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

Urban ecosystems

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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.

Instytut Geografii i Przestrzennego Zagospodarowania im. Stanisława Leszczyckiego
Polska Akademia Nauk

Marek Degórski, Andrzej Affek, Bożena Degórska, Anna Kowalska, Jacek Wolski, Jerzy Solon, Edyta Regulska

Summary Report

Identification of the significant interactions (synergies and trade-offs between ecosystem services and important ES bundles on the example of Warsaw

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 rapidly urbanizing world, cities have become major centres of demand for ecosystem services (ES) as well as places with high environmental impact. In the future, cities' pressure on ecosystems will increase, as will their spatial and demographic development. Urbanization, therefore, presents fundamental challenges to sustainable development, but also creates unprecedented opportunities for innovative forms of design and management of urban ecosystems to secure their ability to sustain ES and their resilience to cope with changes in the geographic mega-system. Planning and strategic documents increasingly emphasize the huge role of blue-green infrastructure (BGI), which is perceived as a key component of urban space in building adaptive capacity to deal with climate change and other global changes (Depietri et al., 2012). Strategies based on investments in urban green infrastructure and adaptation to climate change based on ecosystems are gaining more and more interest all over the world, especially as such investments simultaneously generate many ES, improving human well-being (Elmqvist et al. 2013, 2016).

There are many studies that model and map ES, however integrating the results of ES assessments to provide recommendations for spatial planning based on nature's potential remains a very important challenge. Moreover, the studies emphasize an important role of identification of ES synergies and trade-offs as well as ES bundles and hotspots in planning processes and at the stage of preparing development strategies (Cueva et al., 2022; Lourdes et al., 2022).

The aim of the fourth stage of the task on urban ecosystems within the project "Services provided by main types of ecosystems in Poland – an applied approach" was to identify significant ES interactions (synergies and trade-offs), and important ES bundles and hotspots. Our research focused on seven ES calculated for Warsaw, selected as the case study. The choice of services resulted from indications of the representatives of the Warsaw City Hall (Studium ..., 2020) and the availability of data needed to calculate individual indicators. However, the report presents the methodology and analytical procedure that can be implemented in other Polish cities at the level of local planning. The obtained results may be very useful in determining the directions of commune (city) spatial development expressed in the "Study of conditions and directions of spatial development". Knowledge of the ES interactions allows for optimization of solutions in the development of urban space in terms of improving the living conditions of residents and their well-being.

2. CHARACTERISTICS OF THE STUDY AREA

Warsaw was chosen as a case study for detailed research. It is the capital of Poland and at the same time the largest city, with a population of nearly 1.8 million people (Report, 2021). However, during a working day there are approx. 2.5 million people (Bijak and Kicinger, 2007). Warsaw occupies 517.2 square kilometers, so there are on average 3 467 people per square kilometer. The population density of Warsaw ranges from 992 people/km^2 in Wawer district to 8 438 people/km^2 in Ochota district (GUS, 2021). Administratively, Warsaw constitutes an urban municipality divided into 18 districts. In addition, Warsaw is divided into 143 units of the Municipal Information System (MSI), which is the city's local signage system. In this study, MSI units were used to present part of the study results (Figure 1).

Figure 1. Districts and units of the Municipal Information System (MSI) in Warsaw

Functional and spatial structure of the city constitute one of its most important characteristics, considering ecosystem service and local spatial planning. According to the register of functional structure in Warsaw, which is updated on an ongoing basis by the Warsaw City Hall, 32 functional types of land use have been distinguished (Table 1). Individual areas representing the functional types of land were the basis for the assessments presented in this report. Averaged values for functional types correspond to the indicators of the potential of ES, described in Chapter 4.

The most distinctive feature of land use in Warsaw is that in contrast to intensively built-up and heavily transformed areas, there are also significant areas of arable land and above all, there are also fairly natural and seminatural areas such as large complexes of valuable forests and meadows (Figure 2).

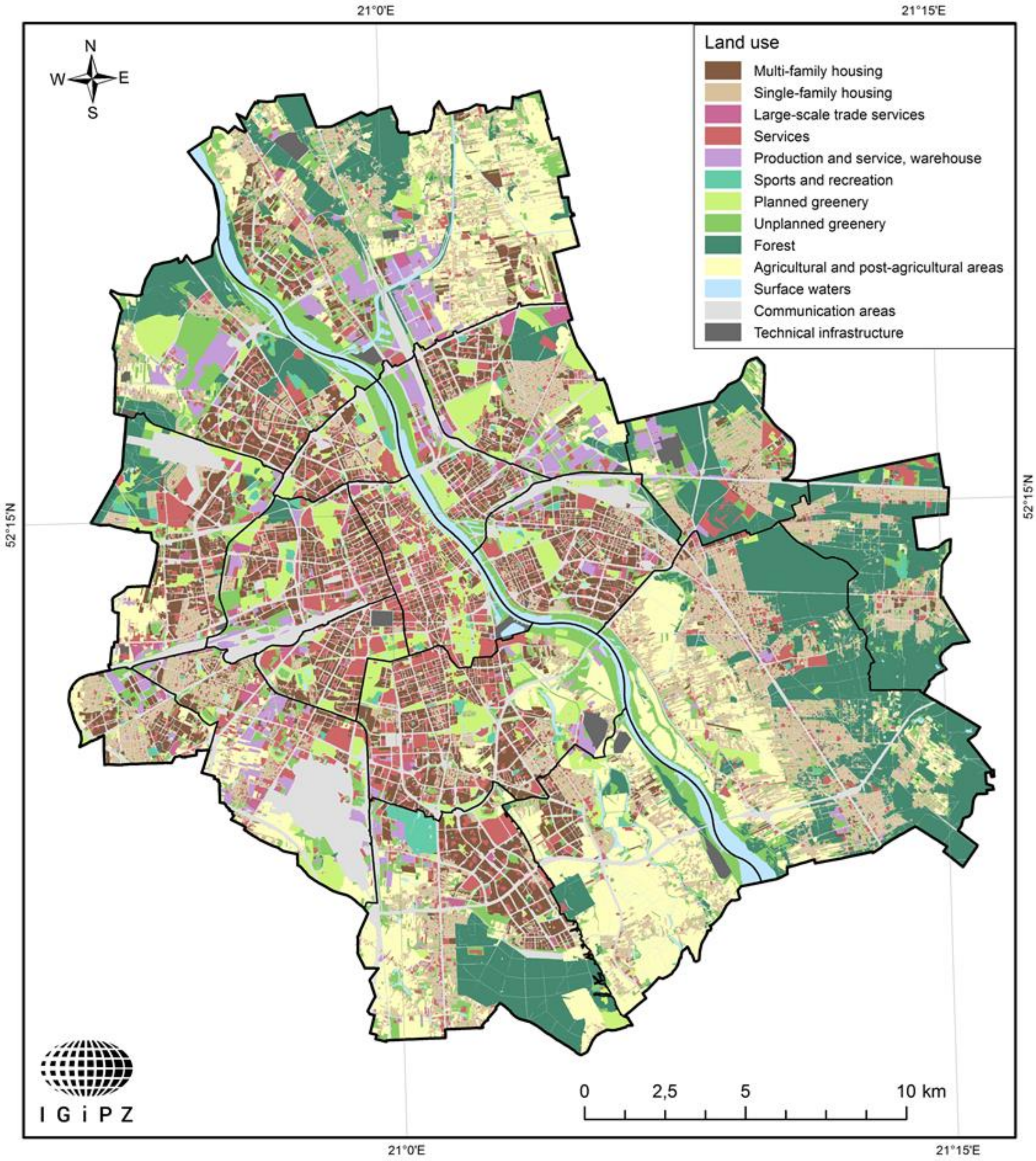


Figure 2. Map of land use in Warsaw

Table 1. Land functions and characteristics in Warsaw

Land functions	Area [ha]	%	Number of patches	Average area of patches [ha]	Standard deviation
Multi-family housing	2728.10	5.28	3518	0.692	1.269

