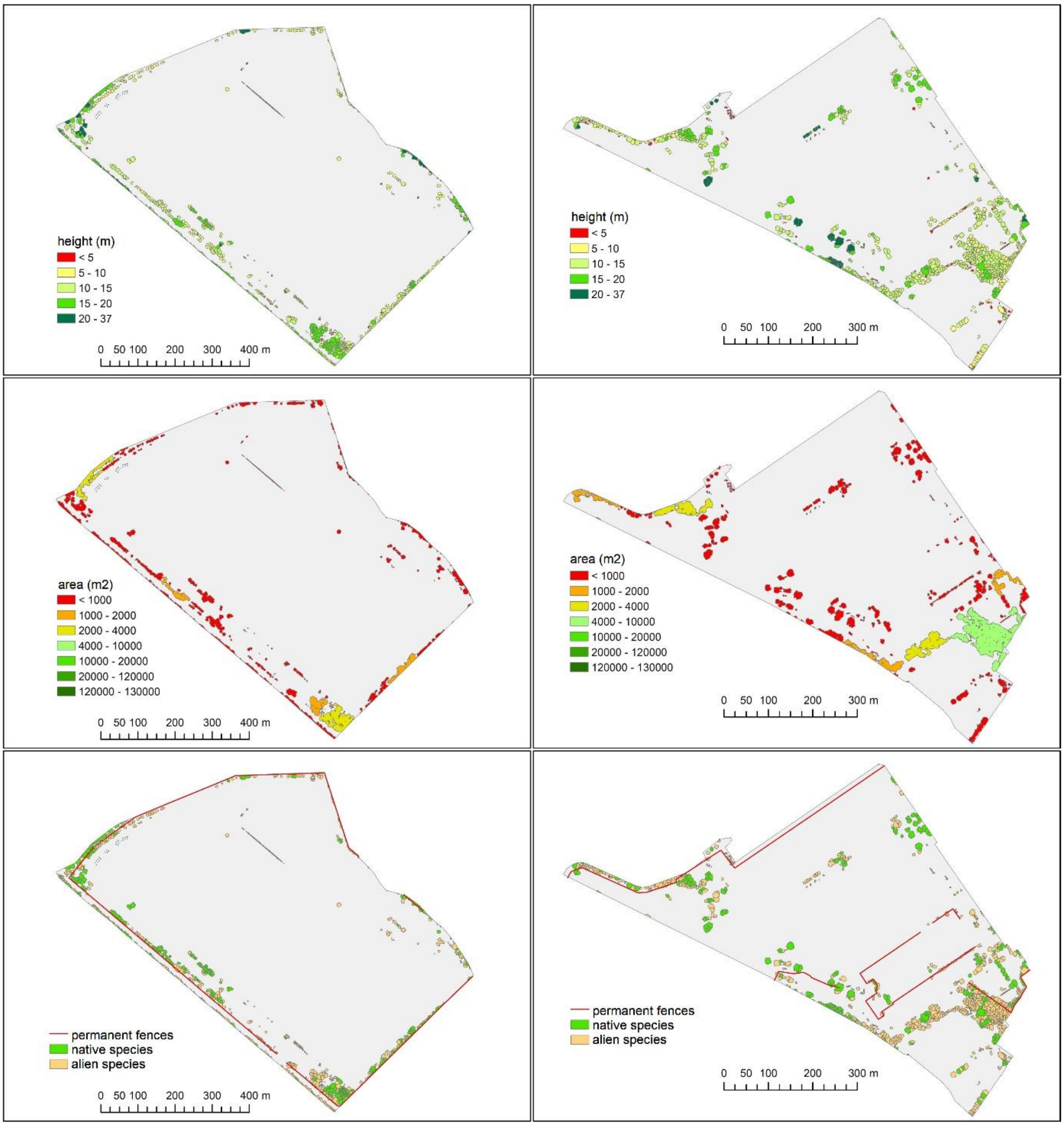

Fig. 6. Selected characteristics affecting the ecosystem service potential: top row – distribution of trees of different height classes; middle row – size of tree clump crown projection area; bottom row – distribution of native and non-native trees and presence of permanent fences. Left column – Czajka, right column – Żerań

Tenement housing: Śródmieście Północne and Nowa Praga

Both areas are characterized by a very low potential for the service in question, with the Śródmieście Północne standing out due to the least developed herbaceous layer, the lowest density of trees >10 ms in height, and relatively the weakest contact of tree crowns (the KORONY index is 520 m^2, or 0.47% of the total area). Slightly better indicators characterize Nowa Praga, although the tree stand naturalness index has the lowest value (Fig. 7).

