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## Assessment of Heat Reduction Ecosystem Services by Urban Green Spaces of Kyiv

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**Abstract.** An effective tool in combating Urban Heat Islands (UHI) manifestations is the development of urban blue-green infrastructure (BGI). BGI, through its functioning, provides various ecosystem services (ES), including heat reduction ES. This study aims to assess the heat-reduction ecosystem services provided by BGI and by specific urban green spaces (UGS) within the city. In this study, we employ a spatially explicit method for UHI assessment based on remote sensing of Land Surface Temperature (LST). We also use open data on Kyiv city's urban green infrastructure (BGI), including the ESA WorldCover 2020 land cover map, the Copernicus Global Land Service Land Cover, and the OpenStreetMap database. The assessment involves modeling the cooling function, determining its effectiveness, translating this effectiveness into ecosystem service quantities, and exemplifying these with the case of the BGI of Kyiv.

The study's results reveal that BGI cools surfaces by up to 16°C. The least efficient green areas, occupying 23–29% of the polygon area and having a perforation of 70–80 km/km<sup>2</sup>. Overall, Kyiv's BGI provides heat reduction ES at average (33% of cases) and above-average (30% of cases) volumes. 16.7% of green spaces provide their maximum ES, while the rest require modifications to enhance efficiency.

**Keywords:** *urban heat island (UHI), urban green space (UGS), blue-green infrastructure (BGI), ecosystem services (ES), assessment.*

### Relevance of the research

According to the United Nations, by 2050, more than 65% of the world's population will be concentrated in cities [1]. Among the significant problems arising from urbanization processes that lead to a decline in the quality of urban residents' lives, researchers identify the phenomenon of the urban heat island [2]. The emergence of urban heat islands (UHIs), their spatial characteristics, and the temperature differences they produce are influenced by numerous factors, primarily anthropogenic. These factors include the expansion of built-up areas, atmospheric pollution, degradation or reduction of green spaces, and more [3]. Ecological changes in urban ecosystems due to UHI primarily result in decreased air and water quality.

Economic losses are attributed to increased energy consumption for cooling indoor spaces. Most importantly, UHI leads to heightened heat stress and, consequently, an increase in health issues among urban residents, even contributing to higher mortality rates. In the policies of the European community, the development of urban blue-green infrastructure (BGI) has been recognized as an effective tool for combating UHI manifestations. BGI comprises a network of urban green spaces (UGS) (natural, semi-natural, and artificial vegetation) and water bodies within cities. During its functioning, BGI provides a wide range of benefits to urban dwellers in the form of ecosystem services, including heat reduction services [4–5]. The mechanism behind this service involves

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natural shading, evapotranspiration, increased absorption and reflection of solar radiation, and more [6–8].

### The state of research on the issue

Existing scientific research has primarily focused on assessing the ecosystem services provided by UGS, specifically heat mitigation. These works mainly investigate temperature indicators within specific green infrastructure elements [1, 9, 10] and the dispersion of cooling effects from green spaces to adjacent areas [2, 11–14]. Numerous studies also explore the utilization of remote sensing and geospatial modeling in UHI research. For instance, a study [2] analyzed UHI characteristics using Landsat-8 surface temperature data. The InVEST project offers modules (tools) for analyzing urban cooling and UHI reduction [15]. In Ukraine, such studies have also been conducted, particularly concerning the city of Kyiv [3, 16].

### The purpose of the research

Collectively, these studies indicate that the strength and spatial extent of cooling effects depend on both qualitative factors and quantitative metrics of green spaces [1, 17]. However, there is insufficient coverage of assessing the cooling properties of the entire BGI. Additionally, we did not identify research specifically addressing the assessment of cooling services provided by small squares or building-associated UGS, despite their role as primary contributors to cooling in densely built areas. The effectiveness of the existing BGI in providing cooling services and the extent of these ecosystem services remain open questions. In our opinion, the assessment should rely on quantitative and qualitative indicators of the entire available infrastructure, accessible through remote sensing data. Consequently, the goal of this study is to assess the heat-reduction ecosystem services provided by the entire existing BGI and specific UGS within the city using remote sensing data.