Multi-family housing (estates with an increased share of greenery)	2549.53	4.93	1091	2.343	2.955
Single-family housing	5738.89	11.10	10197	0.545	0.672
Single-family housing (in forest areas)	233.11	0.45	856	0.261	0.384
Large-scale trade services	356.87	0.69	77	4.658	5.774
Social services (education)	752.72	1.46	995	0.734	0.778
Social services (science)	498.03	0.96	199	2.488	6.282
Social services (culture)	107.49	0.21	184	0.532	1.177
Social services (health)	241.03	0.47	276	0.867	2.501
Other services (public administration)	553.21	1.07	401	1.392	4.33
Other services (trade)	560.55	1.08	2057	0.276	0.511
Other services (religious worship)	155.26	0.30	230	0.678	0.689
Other services (offices)	1090.80	2.11	2481	0.43	0.978
Other services (tourism / hotels)	67.41	0.13	129	0.515	0.755
Sports services (with cubature)	109.91	0.21	68	1.57	3.821
Sports and recreation (sports fields / playgrounds)	482.02	0.93	268	1.757	6.536
Production and service, warehouse and post-production areas	1729.51	3.34	973	1.835	5.577
Forest	7941.00	15.36	3298	2.423	7.766
Planned greenery	1062.00	2.05	530	1.95	5.293
Unplanned greenery with dominance of trees	2831.11	5.47	4358	0.665	2.862
Different greenery, undeveloped areas	2289.78	4.43	5098	0.453	1.833
Allotment gardens	1330.43	2.57	280	4.837	8.517
Cemeteries	481.63	0.93	46	10.462	27.33
Agricultural and post-agricultural areas	6611.21	12.78	2337	3.083	6.678
Surface waters	1590.79	3.08	1814	0.885	10.181
Surface waters (in parks)	86.79	0.17	239	0.362	0.826
Technical infrastructure	473.91	0.92	364	1.335	6.478
Depots, facilities and devices for public transport service	134.27	0.26	19	5.621	6.611
Road communication facilities and devices	343.34	0.66	820	0.456	0.64
Airports	793.56	1.53	19	41.691	135.778
Railway transport facilities and devices	1183.64	2.29	112	10.838	35.123
Roads	6604.88	12.77	314	19.86	80.498

From urban ecosystem services point of view, the functional structure of Warsaw can be considered very favourable. As much as 46.8% of the total area of this city is occupied by green and blue infrastructure (urban agriculture is included into this category). Significant share of forests (15.4%) in the functional structure of Warsaw constitutes another factor worth special attention. In the total area of green and blue infrastructure, the share of forests amounts to

32.8%. Many of Warsaw's forest complexes have been included into various forms of legal nature protection, with more important ones constituted by: Natura 2000, landscape park, nature reserves, protected landscape areas. According to the current Warsaw's Spatial Development Conditions and Directions Study, almost all forest ecosystems constitute an essential component of the Natural System of Warsaw, designated in this planning document. Better adaptation of forests for recreation and leisure services represents a positive change, while increasing fragmentation and isolation due to build-up of ecotone zones, following currently increasing pressure on private forest plots to be turned into residential development, represents a negative change.

Areas with planned greenery (developed greenery), mainly urban parks, are located in zones of high population density and high development intensity, mainly in the core districts of Warsaw. They occupy only 2% of the city's area (Table 1). Warsaw has a significant shortage of urban parks in other districts, although several have been created in recent years. Currently, more and more attention is being paid to the process of greening streets and squares, creating pocket parks, rain gardens, and occasionally green roofs and vertical gardens. Warsaw green infrastructure includes also unplanned (undeveloped) green areas, tree plantings, allotment gardens, cemeteries, the greenery of other unbuilt and undeveloped areas, which together account for about 13% of the city's area (Table 1). It is worth noting that during the COVID 19 pandemic, interest in recreation and owning an allotment gardens in the city has significantly increased. However, only a few gardens in Warsaw are made available as walking areas for people from outside of the allotment association. Large area is still occupied by urban agriculture (12.4%), although this land has been systematically developed.

The Vistula River definitely stands out in the spatial structure of the city. The length of its Warsaw section amounts to 31.5 km. River divides the city into two parts and in view of poor infrastructure connectivity, determines the development of the city, mainly its right bank part. The Vistula River plays an important role in creating the cultural and landscape potential of Warsaw. Recently, the use of its recreational potential has increased. Due to water pollution swimming in the river is still unavailable.

The Vistula River valley in the zone between the flood embankments, apart from the inner-city, mainly left-bank section of the developed waterfront, is characterised by high naturalness and valuable ecosystems. This strip is among others an international ecological corridor, an ornithofauna sanctuary, a bird migration route and a concentration of valuable biodiversity. These values are reflected as an inclusion of this range into the Natura 2000 network and a creation of several nature reserves. However, the Vistula River poses also a flood hazard, due to the location of some of development areas, mainly residential, within a zone under the risk of breaking the flood embankments. Total share of surface water accounts for approximately 3% of the city's area.

Green areas accompany also the built-up areas of various functions, with residential development accounting for the majority. Share of single-family housing in the city's area amounts to 11.6%, while multi-family housing amounts to only slightly less i.e. 10.2%. Many residential areas are characterised by an increased proportion of greenery, which is predominant in the case of multi-family developments, mainly from the 1970s and 1980s. However, the density of both types of development has increased in recent years. Houses are built on smaller and smaller plots of land. Such trends contribute to a reduction in biologically active area and

urban ecosystem services. Nonetheless, there has been recently a little more attention paid to the development of green spaces close to the places of people residence, as well as close to the other buildings. This is particularly important in terms of current climate change and needs of children, as well as of large population of the elderly living in Warsaw.
Warsaw, as already noted, is characterised by a large area under nature protection. In total, the area of special nature value under legal protection within the city amounts to 18 546.9 hectares (some of the forms overlap). These are: European Ecological Network Natura 2000 (6 sites), 12 nature reserves, Mazovian Landscape Park, Warsaw Protected Landscape Area, 5 ecological areas, 5 landscape-nature complexes, 486 monuments of nature (data according to the Warsaw Ecophysiographic Atlas), (Atlas Ekofizjograficzny Warszawy 2018).

The detailed functional structure of the land in Warsaw is presented in Table 1, and the aggregated spatial structure in Figure 2.

3. ASSESSMENT OF THE ECOSYSTEM SERVICES POTENTIAL IMPORTANT FOR URBAN ECOSYSTEMS

3.1. Wild plants (terrestrial and aquatic) for nutrition, materials or energy (PROD)

One of the strategies for sustainable development is the shift towards renewable energy sources such as biomass, which should be generated locally (Kammen and Sunter, 2016). The potential of urban areas for biomass production is rarely exploited, although many of its sources are in cities, from the fringes of roads to public parks. However, there is a growing interest in these potential biomass sources as they are close to consumers and offer opportunities to reduce the maintenance costs of urban green areas (Brunzel et al., 2018; Sikorska et al., 2020).

The indicandum is the potential of urban functional types for the production of biomass used as a source of "clean" energy, and the indicator is the average annual gross primary production of individual functional types. The values of the average gross primary production were converted into a five-point rank scale (Table 2).

Table 2. Average annual gross primary production in different urban functional types. In brackets, the potential on a rank scale from 1 to 5

Land use	Value of the indicator [PPI × day]
Multi-family housing	433.1 [1]
Multi-family housing (estates with an increased share of greenery)	790.6 [3]
Single-family housing	768.4 [3]
Single-family housing (in forest areas)	865.1 [3]
Large-scale trade services	200.5 [1]
Social services (education)	640.4 [2]
Social services (science)	722.0 [3]
Social services (culture)	509.0 [2]
Social services (health)	616.3 [2]
Other services (public administration)	633.8 [2]

Other services (trade)	360.0 [1]
Other services (religious worship)	644.8 [2]
Other services (offices)	384.4 [1]
Other services (tourism / hotels)	427.9 [1]
Sports services (with cubature)	747.7 [3]
Sports and recreation (sports fields / playgrounds)	1271.8 [5]
Production and service, warehouse and post-production areas	401.5 [1]
Forest	1156.4 [5]
Planned greenery	1481.4 [5]
Unplanned greenery with dominance of trees	1503.3 [5]
Different greenery, undeveloped areas	1261.1 [5]
Allotment gardens	1293.7 [5]
Cemeteries	971.8 [4]
Agricultural and post-agricultural areas	1509.5 [5]
Surface waters	491.6 [1]
Surface waters (in parks)	724.4 [3]
Technical infrastructure	749.7 [3]
Depots, facilities and devices for public transport service	361.0 [1]
Road communication facilities and devices	493.9 [1]
Airports	964.4 [4]
Railway transport facilities and devices	700.3 [3]
Roads	560.4 [2]

PPI – Plant Phenology Index (Jin and Eklundh, 2014)

3.2. Erosion reduction by vegetation (EROSION)

Water erosion, and in particular surface erosion, is one of the main causes of soil degradation in Europe. For Poland, the average soil loss as a result of water erosion is estimated at over 70 × 103 × kg · km^{-2} · year^{-1} (Józefaciuk and Józefaciuk, 1995), and on a local scale, depending on abiotic conditions and land use, it may exceed 250 · 103 · kg · km^{-2} · year^{-1} (Maruszczak, 1991), which is a serious economic and environmental problem. The problem is particularly important in agricultural areas, while in cities, surface water erosion is important mainly in areas outside the strict city core. The vegetation cover of the city reduces potential erosion. Its influence depends on the type of plant community, as well as the morphology of individual species (including, among others, the size and durability of leaves and the type of root system), their height and density.