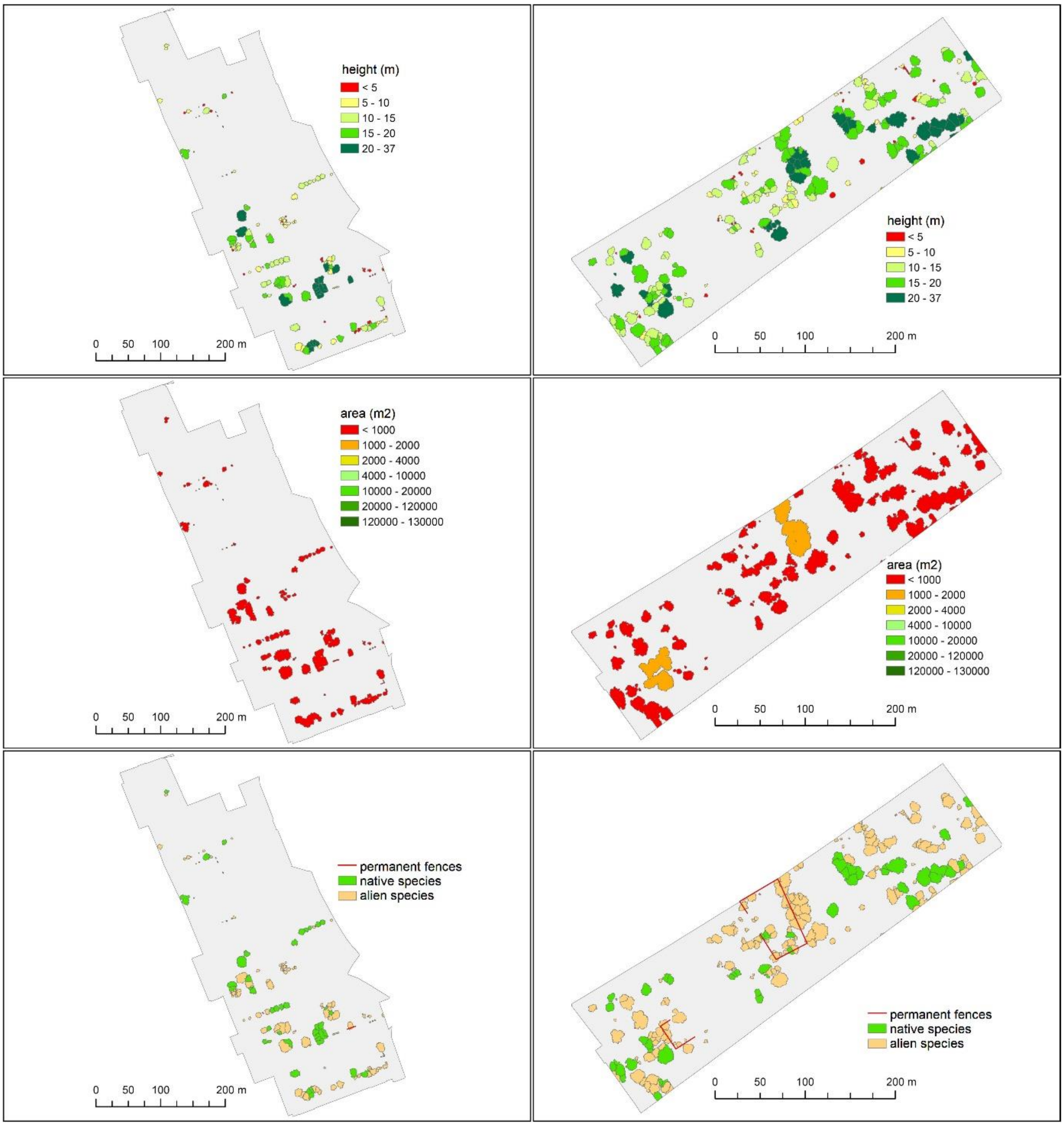

Fig. 7. Selected characteristics affecting the ecosystem service potential: top row – distribution of trees of different height classes; middle row – size of tree clump crown projection area; bottom row – distribution of native and non-native trees and presence of permanent fences. Left column – Śródmieście Północne, right column – Nowa Praga

Large-scale housing estate: Bemowo-Lotnisko and Chomiczówka

The analysed large-scale housing estates differ quite strongly in the potential for the analysed service, from low (rank 3) in Bemowo to high (rank 4) in Chomiczówka. Although the overall density of trees in both areas is similar (83 in Bemowo and more than 99 ha^{-1} in Chomiczówka), the density of biocenotically important trees, i.e. those >10 m in height, is markedly different (18.2 and 45.5 ha^{-1}, respectively). A consequence of the differences in tree height is, among others, the difference in the KORONY index, which in Chomiczówka is almost six times higher (Fig. 8).

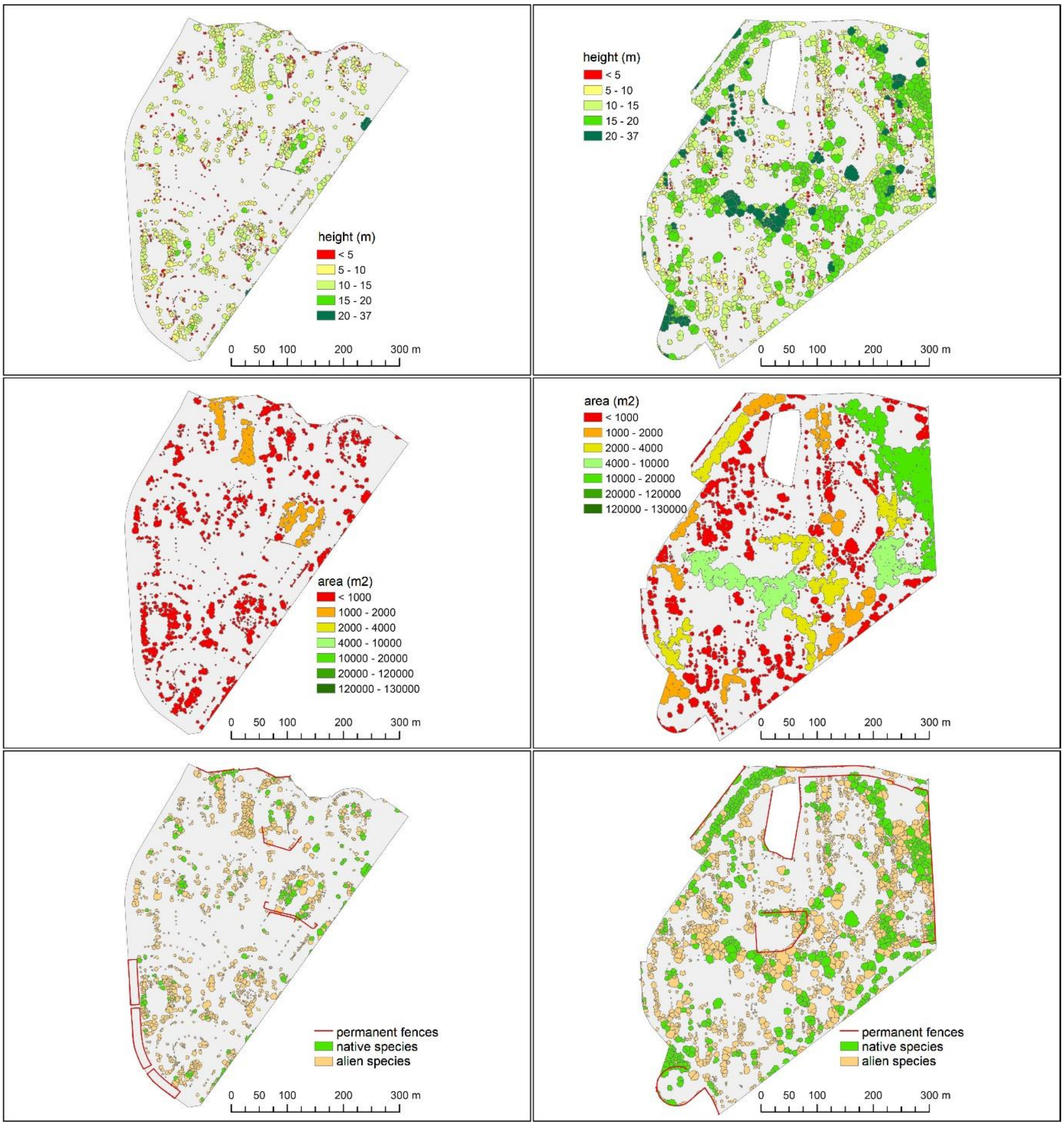

Fig. 8. Selected characteristics affecting the ecosystem service potential: top row – distribution of trees of different height classes; middle row – size of tree clump crown projection area; bottom row – distribution of native and non-native trees and presence of permanent fences. Left column – Bemowo-Lotnisko, right column – Chomiczówka