### Research methods

To analyze temperature distribution, a spatially explicit method for UHI assessment based on remote sensing of Land Surface Temperature (LST) was employed [18].

The materials used for this study include:

- A series of multispectral satellite images acquired by the Landsat-8 satellite from May to September for the years 2019–2022 [19–24]. Landsat-8

data provide high-resolution thermal channel data (B10) at 30 meters. Thermal infrared (TIR) remote sensing data were used for LST modeling, with cloud cover limited to 20% and additional masking of clouds, cloud shadows, ice, and snow [25].

- OpenStreetMap database for identifying specific boundaries of UGS [26].

- ESA WorldCover 2020 land cover map product based on Sentinel-1 and Sentinel-2 data, providing land cover information at a resolution of 10 meters [27]. These datasets help determine qualitative characteristics of green spaces that OpenStreetMap data might not identify.

The methodology of this study is based on the premise that UGS provides its maximum ecosystem services when it functions effectively. The effectiveness of functioning depends on the UGS's characteristics. Among the indicators suitable for evaluating the provision of these services, the following are notable:

- The area of the UGS. This parameter is crucial for assessment, as it has been established that an average park of 6 hectares produces a noticeable cooling effect. Large green spaces can also have a cooling effect beyond their boundaries [9, 11]. A linear relationship between the size of the UGS and the distance at which cooling occurs was established in [1].
- The type and distribution pattern of vegetation. The presence of mature deciduous trees significantly impacts temperature indicators [28].

### Statement of basic materials

The calculation indicators for assessing these services for urban BGI or individual green spaces are as follows: average surface temperature in model polygons within the city ( $t_{pg}$ ), average temperature in individual green spaces ( $t_{g,a}$ ), average temperature outside the city ( $t_{suburb}$ ), area of the green space ( $S_{g,a}$ ), predominant type of vegetation ( $Type_{veg}$ ), proportion of the area occupied by green spaces in the polygon ( $P_s$ ). The assessment of ecosystem services provision for cooling entails determining this service's contribution from the entire BGI and the UGS separately. As a result, the assessment should be conducted on two spatial levels: city-wide and local.

The assessment algorithm for ecosystem services provision for cooling involves the sequential completion of tasks:

1. Identify cooling effects from green spaces in territories and simulate the “implementation” of this function.

2. Assess the effectiveness of the cooling function.

3. Convert the effectiveness values into cooling ecosystem service quantities.

4. Determine the volume of the ecosystem services.

To effectively accomplish these tasks, it is necessary to define the modeling units. The “floating territorial assessment unit” hypothesis was implemented for this purpose. It was determined that hexagonal polygons are the most effective for GIS-based modeling. The dimensions of the model polygons used to assess the cooling function of green spaces in Kyiv were determined using variography. Most topographical surfaces exhibit a statistical nature when modeled using regionalized variables, such as vegetation change surfaces and microclimatic indicators. In regionalized variable modeling, it is assumed that the locations of the statistical surface are spatially correlated. The empirical variogram of the statistical surface’s locations quantifies the degree of statistical correlation as a function of the distance between locations [29]. In modeling, the increasing variogram graph begins to flatten at a threshold value (semi-variance  $\gamma \sim 2.534$ ), and the distance  $h$  at which the variogram levels off represents the range of increase, or the radius of influence (rang). The value of rang is the boundary at which the variance reaches a limit and remains constant thereafter. Beyond its boundaries, the distance between locations becomes insignificant, as they are independent at any distance beyond the radius of influence. When modeling the cooling function of urban green spaces using GIS tools, the radius of influence indicates the range required for interpolation to encompass all locations whose values are correlated. For example, in the Kyiv territory, a correlation in values is observed between locations within a coverage radius of 1325 m. Therefore, for this study, hexagons of the appropriate size were selected as model polygons.