The indicandum is the potential of urban functional types to reduce the risk of water erosion, and the area-weighted indicator is the average coefficient of reduction of surface erosion by vegetation. The erosion reduction coefficients assigned to individual vegetation types were determined on the basis of literature data (according to Gassman et al., 2007; Benavidez et al., 2018) and presented in detail in another study (Degórski et al., 2021).

The value of the indicator was calculated separately for each individual area with a specific functional type and then averaged for the urban functional types. The calculated index values were converted into a five-point rank scale (Table 3).

Table 3. Factors for reducing the risk of surface water erosion by vegetation as an indicator of the potential of urban functional types to reduce erosion. In brackets the potential on a scale from 1 to 5, where 1 is the smallest potential and 5 the greatest potential

Land use	Value of the indicator
Multi-family housing	0.07 [2]
Multi-family housing (estates with an increased share of greenery)	0.07 [2]
Single-family housing	0.07 [2]
Single-family housing (in forest areas)	0.07 [2]
Large-scale trade services	0.07 [2]
Social services (education)	0.07 [2]
Social services (science)	0.0698 [2]
Social services (culture)	0.07 [2]
Social services (health)	0.07 [2]
Other services (public administration)	0.0699 [2]
Other services (trade)	0.07 [2]
Other services (religious worship)	0.07 [2]
Other services (offices)	0.07 [2]
Other services (tourism / hotels)	0.07 [2]
Sports services (with cubature)	0.05 [3]
Sports and recreation (sports fields / playgrounds)	0.0489 [3]
Production and service, warehouse and post-production areas	0.0992 [1]
Forest	0.0131 [4]
Planned greenery	0.0401 [4]
Unplanned greenery with dominance of trees	0.0413 [4]
Different greenery, undeveloped areas	0.0587 [2]
Allotment gardens	0.05 [3]
Cemeteries	0.049 [3]
Agricultural and post-agricultural areas	0.0497 [3]
Surface waters	0.0034 [5]
Surface waters (in parks)	0.0051 [5]
Technical infrastructure	0.0982 [1]
Depots, facilities and devices for public transport service	0.0932 [1]
Road communication facilities and devices	0.0971 [1]
Airports	0.0273 [4]
Railway transport facilities and devices	0.0996 [1]
Roads	0.05 [3]

3.3. Hydrological cycle and water flow regulation (including flood control, and coastal protection) – (HYDRO)

The urban development increases the share of impervious surfaces. The effect of soil sealing is a deterioration of the infiltration properties of the substrate, and thus a greater risk of flash floods and waterlogging, a deterioration in water quality (Tu et al., 2007; Livesley, 2016), and rapid fluctuations in the stream flow (Paul and Meyer, 2001; Schoonover et al., 2006). Thus, surface sealing has a significant impact on the overall urban water balance (Haase and Nuissl, 2007). Trees also play a key role in the hydrological cycle in cities (Crockford and Richardson, 2000). Their crowns effectively reduce the runoff of rainwater thanks to the interception process consisting in partial retention and storage of rainwater on the surface of leaves. Moreover, the roots penetrating the compacted soil increase the infiltration coefficient (Puchalski and Prusinkiewicz, 1990; Bartens et al., 2008, 2009).

The used indicator takes into account: infiltration properties of lithological material and soil substrate, the degree of soil permeability, the tree cover density and the type of foliage (Table 4). The theoretical justification and the methodology of the indicator calculation are presented in detail in another study (Degórski et al., 2021).

Table 4. Average value of the infiltration-interception coefficient as an indicator of the potential ability of the subsoil and tree crowns to regulate water conditions in the urban functional types. In brackets, the potential on a rank scale from 1 to 5

Land use	Value of the indicator
Multi-family housing	0.30 [1]
Multi-family housing (estates with an increased share of greenery)	0.51 [3]
Single-family housing	0.47 [2]
Single-family housing (in forest areas)	0.65 [4]
Large-scale trade services	0.09 [1]
Social services (education)	0.42 [2]
Social services (science)	0.46 [2]
Social services (culture)	0.36 [1]
Social services (health)	0.42 [2]
Other services (public administration)	0.43 [2]
Other services (trade)	0.25 [1]
Other services (religious worship)	0.39 [1]
Other services (offices)	0.26 [1]
Other services (tourism / hotels)	0.28 [1]
Sports services (with cubature)	0.35 [1]
Sports and recreation (sports fields / playgrounds)	0.58 [3]
Production and service, warehouse and post-production areas	0.26 [1]
Forest	0.84 [5]
Planned greenery	0.69 [4]
Unplanned greenery with dominance of trees	0.71 [5]
Different greenery, undeveloped areas	0.55 [3]
Allotment gardens	0.59 [3]
Cemeteries	0.63 [4]
Agricultural and post-agricultural areas	0.52 [3]
Surface waters	not applicable
Surface waters (in parks)	not applicable
Technical infrastructure	0.39 [1]
Depots, facilities and devices for public transport service	0.21 [1]
Road communication facilities and devices	0.30 [1]
Airports	0.48 [2]
Railway transport facilities and devices	0.50 [2]
Roads	0.37 [1]

3.4. Regulation of air temperature and humidity (TEMP)

From the point of view of the quality of life in the city, high air temperatures are particularly dangerous. In urban areas, the global increase in air temperature is additionally reinforced by the urban heat island (UHI) effect. UHI is defined as a climatic phenomenon consisting in the occurrence of an increased air temperature in a city in relation to the surrounding peripheral areas (Błażejczyk et al., 2014). In the period of high air temperatures, UHI shows an aggravating effect on the functioning of the human body by increasing heat stress (Kuchcik, 2017). In addition to its health effects, UHI increases summer energy demand, air conditioning costs, air pollution and greenhouse gas emissions, and reduces water quality. UHI can be determined on the basis of two characteristics: (1) air temperature (atmospheric UHI) or (2) surface temperature (surface UHI).

The indicandum is the potential of the UHI reduction, and the indicator is the difference in temperature of the land surface compared to the reference surface. The smaller the temperature difference relative to the reference plot, the greater the potential of ecosystems within a given urban functional type to reduce the UHI.

To estimate the potential of ecosystems to reduce the UHI, multispectral images recorded by the Landsat 8 satellite at a resolution of 30 × 30 m were used. A modified so-called single-channel algorithm developed by Jimenez-Munoz et al.(2009) was used to calculate the land surface temperature (LST). Methodological details were given in the previous report (Degórski et al., 2021).

The calculated indicator of the potential of ecosystems to reduce the UHI shows that the greatest potential is characteristic of ecosystems in the areas of surface waters (0.5°C) and forests (2.1°C), as well as in unplanned green areas with dominance of trees (2.9°C) and surface waters in parks (3.3°C).

In turn, the lowest potential is characteristic of ecosystems in areas with a commercial function, in particular in large-scale trade services (10.5°C), in the areas of depots and other public transport facilities, as well as in areas with production and service, warehouse and post-production functions (8.4°C) (Table 5). The raw values of the index were transformed to the five-point rank scale of the potential with the following ranges (>8°C → 1; 6-8°C → 2; 4-6°C → 3; 2-4°C → 4; <2°C → 5).

Table 5. Average difference in the temperature of the land surface in relation to the reference area as an indicator of the potential to reduce the UHI by the urban functional types. In brackets the potential on a scale from 1 to 5, where 1 is the lowest potential and 5 the highest potential

Land use	Value of the indicator [ºC]
Multi-family housing	7.03 [2]
Multi-family housing (estates with an increased share of greenery)	6.76 [2]
Single-family housing	5.98 [3]
Single-family housing (in forest areas)	3.67 [4]
Large-scale trade services	10.53 [1]
Social services (education)	7.20 [2]
Social services (science)	6.94 [2]
Social services (culture)	6.81 [2]
Social services (health)	7.18 [2]
Other services (public administration)	6.97 [2]
Other services (trade)	7.58 [2]
Other services (religious worship)	6.83 [2]
Other services (offices)	7.65 [2]

Other services (tourism / hotels)	6.93 [2]
Sports services (with cubature)	6.75 [2]
Sports and recreation (sports fields / playgrounds)	5.30 [3]
Production and service, warehouse and post-production areas	8.44 [1]
Forest	2.06 [4]
Planned greenery	4.44 [3]
Unplanned greenery with dominance of trees	2.94 [4]
Different greenery, undeveloped areas	5.74 [3]
Allotment gardens	4.32 [3]
Cemeteries	4.48 [3]
Agricultural and post-agricultural areas	3.89 [4]
Surface waters	0.52 [5]
Surface waters (in parks)	3.25 [4]
Technical infrastructure	6.52 [2]
Depots, facilities and devices for public transport service	9.32 [1]
Road communication facilities and devices	7.27 [2]
Airports	6.83 [2]
Railway transport facilities and devices	7.06 [2]
Roads	6.58 [2]

3.5. Filtration / sequestration / storage / accumulation by microorganisms, algae, plants and animals (PM)

Air pollution in urban areas is an increasing threat to human health. One of the most dangerous pollutants that is inhaled is particulate matter (PM), which consists of liquid and solid particles, both organic and inorganic, with a diameter ranging from 0.001–100 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 their 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 surface area (Manes et al., 2014; Maes et al., 2016).