Single-family housing areas: Zacisze and Anin

Both areas, although they represent the same subtype, differ strongly in the potential of the service in question. Zacisze has low (rank 3) potential, while Anin has very high (rank 5) potential. One of the few features that collectively distinguish this type from the other morphological types analysed is the high density of fences, most of which are permanent. Although the overall density of trees in both areas is similar (113 in Zacisze and 173 ha^{-1} in Anin), the density of biocenotically important trees. i.e. those >10 m in height, is markedly different (19 and 134 ha^{-1}, respectively). The consequence of the differences in tree height is, among others, the difference in the KORONY index, which is more than 70 times higher in Anin than in Zacisze (Fig. 9).

Fig. 9. Selected characteristics affecting the ecosystem service potential: top row – distribution of trees of different height classes; middle row – size of tree clump crown projection area; bottom row –

distribution of native and non-native trees and presence of permanent fences. Left column – Zacisze, right column – Anin

City parks: Górczewska Park and Praski Park

City parks are characterized by high (Górczewska Park - rank 4) or very high (Praski Park - rank 5) potential of the service "Preservation of breeding sites and ecological connectivity between populations and habitats". The distinguishing feature in relation to the other analysed areas is the minimal share of internal barriers, resulting from the low proportion of impervious areas and the low density of permanent fences. Other sub-indices can be relatively variable, such as DRZEWA10m, which range from 37.4 for Górczewska Park (lower than in some residential areas) to 82.9 in Praski Park (Fig. 10).

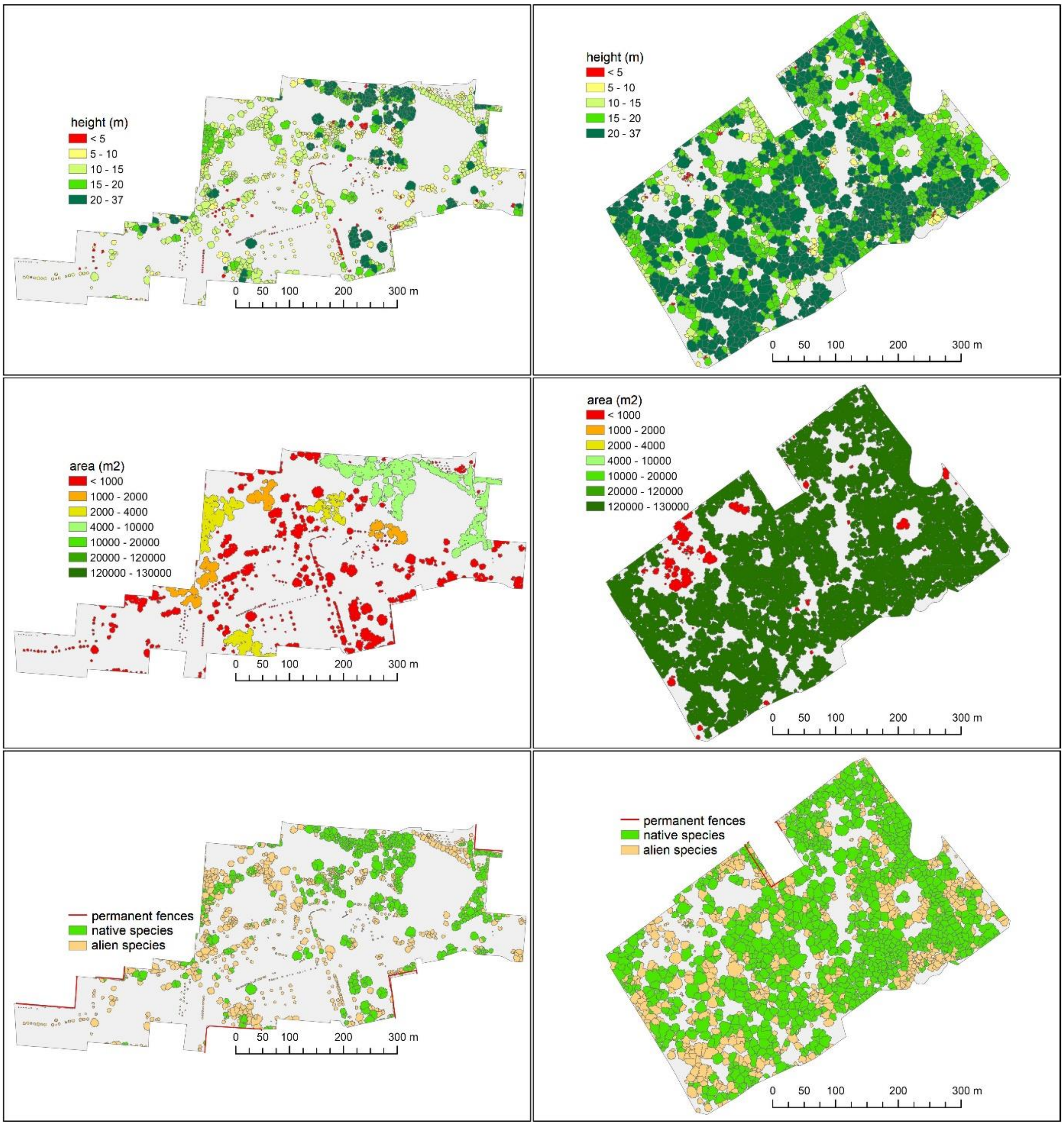

Fig. 10. Selected characteristics affecting the ecosystem service potential: top row – distribution of trees of different height classes; middle row – size of tree clump crown projection area; bottom row –

distribution of native and non-native trees and presence of permanent fences. Left column – Górczewska Park, right column – Praski Park

3.2. Mediation of nuisances of anthropogenic origin, including smell reduction, noise attenuation and visual screening

The group of ecosystem services related to the mediation of nuisances of anthropogenic origin belongs to the Regulation and Maintenance section in CICES V5.1. There are 3 classes of services in this group: smell reduction, noise attenuation and visual screening. They are related to the buffering role of vegetation, separating sources of nuisance of anthropogenic origin from places of regular human occurrence (places of residence, work, commuting or recreation). This is of particular importance in cities, where, on the one hand, we are dealing with numerous industrial facilities generating the above-mentioned nuisances, and on the other hand, with a large number of people directly exposed to their negative impact. The subject of the measurement is the use of vegetation to mitigate nuisances generated by urban industrial areas.