For modeling the cooling function at the city-wide level within the constructed model polygons of the chosen size, the following steps are required:

1.1.1. Determine the average surface temperature within the polygon ( $t_{plg}$ ).

1.1.2. Calculate the cooling function provided by the BGI within the city, denoted as  $Cooling_{(BGI)}$ . This function is calculated similarly to determining the manifestations of UHI effects, as in equation (1).

$$Cooling_{(BGI)} = t_{plg} - t_{suburb}, \quad (1)$$

where  $Cooling_{(BGI)}$  is the cooling function performed by BGI,  $t_{plg}$  — the average surface temperature within the polygon, and  $t_{suburb}$  — the average temperature outside the city.

At the local level, to determine the realization of the cooling function provided by each specific green space, the following steps are required:

1.2.1. Determine the average surface temperature within the UGS ( $t_{g.a}$ ).

1.2.2. Determine the contribution of each UGS to the microclimate formation within the polygon using equation (2):

$$Cooling_{(g.a)} = t_{g.a} - t_{plg}, \quad (2)$$

where  $Cooling_{(g.a)}$  — the cooling function performed by each UGS,  $t_{plg}$  — the average surface temperature within the polygon,  $t_{g.a}$  — the average temperature within the green space.

The effectiveness of each UGS (or BGI) in performing the cooling function is understood as its influence on the overall temperature. Accordingly, its determination at the city-wide level involves the following steps:

2.1.1. Determine the polygon with the maximum surface temperature —  $t_{plg(max)}$ .

2.1.2. Establish the proportion of model polygons occupied by vegetation —  $P_s$ .

2.1.3. The effectiveness of the cooling function performed by BGI —  $Ecooling_{(BGI)}$  should be calculated using equation (3):

$$Ecooling_{(BGI)} = t_{plg} - t_{plg(max)}, \quad (3)$$

where  $Ecooling_{(BGI)}$  is the effectiveness of the cooling function performed by BGI,  $t_{plg(max)}$  — the average temperature within the polygon with the maximum value in the city,  $t_{plg}$  — the average surface temperature within the polygon.

At the local level:

2.2.1. Determining the effectiveness of UGS in performing the cooling function —  $Ecooling_{(g.a)}$  involves identifying differences between the temperature indicators of individual UGS —  $t_{g.a}$  and the minimum temperature within the green spaces of the city —  $t_{g.a(min)}$ , as described by equation (4).

$$Ecooling_{(g.a)} = t_{plg} - t_{g.a(min)}, \quad (4)$$

where  $Ecooling_{(g.a)}$  — the effectiveness of the cooling function performed by each individual UGS,  $t_{g.a}$  — the average surface temperature within the green space,  $t_{g.a(min)}$  — the minimum temperature within the UGS.

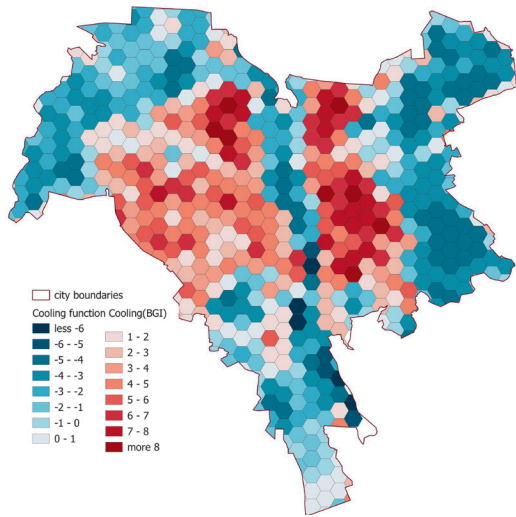


Fig. 1. Cooling function performed by urban green infrastructure in Kyiv —  $Cooling_{(BGI)}$