The indicandum is the potential of urban functional types for PM accumulation, and the LAI - the ratio of the leaf area to the surface area of individual urban functional types. The index values were converted into a five-point rank scale (Table 6).

Table 6. LAI as an indicator of the PM accumulation potential of urban functional types. In brackets the potential on a scale from 1 to 5, where 1 is the smallest potential and 5 the greatest potential

Land use	Value of the indicator [m^2 m^{-2}]
Multi-family housing	0.80 [2]
Multi-family housing (estates with an increased share of greenery)	1.32 [3]
Single-family housing	1.40 [3]

Single-family housing (in forest areas)	1.74 [4]
Large-scale trade services	0.33 [1]
Social services (education)	1.11 [3]
Social services (science)	1.25 [3]
Social services (culture)	0.99 [2]
Social services (health)	1.09 [3]
Other services (public administration)	1.09 [3]
Other services (trade)	0.59 [2]
Other services (religious worship)	1.06 [3]
Other services (offices)	0.67 [2]
Other services (tourism / hotels)	0.74 [2]
Sports services (with cubature)	1.30 [3]
Sports and recreation (sports fields / playgrounds)	2.03 [4]
Production and service, warehouse and post-production areas	0.68 [2]
Forest	2.54 [5]
Planned greenery	2.57 [5]
Unplanned greenery with dominance of trees	3.08 [5]
Different greenery, undeveloped areas	2.14 [4]
Allotment gardens	2.55 [5]
Cemeteries	1.68 [4]
Agricultural and post-agricultural areas	2.64 [5]
Surface waters	1.32 [3]
Surface waters (in parks)	1.61 [4]
Technical infrastructure	1.13 [3]
Depots, facilities and devices for public transport service	0.49 [1]
Road communication facilities and devices	0.62 [2]
Airports	1.35 [3]
Railway transport facilities and devices	1.28 [3]
Roads	0.92 [2]

3.6. Physical and experimental interactions with natural environment (REC)

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). The recreational values of green areas are closely related to their aesthetic values, as well as climatic 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 (largely dependent on shading and evapotranspiration) are much greater in green areas with trees compared to green areas without trees (Armson et al., 2012; Skelhorn et al., 2014; Yu et al., 2020; Zardo et al., 2017). When assessing the potential of green areas for recreation, as in the case of other cultural services, it is also worth considering the preferences and needs of people using them. The best source of knowledge is the direct opinions of city residents (e.g. Coles and Bussey, 2000; De Luca et al., 2021).

The indicandum is the potential of urban functional types for recreation and recuperation in nature. The indicator was built based on data on (1) the average tree cover density for a given type (%) and (2) the frequency of indications of particular types as recreational areas by city residents (%) in an online survey. The percentages were converted to a five-point rank scale, and then (3) the mean rank (from 1 and 2) for each urban functional type was presented as the potential (Table 7).

Table 7. The potential of urban functional types for recreation and recuperation in nature (3) - 1 means the lowest potential, 5 the greatest potential; average tree cover density (1); frequency of indications of particular functional types as recreational areas by city residents (2)

Land use	Value of the indicator (1) [%]	Value of the indicator (2) [%]	Value of the indicator (3)
Multi-family housing	5.26 [1]	2.0 [2]	2
Multi-family housing (estates with an increased share of greenery)	19.68 [2]	6.0 [4]	3
Single-family housing	17.25 [2]	0.0 [0]	1
Single-family housing (in forest areas)	32.08 [3]	0.0 [0]	2
Large-scale trade services	0.51 [1]	0.0 [0]	1
Social services (education)	12.65 [2]	0.0 [0]	1
Social services (science)	15.28 [2]	0.0 [0]	1
Social services (culture)	8.46 [1]	0.5 [1]	1
Social services (health)	14.38 [2]	0.2 [1]	2
Other services (public administration)	12.52 [2]	0.2 [1]	2
Other services (trade)	3.18 [1]	0.0 [0]	1
Other services (religious worship)	11.83 [2]	0.0 [0]	1
Other services (offices)	4.58 [1]	0.0 [0]	1
Other services (tourism / hotels)	5.69 [1]	0.0 [0]	1
Sports services (with cubature)	8.98 [1]	0.0 [0]	1
Sports and recreation (sports fields / playgrounds)	14.58 [2]	2.0 [2]	2
Production and service, warehouse and post-production areas	4.35 [1]	0.0 [0]	1
Forest	75.89 [5]	26.4 [5]	5
Planned greenery	39.05 [3]	32.7 [5]	4
Unplanned greenery with dominance of trees	57.32 [4]	8.7 [4]	4
Different greenery, undeveloped areas	19.71 [2]	2.7 [2]	2
Allotment gardens	42.12 [3]	4.7 [3]	3
Cemeteries	25.45 [2]	0.2 [1]	2
Agricultural and post-agricultural areas	15.42 [2]	4.7 [3]	3
Surface waters	10.68 [2]	1.7 [2]	2
Surface waters (in parks)	18.76 [2]	6.7 [4]	3
Technical infrastructure	6.85 [1]	0.0 [0]	1
Depots, facilities and devices for public transport service	2.54 [1]	0.0 [0]	1
Road communication facilities and devices	3.93 [1]	0.0 [0]	1
Airports	3.47 [1]	0.0 [0]	1
Railway transport facilities and devices	12.42 [2]	0.2 [1]	2
Roads	8.28 [1]	0.0 [0]	1

3.7. Intellectual and representative interactions with natural environment (EDU)

Many studies to date (Affek and Kowalska, 2017; Hutcheson et al., 2018) have shown that the awareness of the ecological processes taking place and the benefits of nature increases with the frequency of direct interactions with the natural environment, therefore ecological education in nature is of particular importance for promoting principles of sustainable development in society. Getting to know nature can take place through spontaneous contact (e.g. watching the animal habits, observing the development of plants), as well as using the field infrastructure for environmental education, based on the potential of a given place (e.g. information boards, educational paths, identifiers of tree species, e-guides). Natural areas in the immediate vicinity of places of residence are particularly important in terms of interactions with nature. They create refuge areas for flora and fauna in the urban space subject to enormous urban pressure (Elmqvist et al., 2013).

The indicandum is the potential of urban functional types for environmental education in nature, and the indicator is the percentage share of valuable natural areas in the area of urban functional types. The selection of areas was made based on experiences from the ecological inventory of the Warsaw City Hall and the list of conditions for the study (Studium…, 2020). The percentages were converted to a five-point ranking scale (Table 8).

Table 8. Percentage share of valuable natural areas as an indicator of the potential of urban functional types for environmental education in nature. In brackets the potential on a scale from 1 to 5, where 1 is the smallest potential and 5 the greatest potential

Land use	Value of the indicator
Multi-family housing	5.14 [1]
Multi-family housing (estates with an increased share of greenery)	1.69 [1]
Single-family housing	11.89 [2]
Single-family housing (in forest areas)	79.38 [4]
Large-scale trade services	0.89 [1]
Social services (education)	6.86 [1]
Social services (science)	15.28 [2]
Social services (culture)	15.76 [2]
Social services (health)	14.01 [2]
Other services (public administration)	28.79 [3]
Other services (trade)	4.43 [1]
Other services (religious worship)	11.95 [2]
Other services (offices)	8.63 [1]
Other services (tourism / hotels)	17.76 [2]
Sports services (with cubature)	7.83 [1]
Sports and recreation (sports fields / playgrounds)	29.15 [3]
Production and service, warehouse and post-production areas	3.96 [1]
Forest	92.01 [5]
Planned greenery	59.42 [4]
Unplanned greenery with dominance of trees	62.23 [4]
Different greenery, undeveloped areas	15.38 [2]
Allotment gardens	27.14 [3]
Cemeteries	55.36 [4]
Agricultural and post-agricultural areas	40.95 [3]
Surface waters	92.86 [5]
Surface waters (in parks)	88.11 [5]
Technical infrastructure	27.18 [3]
Depots, facilities and devices for public transport service	0.62 [1]

Road communication facilities and devices	7.37 [1]
Airports	3.04 [1]
Railway transport facilities and devices	6.36 [1]
Roads	14.18 2]

4. AGGREGATE MATRIX FOR ASSESSING POTENTIAL

The obtained rank values for the seven indicators were used to calculate aggregate potentials and multi-service hotspots, as well as to analyze the interactions between services. The values of ranks (on a scale of 1-5) are presented in the form of a table (matrix of indicators and urban functional types - Table 9, Fig. 3). The adopted rank scale and tabular layout are based on the solutions proposed by Burkhard et al. (2014, 2012, 2009). Hereby, the obtained results can be easily compared with the works of these and other authors, even if the methodology of indicators and the area of research are different.