To estimate the use of vegetation to mitigate the above-mentioned nuisances generated by urban industrial areas, two groups of indicators were proposed, adapted to the local scale: 1. general indicators based on the calculation of the average leaf area per square meter (LAI) of 60 m buffer around the facility, and 2. detailed indicators relating to the volume and height of vegetation in each 5 m segment of a buffer around the facility. Based on the literature review, it was concluded that these groups of indicators would give a good approximation of the use of vegetation for both smell reduction, noise attenuation and visual screening, and that these ecosystem services could be considered jointly as a bundle.

The general indicator showing the average area of leaves in the buffer around the facility based on LAI is 1.77 $m^2 \cdot m^{-2}$ in the summer for the Czajka sewage treatment plant, and 1.38 $m^2 \cdot m^{-2}$ for the Żerań heat and power plant (Tab. 4, Fig. 11).

Table 4. Values of general and detailed indicators of the use of vegetation to mediate nuisances generated by two urban industrial areas: the Czajka sewage treatment plant and the Żerań heat and power plant

Industrial area	Average LAI in the buffer in summer [$m^2 \cdot m^{-2}$]	Average LAI in the buffer in winter [$m^2 \cdot m^{-2}$]	LAI averaged from winter and summer [$m^2 \cdot m^{-2}$]	Average volume of vegetation per m^2 of a buffer [$m^3 \cdot m^{-2}$]	% of buffer length with vegetation volume up to:				Average maximum height of vegetation from buffer segments [m]
					1 $m^3 \cdot m^{-2}$	2 $m^3 \cdot m^{-2}$	5 $m^3 \cdot m^{-2}$	10 $m^3 \cdot m^{-2}$	
Czajka (sewage treatment plant)	1.77	0.30	1.04	4.11	99.32	99.15	97.29	92.37	17.20
Żerań (heat and power plant)	1.38	0.24	0.81	1.71	86.20	81.36	72.58	56.45	12.01

The analogous indicator for the winter period is 0.30 and 0.24 m2·m-2, respectively. Detailed indicators also consistently show a greater use of vegetation for smell reduction, noise attenuation and visual screening in the case of Czajka sewage treatment plant than in the case of Żerań CHP plant. The average vegetation volume per square meter of a buffer is 4.11$m^3 \cdot m^{-2}$ for Czajka and 1.71 $m^3 \cdot m^{-2}$ for Żerań. In turn, the average maximum height of vegetation reached in individual segments of the buffer around Czajka is 17.2 m, and around Żerań – 12.01 m.

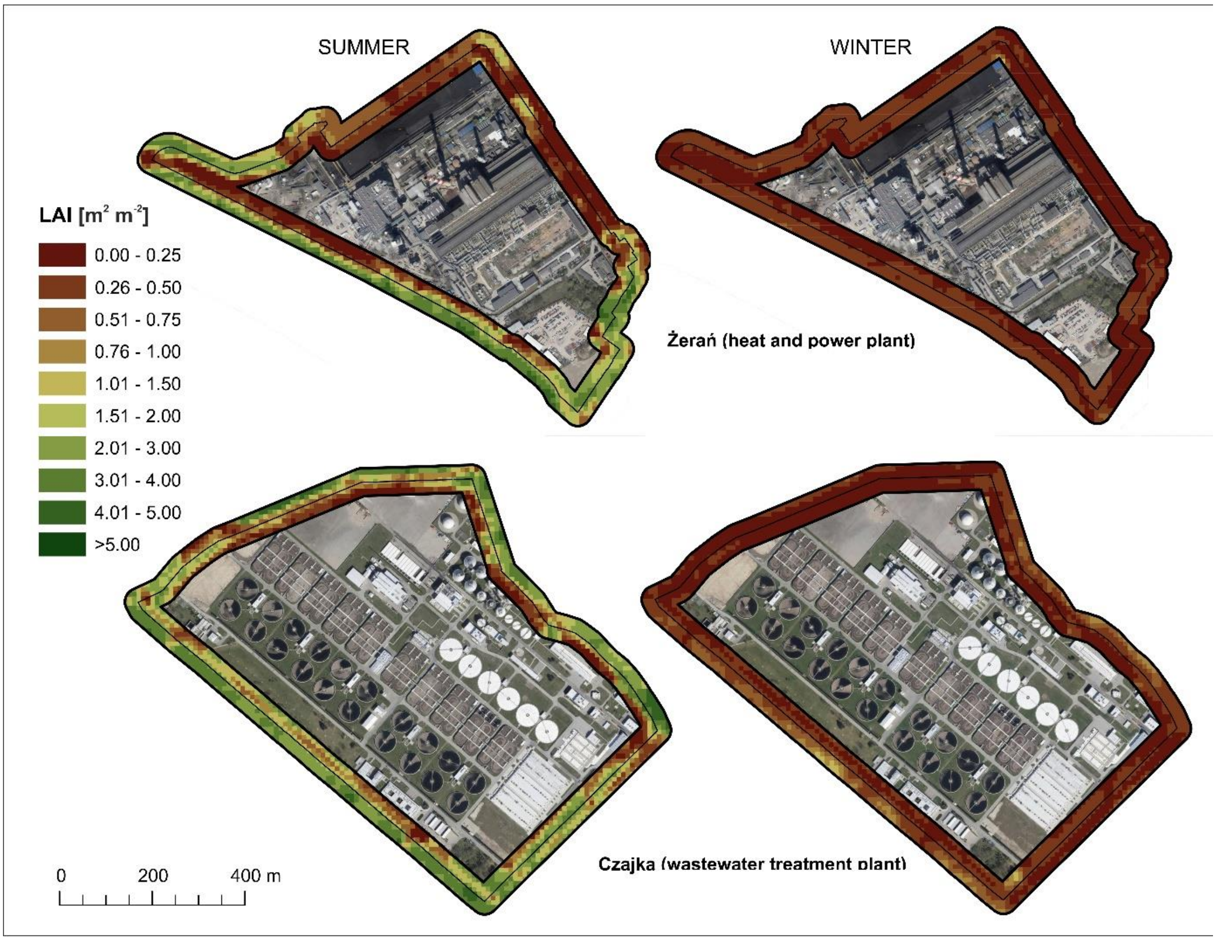

Fig. 11. The use of vegetation to mitigate nuisances generated by the two urban industrial areas (Czajka sewage treatment plant and Żerań heat and power plant) presented by means of two general indicators: LAI values in the buffer around the objects 1. in summer and 2. in winter. Orthophoto source: geoportal.gov.pl

3.3. Purification of the air from particulate matter generated by humans

Air pollution in urban areas is an increasing threat to human health. One of the most dangerous pollutants inhaled is particulate matter (PM), which consists of liquid and solid particles, both organic and inorganic, with a diameter ranging from 0.001 to 100 µm. The main source of PM in cities is low emissions, car transport and industry (Popek et al., 2015; Przybysz et al., 2020).