Table 9. The potential of urban ecosystems to provide ES according to the urban functional types, based on the example of Warsaw. Potential on a scale of 1-5, where 1 - very low potential, 5 - very high potential, N - not applicable

Land use		Provisioning	Regulation and maintenance				Cultural	
		PROD	EROSION	HYDRO	PM	TEMP	REC	EDU
Multi-family housing	MW	1	2	1	2	2	2	1
Multi-family housing (estates with an increased share of greenery)	MWZos	3	2	3	3	2	3	1
Single-family housing	MN	3	2	2	3	3	1	2
Single-family housing (in forest areas)	MNL	3	2	4	4	4	2	4
Large-scale trade services	UH/WOH	1	2	1	1	1	1	1
Social services (education)	UO	2	2	2	3	2	1	1
Social services (science)	UN	3	2	2	3	2	1	2
Social services (culture)	UK	2	2	1	2	2	1	2
Social services (health)	UZ	2	2	2	3	2	2	2
Other services (public administration)	UA	2	2	2	3	2	2	3
Other services (trade)	UH	1	2	1	2	2	1	1
Other services (religious worship)	UW	2	2	1	3	2	1	2
Other services (offices)	U	1	2	1	2	2	1	1
Other services (tourism / hotels)	UT	1	2	1	2	2	1	2
Sports services (with cubature)	US	3	3	1	3	2	1	1
Sports and recreation (sports fields / playgrounds)	US-rek	5	3	3	4	3	2	3
Production and service, warehouse and post-production areas	PU	1	1	1	2	1	1	1
Forest	Ls	5	4	5	5	4	5	5
Planned greenery	ZP1	5	4	4	5	3	4	4
Unplanned greenery with dominance of trees	ZN	5	4	5	5	4	4	4
Different greenery, undeveloped undeveloped areas	ZI	5	2	3	4	3	2	2
Allotment gardens	ZD	5	3	3	5	3	3	3

Cemeteries	ZC	4	3	4	4	3	2	4
Agricultural and post-agricultural areas	R	5	3	3	5	4	3	3
Surface waters	W	1	5	N	3	5	2	5
Surface waters (in parks)	W/ZP1	3	5	N	4	4	3	5
Technical infrastructure	I	3	1	1	3	2	1	3
Depots, facilities and devices for public transport service	KM	1	1	1	1	1	1	1
Road communication facilities and devices	KS	1	1	1	2	2	1	1
Airports	KL	4	4	2	3	2	1	1
Railway transport facilities and devices	KK	3	1	2	3	2	2	1
Roads	dr	2	3	1	2	2	1	2

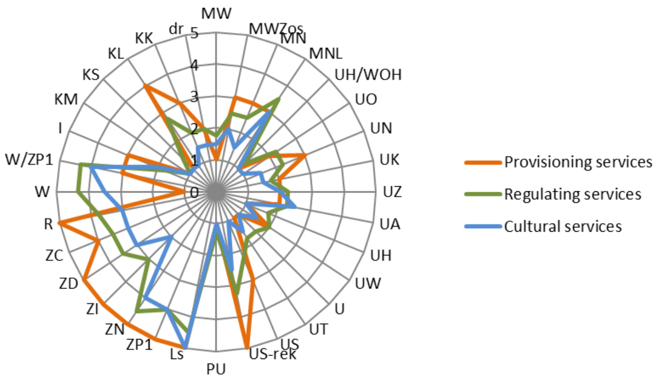


Figure 3. Potential to provide seven services important for urban areas, divided by urban functional types, based on the example of Warsaw (explanations in the table 9).

5. AGGREGATED POTENTIAL

In order to determine the average potential of ecosystems, taking into account the selected seven important services in urban areas, mean values from ranks for a given urban functional type were calculated. Aggregate potential was calculated both for all seven services and broken down into three main sections of services: provisioning, regulating, and cultural Table 10, Fig. 4). We used ranks 1-5 as input. The obtained values were also used to map the total potential for Warsaw at the MSI level (Fig. 5). The scale range on all maps was standardized by adjusting to the extreme values obtained.

In the case of provisioning services, forests, green areas of various types as well as agricultural and post-agricultural areas have the highest aggregate potential. In the case of regulating and cultural services, apart from forests and green areas, both planned and unplanned, surface waters are characterized by a high aggregate potential (Table 10, Figure 4).

Table 10. Aggregate potential to provide ES by urban functional types on the example of Warsaw

Land use		PS	RS	CS	All ES
Multi-family housing	MW	1.00	1.75	1.50	1.57

Multi-family housing (estates with an increased share of greenery)	MWZos	3.00	2.50	2.00	2.43
Single-family housing	MN	3.00	2.50	1.50	2.29
Single-family housing (in forest areas)	MNL	3.00	3.50	3.00	3.29
Large-scale trade services	UH/WOH	1.00	1.25	1.00	1.14
Social services (education)	UO	2.00	2.25	1.00	1.86
Social services (science)	UN	3.00	2.25	1.50	2.14
Social services (culture)	UK	2.00	1.75	1.50	1.71
Social services (health)	UZ	2.00	2.25	2.00	2.14
Other services (public administration)	UA	2.00	2.25	2.50	2.29
Other services (trade)	UH	1.00	1.75	1.00	1.43
Other services (religious worship)	UW	2.00	2.00	1.50	1.86
Other services (offices)	U	1.00	1.75	1.00	1.43
Other services (tourism / hotels)	UT	1.00	1.75	1.50	1.57
Sports services (with cubature)	US	3.00	2.25	1.00	2.00
Sports and recreation (sports fields / playgrounds)	US-rek	5.00	3.25	2.50	3.29
Production and service, warehouse and post-production areas	PU	1.00	1.25	1.00	1.14
Forest	Ls	5.00	4.50	5.00	4.71
Planned greenery	ZP1	5.00	4.00	4.00	4.14
Unplanned greenery with dominance of trees	ZN	5.00	4.50	4.00	4.43
Different greenery, undeveloped areas	ZI	5.00	3.00	2.00	3.00
Allotment gardens	ZD	5.00	3.50	3.00	3.57
Cemeteries	ZC	4.00	3.50	3.00	3.43
Agricultural and post-agricultural areas	R	5.00	3.75	3.00	3.71
Surface waters	W	1.00	4.33	3.50	3.50
Surface waters (in parks)	W/ZP1	3.00	4.33	4.00	4.00
Technical infrastructure	I	3.00	1.75	2.00	2.00
Depots, facilities and devices for public transport service	KM	1.00	1.00	1.00	1.00
Road communication facilities and devices	KS	1.00	1.50	1.00	1.29
Airports	KL	4.00	2.75	1.00	2.43
Railway transport facilities and devices	KK	3.00	2.00	1.50	2.00
Roads	dr	2.00	2.00	1.50	1.86

PS - provisioning services; RS – regulating services; CS – cultural services

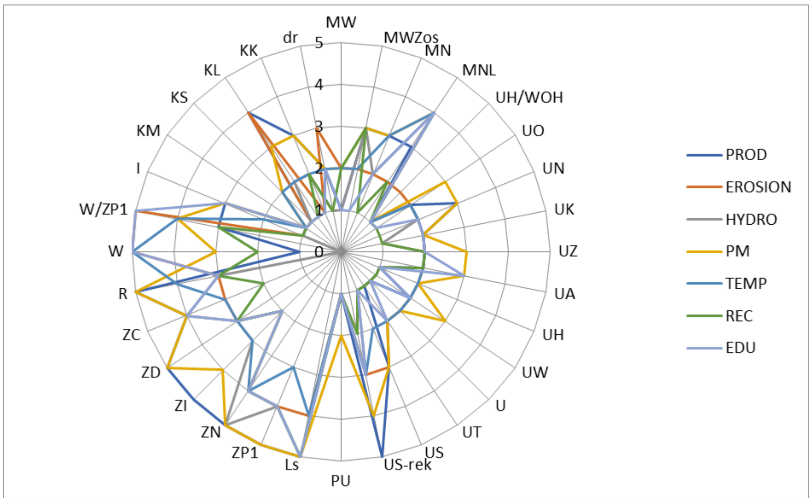


Figure 4. Aggregate potential to provide services from the provisioning, regulating, and cultural sections and jointly for all considered services, broken down by urban functional type, based on the example of Warsaw.

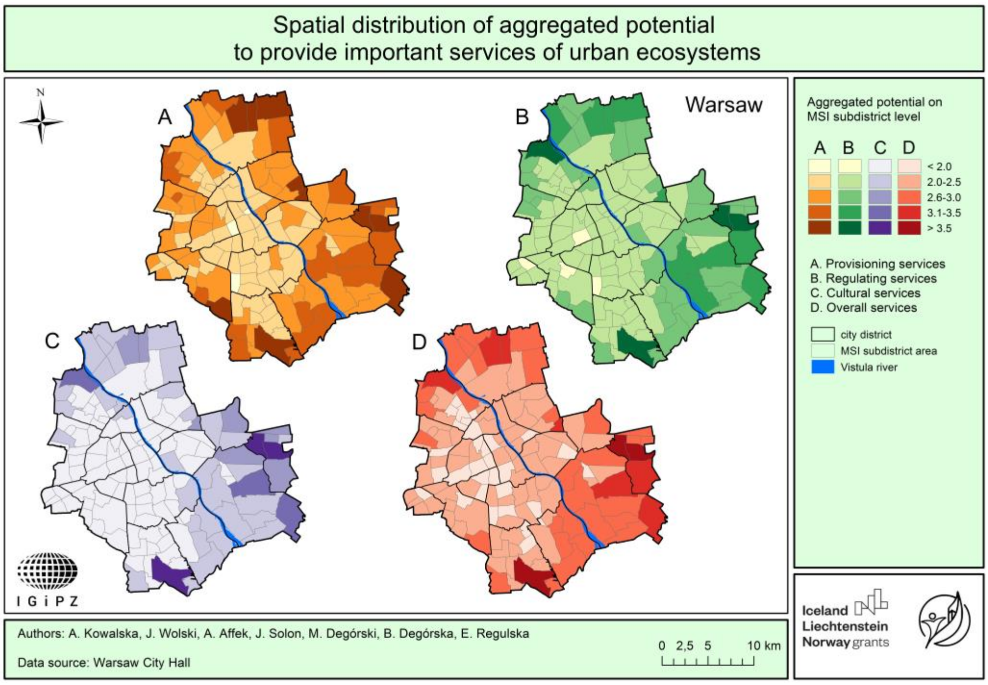


Figure 5. Spatial distribution of aggregated potential (for individual sections and in total) to provide services important for urban areas at the MSI level, based on the example of Warsaw. The scales of individual maps were standardized by adjusting to the obtained extreme values.

6. HOTSPOTS AND THEIR CHARACTERISTICS

Functional types that show high or very high potential (rank 4 or 5) to provide multiple services are designated as hotspots. Moreover, it was assumed that a functional type can be considered a hotspot if it has the potential to provide at least half of the analyzed services at a high or very high level.

In the case of Warsaw, hotspots include forests, green areas of various types, surface waters as well as agricultural and post-agricultural areas; and for regulating and cultural services also single-family housing in forest areas (Table 11).

Table 11. Number and percentage of services with high or very high (rank 4 or 5) potential for a given urban functional type on the example of Warsaw

Land use		PS		RS		CS		All ES	
		N	%	N	%	N	%	N	%
Multi-family housing	MW	0	0	0	0	0	0	0	0
Multi-family housing (estates with an increased share of greenery)	MWZos	0	0	0	0	0	0	0	0
Single-family housing	MN	0	0	0	0	0	0	0	0

Single-family housing (in forest areas)	MNL	0	0	3	75	1	50	4	57
Large-scale trade services	UH/WOH	0	0	0	0	0	0	0	0
Social services (education)	UO	0	0	0	0	0	0	0	0
Social services (science)	UN	0	0	0	0	0	0	0	0
Social services (culture)	UK	0	0	0	0	0	0	0	0
Social services (health)	UZ	0	0	0	0	0	0	0	0
Other services (public administration)	UA	0	0	0	0	0	0	0	0
Other services (trade)	UH	0	0	0	0	0	0	0	0
Other services (religious worship)	UW	0	0	0	0	0	0	0	0
Other services (offices)	U	0	0	0	0	0	0	0	0
Other services (tourism / hotels)	UT	0	0	0	0	0	0	0	0
Sports services (with cubature)	US	0	0	0	0	0	0	0	0
Sports and recreation (sports fields / playgrounds)	US-rek	1	100	1	25	0	0	2	29
Production and service, warehouse and post-production areas	PU	0	0	0	0	0	0	0	0
Forest	Ls	1	100	4	100	2	100	7	100
Planned greenery	ZP1	1	100	3	75	2	100	6	86
Unplanned greenery with dominance of trees	ZN	1	100	4	100	2	100	7	100
Different greenery, undeveloped areas	ZI	1	100	1	25	0	0	2	29
Allotment gardens	ZD	1	100	1	25	0	0	2	29
Cemeteries	ZC	1	100	2	50	1	50	4	57
Agricultural and post-agricultural areas	R	1	100	2	50	0	0	3	43
Surface waters	W	0	0	2	66	1	50	3	50
Surface waters (in parks)	W/ZP1	0	0	3	100	1	50	4	67
Technical infrastructure	I	0	0	0	0	0	0	0	0
Depots, facilities and devices for public transport service	KM	0	0	0	0	0	0	0	0
Road communication facilities and devices	KS	0	0	0	0	0	0	0	0
Airports	KL	1	100	1	0	0	0	2	29
Railway transport facilities and devices	KK	0	0	0	0	0	0	0	0
Roads	dr	0	0	0	0	0	0	0	0

PS - provisioning services; RS – regulating services; CS – cultural services

The largest share of functional types with high and very high ES potential at the MSI level is observed outside the very center of Warsaw, on the outskirts of the city and in the MSI units adjacent to the Vistula valley (Fig. 6).

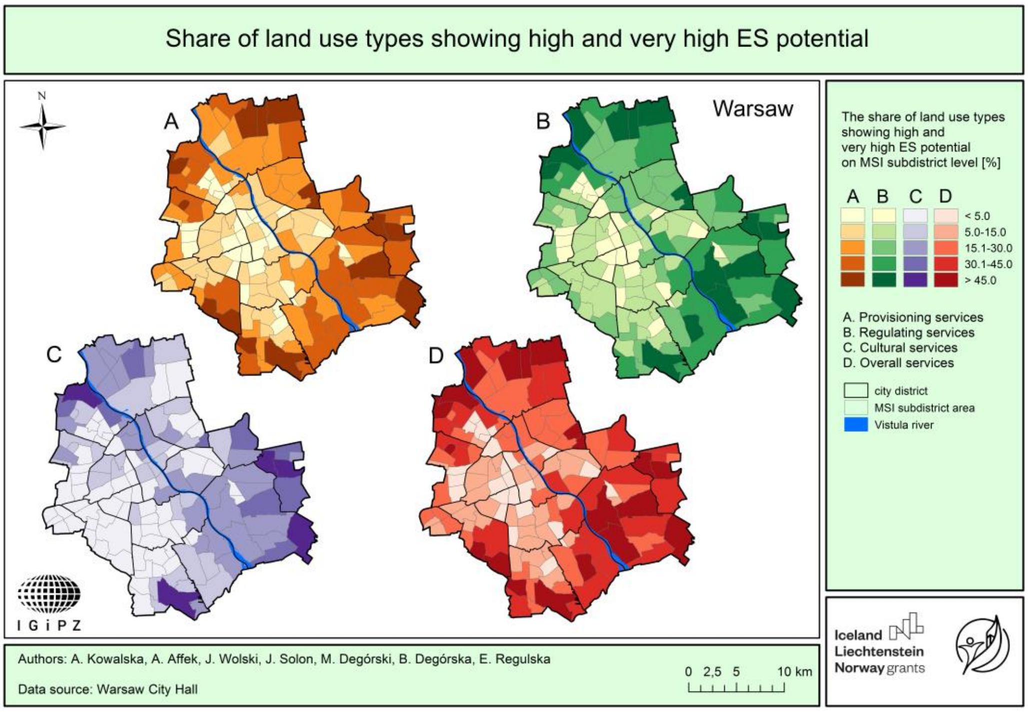


Figure 6. Share of urban functional types with high and very high potential (rank 4 and 5) to provide services (for individual sections and in total) at the MSI level on the example of Warsaw