Urban vegetation can be used as a biological filter that retains PM on the surface of leaves and shoots. Tree and shrub species differ in PM accumulation capacity. Species with large leaves, which have a rough surface or hairs, are more effective at accumulation of PM than species with smooth-surfaced leaves (Sæbø et al., 2012). The total amount of PM accumulation is largely influenced by the cover and structure of vegetation, a good indicator of which is the leaf area index (LAI) - the ratio of the leaf area to the ground area (Manes et al., 2014).

Having the LAI value for a study area and the concentration of PM in the air, we can estimate the amount of PM intercepted and accumulated by vegetation (Q). It is a measure of the use of vegetation to reduce PM air pollution from anthropogenic sources.

Calculations were made for all study areas on two dates: March 13, 2022 (outside the growing season) and July 1, 2022 (in the full growing season). We used the following formula (Nowak, 1994; Yang et al., 2005):

$$Q = V_d \times C \times LAI \times 0.5 \times T$$

where: V_d – dry deposition velocity (mean 0.0064 $m \cdot s^{-1}$), C – PM10 concentration in the air (daily mean) in $\mu g \cdot m^{-3}$, LAI – leaf area index in $m^2 \cdot m^{-2}$, 0.5 – resuspension rate of PM10 deposited that returns to the atmosphere, T – period of time in seconds (Manes et al., 2014; 2016).

Higher values of the indicator are observed for the growing season (July 1, 2022), which is associated with higher LAI values. It should be noted, however, that its value is also strongly affected by the PM10 concentration in the air recorded in the vicinity of the study areas (Table 5, Fig. 12).

Table 5. Indicator of the use of vegetation to reduce PM10 air pollution from anthropogenic sources and its components

Study area	LAI_13.03.2022 [$m^2 \cdot m^{-2}$]	LAI_1.07.2022 [$m^2 \cdot m^{-2}$]	C_13.03.2022 [$\mu g \cdot m^{-3}$]	C_1.07.2022 [$\mu g \cdot m^{-3}$]	Q_13.03.2022 [$\mu g \cdot m^{-2}$]	Q_01.07.2022 [$\mu g \cdot m^{-2}$]
Nowa Praga	0.18	0.55	48.7	71.7	2423.6	10903.0
Śródmieście Północne	0.12	0.25	48.7	71.7	1615.7	4955.9
Chomiczówka	0.26	1.36	64.2	33.3	4615.0	12521.2
Bemowo-Lotnisko	0.21	0.66	64.2	33.3	3727.5	6076.5
Zacisze	0.29	0.76	48.7	71.7	3904.7	15065.9
Anin	0.49	2.43	48.7	20.6	6597.6	13840.0
Praski Park	0.29	1.78	48.7	71.7	3904.7	35286.0
Górczewska Park	0.36	1.35	52.5	26.1	5225.5	9741.8
Żerań (heat and power plant)	0.21	1.18	48.7	71.7	2827.6	23391.9
Czajka (sewage treatment plant)	0.4	1.64	97.3	25.6	10760.6	11607.7

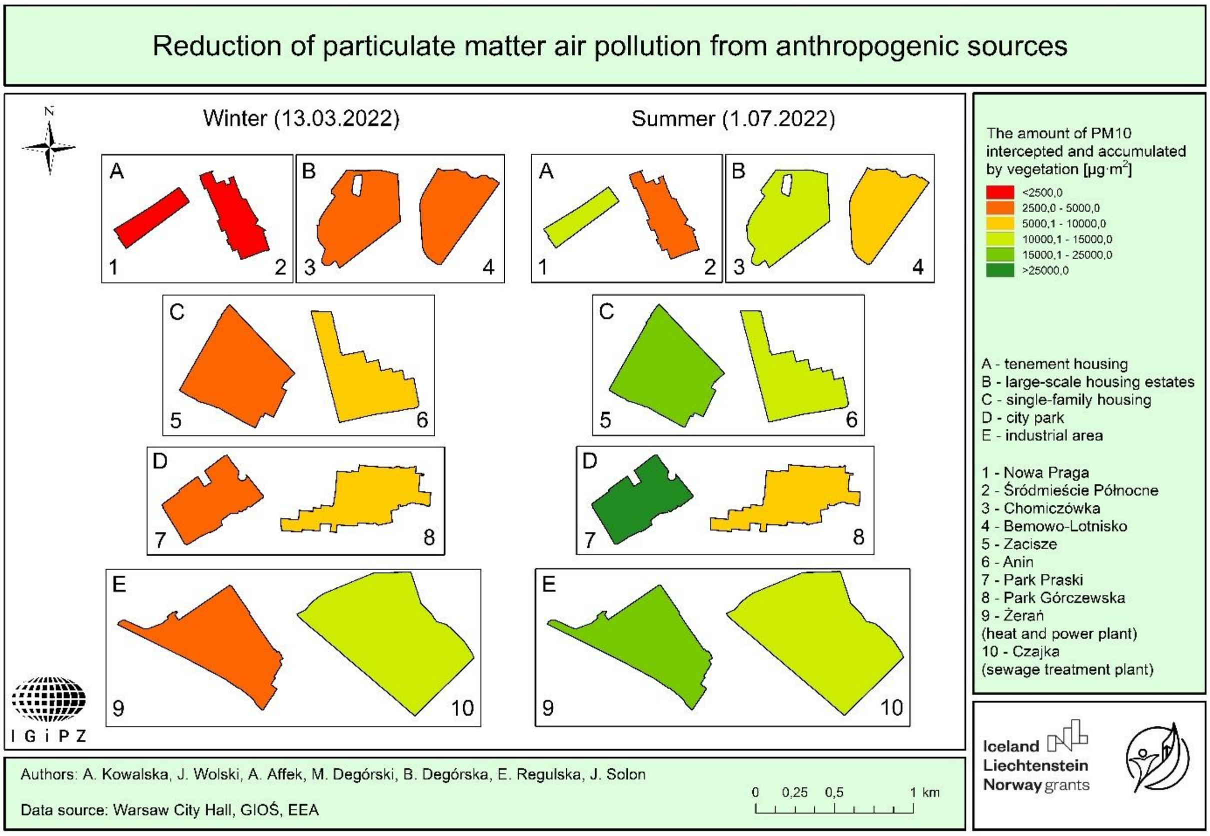

Fig. 12. The amount of PM10 intercepted and accumulated by vegetation in the selected areas in Warsaw

3.4. Regulation of air temperature and humidity

The urban heat island (UHI) is a phenomenon that causes urban residents to be exposed to heat stress and potential heatstroke, as well as increased energy consumption for cooling buildings (Livesley et al., 2016). Urban green spaces contribute substantially to the mitigation of UHI. By improving thermal conditions in the city, they affect the life quality of residents, especially in summer. The cooling effect of vegetation is associated primarily with shading and evapotranspiration (Rocha et al., 2015; Zardo et al., 2017), that is why the share of trees and other biologically active areas in cities is so important (Ziter et al., 2019).

The subject of measurement is the potential of UHI reduction, and the indicator is the amount of water evaporated from plant cells and soil during a day. The evapotranspiration was selected because of its linear relationship with latent heat. The higher the evapotranspiration, the more energy is used for transferring water to the gas phase – and the less energy is available in the form of sensible heat, which is related to actual air temperature (Schwartz et al., 2011). Calculations were made for all the study areas. We used the following formula (FAO, 1998):

$$ETA = K_c \times ET_o$$

where: ETA – evapotranspiration under conditions of unlimited presence of water in the ground ($mm{\cdot}d^{-1}$), Kc – the tree or soil cover coefficient, ET_o – the reference evapotranspiration dependent on air temperature and humidity ($mm{\cdot}d^{-1}$).

The Kc coefficient was calculated according to the formula: $K_c = 1.457 \times NDVI - 0.1725$ (Kamble et al., 2013), and NDVI (mean Normalized Difference Vegetation Index) was calculated based on satellite data, separately for trees and other biologically active areas (with permeable ground and herbaceous vegetation). The value of reference evapotranspiration ET_o acc. to Penman-Monteith was taken from Kasperska-Wołowicz and Łabędzki (2004) for the average growing season in Warsaw ($ET_o = 455$ mm·d^{-1}). ETA of the study area is the sum of evapotranspiration from trees multiplied by their cover and evapotranspiration relating to the remaining biologically active area multiplied by its share (Zardo et al., 2017).

The results indicate a significant contribution of vegetation to the regulation of air temperature and humidity in the city. The highest ETA values were observed for city parks and housing estates with a large share of trees and other biologically active areas, while the former has a much greater impact on the value of the indicator (Tab. 6).

Table 6. Indicator of urban ecosystem potential for UHI reduction and its components

Study area	Type	Area [ha]	Impervious area [%]	Tree cover density [%]	Other biologically active area [%]	NDVI trees	NDVI soil	K_c trees	K_c soil	ETA trees [$mm \cdot d^{-1}$]	ETA soil [$mm \cdot d^{-1}$]	ETA total [$mm \cdot d^{-1}$]
Nowa Praga	tenement housing	6.1	56.6	5.9	37.6	0.443	0.316	0.47	0.29	215.43	131.14	61.89
Śródmieście Północne	tenement housing	11.0	90.6	0.4	9.0	0.319	0.131	0.29	0.02	133.27	8.65	1.26
Chomiczówka	large-scale housing estate	22.0	22.3	27.6	50.1	0.604	0.556	0.71	0.64	322.03	290.26	234.31
Bemowo-Lotnisko	large-scale housing estate	17.9	50.0	6.7	43.4	0.482	0.396	0.53	0.40	240.77	183.83	95.79
Zacisze	single-family housing	30.4	44.8	7.7	47.5	0.447	0.410	0.48	0.42	217.58	193.36	108.52
Anin	single-family housing	21.5	9.5	51.5	38.9	0.745	0.723	0.91	0.88	415.14	400.50	369.90
Praski Park	city park	17.6	1.9	64.1	34.0	0.811	0.789	1.01	0.98	459.30	444.37	445.72
Górczewska Park	city park	21.4	6.1	8.5	85.4	0.666	0.613	0.80	0.72	363.18	328.10	311.07
Żerań (heat and power plant)	industrial area	32.5	56.3	3.0	40.7	0.487	0.250	0.54	0.19	244.13	87.20	42.86
Czajka (sewage treatment plant)	industrial area	53.6	59.5	2.3	38.2	0.620	0.320	0.73	0.29	332.22	133.89	58.87

3.5. Characteristics of living systems that enable aesthetic experiences and activities promoting health, recuperation or enjoyment

Ecosystem services that refer to creating conditions by the living world that enable aesthetic experiences and activities promoting health, recuperation or enjoyment belong to the section of cultural services in CICES V5.1. The condition for the creation of the above benefits is the occurrence of direct interaction between humans and ecosystems. These interactions can be both physical and intellectual. In the urban space, highly transformed by man and with a substantially reduced presence of ecosystems, man has limited opportunities for regular interaction with nature. Therefore, each, even seemingly shallow, interaction with the living world takes on a special meaning. One of the examples of possible everyday interaction with nature in the city is experiencing/observing it through the window from the place of residence or work.

The subject of the measurement was the use of trees visible from the window to generate aesthetic experiences and activities promoting health, recuperation or enjoyment. To estimate it, an indicator dedicated to the local scale and local spatial planning was developed, showing the number of trees visible from the windows on the top floors of buildings. The analysis was performed for all residential, office and service buildings (excluding garages and warehouses) located in six selected housing estates: two tenement housing estates, two single-family housing estates and two large-scale housing estates. In addition to calculating the number of visible trees for a given window (5 m facade segment on the top floor of the building), the minimum, average and maximum number of trees visible from windows in a given housing estate were also counted (Tab. 7).