7. ES BUNDLES

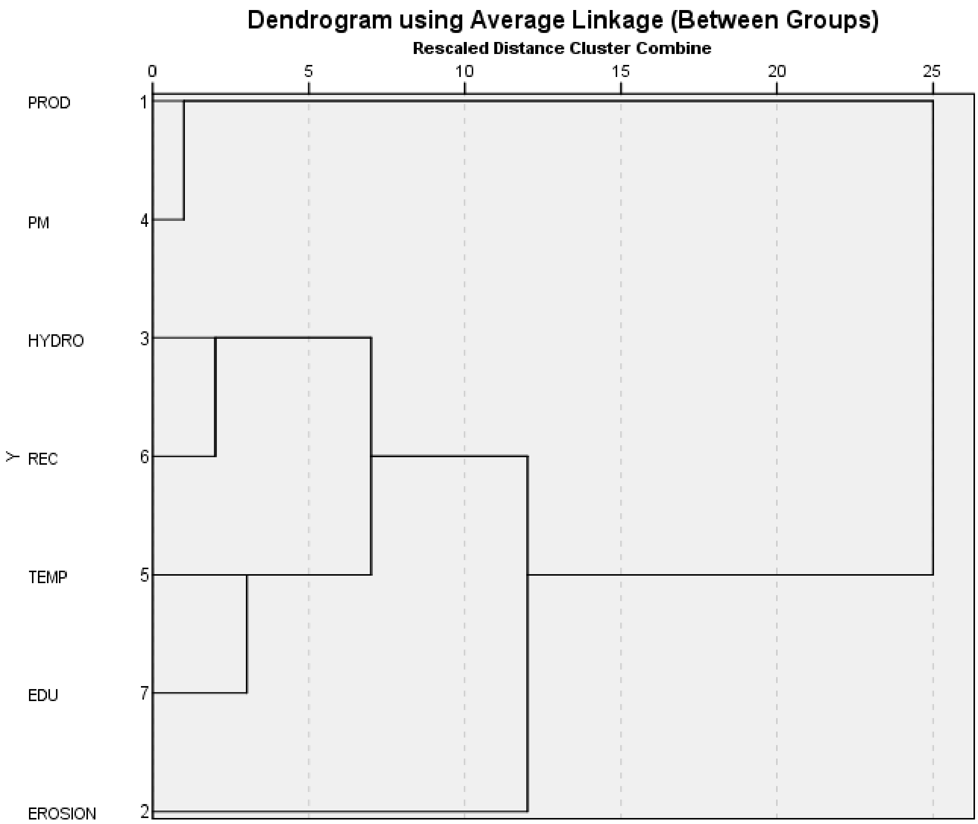
The purpose of this analysis was to identify ES bundles that group services with a similar level of potential supply. A relatively simple statistical tool was used to analyze the relationships between the ES indicators - the correlation matrix analysis. We have investigated synergies and ES trade-offs using pairwise correlations as they are often used as approximate measures of positive and negative ES interactions (Turner et al., 2014; Yang et al., 2015). Although possible synergistic or competitive mechanisms and causal relationships cannot be assessed on their basis, they provide reliable information about the coexistence of certain levels of ES potentials.

We performed a Spearmann r-pair correlation analysis for all ES indicators calculated for the urban functional types (Table 12). If a given type of basic unit was not taken into account when calculating the given service (N), it was omitted when calculating the given pairwise correlation.

Table 12.. Spearmann r-pair correlations between the seven services important for urban ecosystems (N = 30-32). On a gray background the correlation coefficients, on a white background the significance of the coefficient (P values)

	PROD	EROZJA	HYDRO	PYŁY	TEMP	REK	EDU
PROD		0.521	0.837	0.898	0.640	0.626	0.535
EROSION	0.002		0.575	0.604	0.692	0.536	0.606
HYDRO	<0.001	0.001		0.892	0.819	0.830	0.679
PM	<0.001	<0.001	<0.001		0.824	0.779	0.726
TEMP	<0.001	<0.001	<0.001	<0.001		0.708	0.819
REC	<0.001	0.002	<0.001	<0.001	<0.001		0.630
EDU	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	

No trade-offs were observed between the potentials to provide a significant seven services for urban areas. All services are synergistic and form a coherent bundle.



References

Affek, A.N., Kowalska, A., 2017. *Ecosystem potentials to provide services in the view of direct users.* Ecosystem Services, 26: 183-196.

Armson, D., Stringr, P., Ennos, A.R., 2012. *The effect of tree shade and grass on surface and globe temperatures in an urban area*. Urban Forestry and Urban Greening, 11: 245-255.

Atlas Ekofizjograficzny Warszawy, 2018. *Atlas ekofizjograficzny miasta stołecznego Warszawy*. Warszawa. https://architektura.um.warszawa.pl/-/atlas-ekofizjograficzny-warszawy

Benavidez, R., Jackson, B., Maxwell, D., Norton, K., 2018. A *review of the (Revised) Universal Soil Loss Equation (R/USLE): with a view to increasing its global applicability and improving soil loss estimates*. Hydrology and Earth System Sciences, 22: 6059-6086.

Bijak J., Kicinger A. 2007. *Studium metodologiczne oszacowania rzeczywistej liczby ludności Warszawy*. CEFMR Working Paper, 2/2007, Warszawa.

Błażejczyk, K., Kuchcik, M., Milewski, P., Dudek, W., Kręcisz, B., Błażejczyk, A., Szmyd, J., Degórska, B., Pałczyński, C., 2014. *Miejska wyspa ciepła w Warszawie. Uwarunkowania klimatyczne i urbanistyczne*. Warszawa, Wydawnictwo Akademickie Sedno.

Brunzel, S., Kellermann, J., Nachev, M., Sures, B., Hering, D., 2018. *Energy crop production in an urban area: a comparison of habitat types and land use forms targeting economic benefits and impact on species diversity*. Urban Ecosystems, 21: 615-623.

Burkhard B., Kandziora M., Hou Y., Müller F., 2014. *Ecosystem service potentials, flows and demand – concepts for spatial localisation, indication and quantification*. Landscape Online 34, 1: 1-32.

Burkhard B., Kroll F., Nedkov S., Müller F., 2012. Mapping ecosystem service supply, demand and budgets, Ecological Indicators, 21, s. 17–29.

Burkhard, B., Kroll, F., Müller, F., & Windhorst, W., 2009. *Landscapes' capacities to provide ecosystem services - A concept for land-cover based assessments*. Landscape Online, 15. https://doi.org/10.3097/LO.200915

Coles, R.W., Bussey, S.C., 2000. *Urban forest landscape in the UK – progressing the social agenda*. Landscape and Urban Planning, 52: 181-188.

Crockford, R.H., Richardson, D.P., 2000. *Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate*. Hydrological Processes, 14: 2903-2920.

Cueva J., Yakouchenkova J., Fröhlich K., Dermann A., Dermann F., Köhler M., Grossmann J., Meier W., Bauhus J., Schröder D., Sardemann G., Thomas C., Carnicero A.R., Saha S., 2022. *Synergies and trade-offs in ecosystem services from urban and peri-urban forests and their implication to sustainable city design and planning*. Sustainable Cities and Society, 82: 103903

Degórski M., Wolski J., Affek A., Degórska B., Kowalska A., Regulska E., Solon J., 2021. *Opracowanie studium przypadku istotnych usług ekosystemów zurbanizowanych w skali regionalnej oraz lokalnej*. Instytut Geografii i Przestrzennego Zagospodarowania PAN, Warszawa, 52 s.

Depietri, Y., Renaud, F. G., & Kallis, G. (2012). *Heat waves and floods in urban areas: a policy-oriented review of ecosystem services*. Sustainability science, 7, 1: 95-107.

De Luca, C., Libetta, A., Conticelli, E., Tondelli, S., 2021. *Accessibility to and Availability of Urban Green Spaces (UGS) to Support Health and Wellbeing during the COVID-19 Pandemic – The Case of Bologna*. Sustainability, 13: 11054.

Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C., 2013. *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*. Springer.

Elmqvist T., Gómez-Baggethun E., Langemeyer J., 2016. *Ecosystem Services Provided by Urban Green Infrastructure*. In: R. Haines-Young, R. Fish, R. Turner (red.), Routledge Handbook of Ecosystem Services, Routledge, Abingdon.

Fisher B., Turner R.K., Morling P., 2009, *Defining and classifying ecosystem services for decision making*. Ecological Economics, 68, 3 : 643-653.

Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G., 2007. *The soil and water assessment tool: historical development, applications, and future research directions*. Transactions of the ASABE, 50: 1211-1250.

Geary, R.S., Wheeler, B., Lovell, R., Jepson, R., Hunter, R., Rodgers, S., 2021. *A call to action: Improving urban green spaces to reduce health inequalities exacerbated by COVID-19*. Preventive Medicine, 145: 106425.

Haase, D., Nuissl, H., 2007. *Does urban sprawl drive changes in the water balance and policy? The case of Leipzig (Germany) 1870-2003*. Landscape and Urban Planning, 80: 1-13.

Holt, A.R., Mears, M., Maltby, L., Warren, P., 2015. *Understanding spatial patterns in the production of multiple urban ecosystem services*. Ecosystem Services 16, 33e46.

Hutcheson, W., Hoagland, P., Jin, D., 2018. *Valuing environmental education as a cultural ecosystem service at Hudson River Park*. Ecosystem Services, 31: 387-394.

Jimenez-Munoz, J.C., Cristobal, J., Sobrino, J.A., Soria, G., Ninyerola, M., Pons, X., 2009. *Revision of the Single-Channel Algorithm for Land Surface Temperature Retrieval From Landsat ThermalInfrared Data. IEEE.* Transactions on Geoscience and Remote Sensing, 47: 339-349.

Jin, H., Eklundh, L., 2014. *A physically based vegetation index for improved monitoring of plant phenology*. Remote Sensing of Environment, 152: 512-525.

Józefaciuk, C., Józefaciuk, A., 1995. *Erozja agroekosystemów*. Biblioteka Monitoringu Środowiska, Warszawa: Państwowa Inspekcja Ochrony Środowiska.

Kammen, D.M., Sunter, D.A., 2016. *City-integrated renewable energy for urban sustainability*. Science, 352: 922-928.

Kothencz, G., Kolcsár, R., Cabrera-Barona, P., Szilassi, P., 2017. *Urban Green Space Perception and its Contribution to Well-being*. International Journal of Environmental Research and Public Health, 14: 766.

Kuchcik, M., 2017. *Warunki termiczne w Polsce na przełomie XX i XXI wieku i ich wpływ na umieralność*. Prace Geograficzne, 263, Warszawa: IGiPZ PAN.

Livesley, S.J., McPherson, G.M., Calfapietra, C., 2016. *The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale*. Journal of Environmental Quality, 45: 119-124.

Lourdes K., Hamel P., Gibbins C., Sanusi R., Azhar B., Lechner A., 2022. *Planning for green infrastructure using multiple urban ecosystem service models and multicriteria analysis*. Landscape and Urban Planning, 226: 104500.

Maes, J., Zulian, G., Thijssen M., Castell, C., Baró, F., et al. 2016. *Mapping and Assessment of Ecosystems and their Services. Urban Ecosystems*. Publications Office of the European Union, Luxembourg.

Manes, F., Silli, V., Salvatori, E., Incerti, G., Galante, G., Fusaro, L., Perrino, C., 2014. *Urban ecosystem services: tree diversity and stability of PM10 removal in the metropolitan area of Rome*. Annali di Botanica, 4: 19-26.

Maruszczak, H., 1991. Denudacja chemiczna. W: L. Starkel (red.), *Geografia Polski. Środowisko przyrodnicze* (s. 413-416). Warszawa: PWN.

Paul, M.J., Meyer, J.L., 2001. *Streams in the urban landscape*. Annual Review of Ecology and Systematics, 32: 333-365.

Popek, R., Gawrońska, H., Gawroński, S.W., 2015. *The level of particulate matter on foliage depends on the distance from the source of emission*. International Journal of Phytoremediation, 17: 1262-1268.

Przybysz, A., Wińska-Krysiak, M., Małecka-Przybysz, M., Stankiewicz-Kosyl, M., Skwara, M., Kłos, A., Kowalczyk, S., Jarocka, K., Sikorski, P., 2020. *Urban wastelands: On the frontline between air pollution sources and residential areas*. Science of the Total Environment, 721: 137695.

Puchalski, T., Prusinkiewicz, Z., 1990. *Ekologiczne podstawy siedliskoznawstwa leśnego*. Warszawa: PWRiL.

Raudsepp-Hearne C., Peterson G.D., Bennett E.M., 2010. *Ecosystem service bundles for analysing tradeoffs in diverse landscapes*. Proceedings of the National Academy of Sciences.

Raport, 2021. *Raport o stanie miasta: Warszawa 2021*. Biuro Strategii i Analiz Urzędu Miasta Stołecznego Warszawy, Warszawa. https://bip.warszawa.pl/NR/rdonlyres/F3107275-D088-4371-9DC4-3BC08DF11F69/1733219/Raportostaniemiasta2021_poprawka.pdf

Rodríguez-Loinaz G., Alday J.G., Onaindia M., 2015. *Multiple ecosystem services landscape index: A tool for multifunctional landscapes conservation*. Journal of Environmental Management, 147: 152-163.

Sæbø, A., Popek, R., Nawrot, B., Hanslin, H.M., Gawronska, H., Gawronski, S.W., 2012. *Plant species differences in particulate matter accumulation on leaf surfaces*. Science of the Total Environment, 427-428: 347-354.

Schoonover, J.E., Lockaby, B.G., Helms, B.S., 2006. *Impacts of land cover on stream hydrology in the west Georgia piedmont, USA*. Journal of Environmental Quality, 35: 2123-2131.

Sikorska, D., Macegoniuk, S., Łaszkiewicz, E., Sikorski, P., 2020. *Energy crops in urban parks as a promising alternative to traditional lawns – Perceptions and a cost-benefit analysis*. Urban Forestry & Urban Greening, 49: 126579.

Skelhorn, C., Lindley, S., Levermore, G., 2014. *The impact of vegetation types on air and surface temperature in a temperate city: A fine scale assessment in Manchester, UK*. Landscape and Urban Planning, 121: 129-140.

Studium uwarunkowań i kierunków zagospodarowania przestrzennego m.st. Warszawy, 2006. Warszawa.

https://architektura.um.warszawa.pl/-/studium-uwarunkowan-i-kierunkow-zagospodarowania-przestrzennego-warszawy

Studium Uwarunkowań i Kierunków Zagospodarowania Przestrzennego m.st. Warszawy. *Uwarunkowania. 2020*. Miejska Pracownia Planowania Przestrzennego i Strategii Rozwoju. Warszawa, maszynopis.

Syrbe R.-U., Walz U., 2012. *Spatial indicators for the assessment of ecosystem services: Providing, benefiting and connecting areas and landscape metrics*. Ecological Indicators, 21: 80-88.

TEEB, 2010. *The Economics of Ecosystems and Biodiversity*: Ecological and economic foundation, Cambridge.

Tu, J., Xia, Z.-G., Clarke, K.C., Frei, A., 2007. *Impact of urban sprawl on water quality in Eastern Massachusetts, USA*. Environmental Management, 40: 183-200.

Turkelboom F., Thoonen M., Jacobs S., García-Llorente M., Martín-López B., Berry P., 2016, *Ecosystem service trade-offs and synergies*. W: Potschin M.B., Jax K. (red.), OpenNESS Ecosystem Services Reference Book. EC FP7 Grant Agreement No. 308428.

Turner K.G., Vestergaard Odgaard M., Bøcher P.K., Dalgaard T., Svenning J.-C., 2014. *Bundling ecosystem services in Denmark: Trade-offs and synergies in a cultural landscape*. Landscape and Urban Planning, 125: 89-104.

Weinbrenner, H., Breithut, J., Hebermehl, W., Kaufmann, A., Klinger, T., Palm, T., Wirth, K., 2021. *"The Forest Has Become Our New Living Room" – The Critical Importance of Urban Forests During the COVID-19 Pandemic*. Frontiers in Forests and Global Change, 4: 672909.

Yang, G., Ge, Y., Xue, H., Yang, W., Shi, Y., Peng, C., Du, Y., Fan, X., Ren, Y., Chang, J., 2015. *Using ecosystem service bundles to detect trade-offs and synergies across urban-rural complexes.* Landscape and Urban Planning 136: 110-121.

Yu, Z., Yang, G., Zuo, S., Jørgensen, G., Koga, M., Vejre, H., 2020. *Critical review on the cooling effect of urban blue-green space: A threshold size perspective*. Urban Forestry and Urban Greening, 49: 126630.

Zardo, L., Geneletti, D., Pérez-Soba, M., Van Eupen, M., 2017. *Estimating the cooling capacity of green infrastructures to support urban planning*. Ecosystem Services, 26: 225-235.