Table 7. The number of trees visible from the window (on the top floor) as an indicator of their use to generate aesthetic experiences and promote health, recuperation or enjoyment

Residential area	Type of housing estate	Number of 5 m segments (windows on top floor)	Number of visible trees		
			Min	Max	Mean
Nowa Praga	Tenement	828	0	192	50.12
Śródmieście Północne	Tenement	1515	0	86	8.19
Chomiczówka	large-scale	778	19	723	277.29
Bemowo-Lotnisko	large-scale	1440	0	266	79.69
Zacisze	single-family	3990	0	906	153.01
Anin	single-family	1451	0	725	50.94

The indicator values ranged in the selected test areas from 8.19 (trees visible from the window on the top floor) in the tenement housing of Śródmieście Północne to 277.29 in the large-scale housing estate in Chomiczówka (Tab. 7, Fig. 13). The window with the highest recorded number of visible trees (906) was located in a single-family housing estate in Zacisze. In every housing estate except Chomiczówka, windows/facades located on the top floors of buildings, from which no trees were visible, were recorded.

Summing up, it can be concluded that the use of trees to generate aesthetic experiences and promote health, recuperation or enjoyment takes place to the greatest extent in large-scale housing estates, to a slightly lesser extent in single-family housing estates, and to the least extent in the areas of tenement housing. Nevertheless, the high variability within these residential types indicates that the land use in a given housing estate, both in the context of buildings and greenery, can substantially affect the use of this ecosystem service.

Fig. 13. A fragment of the Śródmieście Północne tenement housing estate with the facades of buildings coloured according to the number of visible trees from the top floor and the locations of trees taken into account when calculating the indicator (>10 m high)

3.6. Recreation and recuperation in nature

Green urban spaces provide opportunities for recreation and recuperation in nature, which are of great value for the physical well-being and mental health of residents (Geary et al., 2021; Weinbrenner et al., 2021). Numerous studies emphasize the importance of the proximity and availability of high-quality green areas for regular recreational use (Nielsen and Hansen, 2007). The recreational values of green spaces are closely related to their aesthetic values, as well as microclimatic conditions conducive to recreation (Kothencz et al., 2017). The properties of green areas are particularly important, as they mitigate high temperatures in the summer. It has been shown that the benefits associated with the cooling effect are much greater in green areas with trees compared to green areas without trees and a greater share of impervious areas (Ziter et al., 2019). The size of urban green spaces is also important, as it is assumed that with an increase in area, both recreational opportunities (Cohen et al., 2010) and biodiversity increase (Nielsen et al., 2014).

Parks are important elements of urban green infrastructure, improving the quality of life, promoting the well-being of city residents, as well as providing many social and economic benefits (Brown et al., 2014; Wang et al., 2015). Therefore, a diverse approach to planning and decision-making for sustainable open green spaces and city parks is needed.

Opportunities for recreation and recuperation in nature were estimated for two city parks and six housing estates. Three indicators were developed concerning: (1) the potential and (2) the use of city parks for recreation and recuperation, and (3) the potential of urban green infrastructure accompanying various types of housing estates for recreation and recuperation.

The potential of city parks for recreation and recuperation in nature was estimated through review score of city parks on Google Maps. In Google Maps, each logged-in user can evaluate and express his/her opinion on any object located in space, as well as enter a new object. Assessment is made by assigning points (stars) on a 1-5 scale. It is also possible to leave a comment/opinion and add photos. It should be noted that the reviews on Google Maps are mostly created by regular users, so it occasionally happens that the review does not apply to a particular site or the score is incorrectly assigned (e.g., high score followed by negative review). There are also complex reviews that are generally positive and rated 5 stars, but contain an element of negative comment and vice versa. All reviews were thoroughly checked in this regard and, if questionable, excluded from further analysis.

The number of reviews posted on Google Maps was 5,448 (Praski Park) and 5,824 (Górczewska Park). The review score (the indicator of potential) was the users' average review score on Google Maps.

Moreover, a detailed analysis of user opinions was made. For each park, 50 opinions with the mostpositive score and 50 opinions with the most negative score were taken into account, which is facilitated by the filtering option implemented in Google Maps. Only scores with comments were taken into account, starting with the highest score (5 stars) for positive reviews and the lowest score (1 star) for negative reviews. Reading the opinions, the greatest attention was paid to phrases referring to the potential of parks to provide ecosystem services related to recreation and recuperation in nature, as well as greenery management. A simplified SWOT analysis was used to organize the information obtained from the reviews.

The use of city parks for recreation and recuperation in nature was estimated by the number of people per 1 ha of park area. The number of people living within the 300 m buffer from the borders of the park was taken into account[1]. The adopted distance is in line with the WHO recommendations (2017), which indicate a maximum distance of 300 m to the nearest green space of at least one hectare in size (Konijnendijk van den Bosch, 2022).

The indicator of the potential of urban green infrastructure accompanying various types of housing estates for recreation and recuperation was based on data concerning: (1) tree cover density (a threshold of approx. 30% was adopted as a minimum to ensure appropriate climatic conditions and health benefits – Konijnendijk van den Bosch, 2022), (2) available biologically active area (BAA)[2] per person (following Strategy 2030 for Warsaw, a standard of 6 m^2 BAA per person was adopted), (3) public access to green space (all access limitations observed during field reconnaissance e.g. fences, closed gates to yards, were assessed negatively), (4) aesthetic values determined by the tree diversity indicator[3] (study areas with an indicator value above 3

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[1] The number of residents was determined based on telemetry measurements from 2015 (Degórski et al., 2021)
[2] The BAA was calculated by subtracting the impermeable area (Imperviousness Density, 2018) from the study area.
[3] The measure of diversity is Shannon-Wiener index ($H' = \sum_{i=1}^{S} p_i \, log_2 \, p_i$, where S – number of species, p_i – ratio of the number of individuals of a species to the number of all individuals of all species: $\frac{n_i}{N}$, n_i – number of

were positively assessed). Each element was assigned 0 or 1 point depending on the fulfilment of the above-mentioned criteria. The sum of points obtained is a value of the indicator. Areas with an indicator value of 4 show the highest potential, and the lowest with a value of 1.

Indicator values

The indicator of potential for recreation and recuperation took similar values for both parks: 4.5 (Praski Park) and 4.6 (Górczewska Park).

Analysis of the opinions allowed us to find out the aspects that influence the awarding of scores. Based on the positive comments, we can conclude that, in general, both parks have the potential to provide services associated with nature-based activities. However, there is a significant difference between the parks with regard to the potential of moderately active recreation (walking) and passive recreation (e.g. sitting, reading a book). In this case, Praski Park is characterized by greater potential. In turn, in the case of active recreation (biking, rollerblading, etc.) and benefits related to social interactions (e.g., family gatherings, barbecues, picnics), responses indicate greater potential for Górczewska Park.

Opinions with low scores (non-positive opinions) regarding greenery are particularly pronounced in the case of Górczewska Park, both in terms of their number and the emotional attitude. They indicate a great need to redesign the park's space in terms of greenery, so that it also meets the needs of passive and moderate recreation in nature. A large number of people point to the lack of trees, and thus the paucity of places that create enclaves for passive rest and relaxation, shelter in the shade.

More than three times fewer people live in the vicinity of Praski Park than in the housing estates adjacent to Górczewska Park (8.645 and 29.054 people, respectively, within a 300 m buffer from the borders of parks – Fig. 14). The value of the indicator was 496 people ha^{-1} for Praski Park (area 17.6 ha), and 1360 people ha^{-1} for Górczewska Park (area 21.4 ha). However, the proximity of Praski Park to the Municipal Zoological Garden makes the use of this park, especially on weekends and holidays, much higher than the indicator shows.

The indicator of the potential of urban green infrastructure accompanying various types of housing estates for recreation and recuperation in nature took the highest value 4 and the lowest 1 (Tab. 8). The large-scale housing estate Chomiczówka belongs to the first category. The indicator was significantly lower for the second selected large-scale housing estate Bemowo-Lotnisko (2), which is related to low tree cover density and limited access to green infrastructure accompanying the buildings. The lowest potential for recreation and recuperation was shown by tenement housing in Śródmieście Północne – only in the case of the diversity indicator, it was possible to award 1 point. Tenement housing in Nowa Praga has a much higher potential (3). In this case, only the tree cover density does not meet the adopted criteria and could not be assessed positively. The selected single-family housing estates obtained the same value of the indicator (2). In both areas, access to green infrastructure is limited, but there are differences in tree cover density and diversity index.

individuals of the *i* species, N – the number of all individuals of all species); data on tree species was obtained from the map of Tree Crowns for Warsaw.

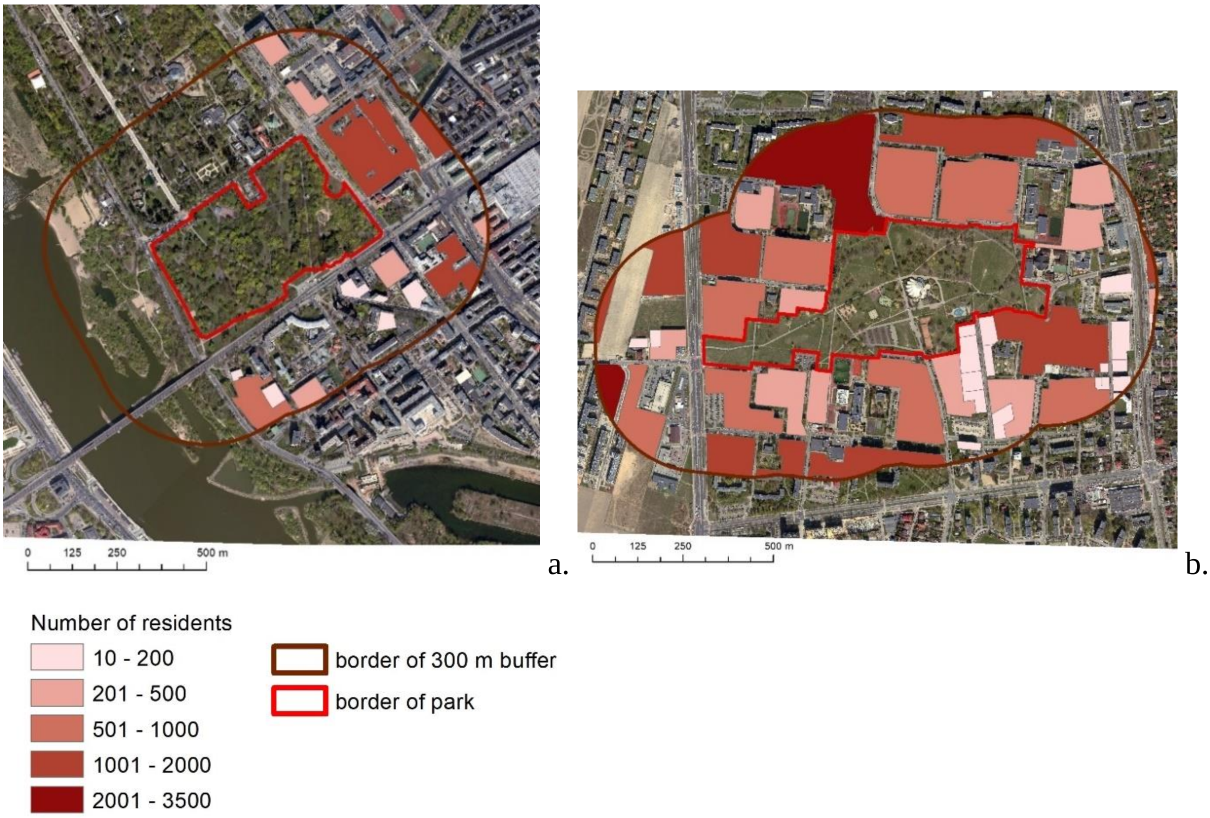

Fig. 14. Number of residents living within a 300 m buffer from the borders of the parks: a. Praski Park, b. Górczewska Park

Table 8. Indicator of the potential of urban green infrastructure accompanying various types of housing estates for recreation and recuperation in nature and its components

Study area	District	Type of housing estate	Area [ha]	Impervious area [%]	Number of residents	Tree cover density [%]	BAA [$m^2 \cdot person^{-1}$]	Access*	Diversity index	Indicator of potential
Nowa Praga	Praga Północ	tenement	6.1	56.6	2411	5.9 [0]	11.1 [1]	d [1]	4.03 [1]	3
Śródmieście Północne	Śródmieście	tenement	11.0	90.6	1766	0.4 [0]	5.8 [0]	bd [0]	3.84 [1]	1
Chomiczówka	Bielany	large-scale	22.0	22.3	4009	27.6 [1]	42.6 [1]	d [1]	4.02 [1]	4
Bemowo-Lotnisko	Bemowo	large-scale	17.9	50.0	8095	6.7 [0]	11.1 [1]	bd [0]	3.98 [1]	2
Zacisze	Targówek	single-family	30.4	44.8	2497	7.7 [0]	67.0 [1]	bd [0]	4.03 [1]	2
Anin	Wawer	single-family	21.5	9.5	377	51.5 [1]	516.8 [1]	bd [0]	2.44 [0]	2

* d/bd – access /no access

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