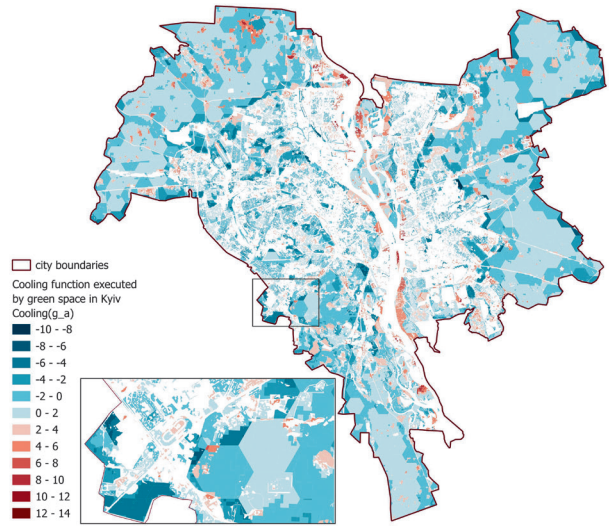


Fig. 2. Cooling function executed by green space in Kyiv —  $Cooling_{(g_a)}$

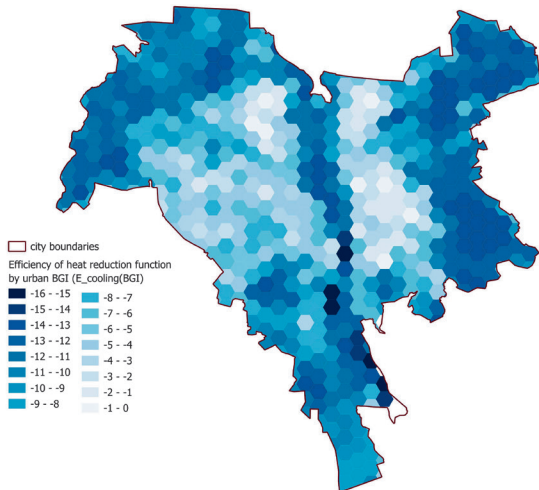


Fig. 3. Efficiency of heat reduction function by urban BGI —  $E_{cooling_{(BGI)}}$

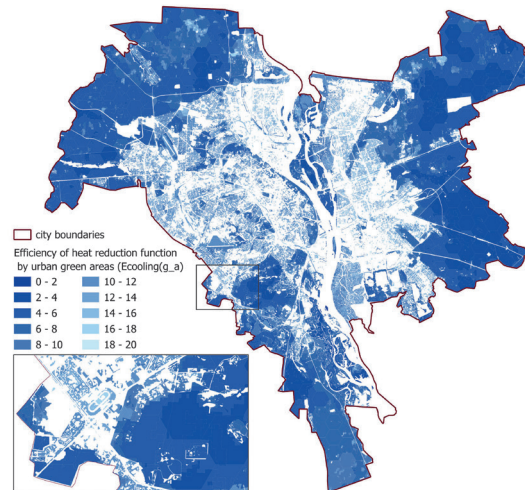


Fig. 4. Efficiency of heat reduction function by urban green spaces —  $E_{cooling_{(g_a)}}$

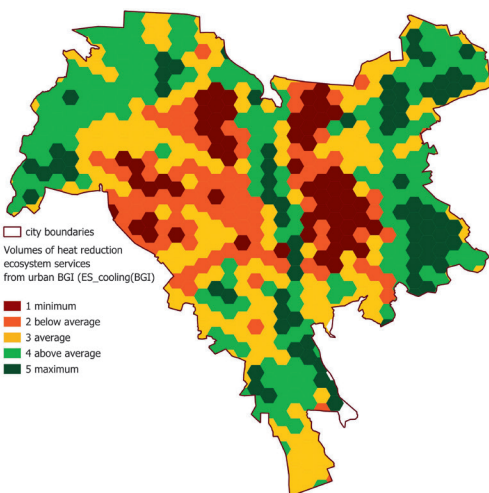


Fig. 5. Volumes of heat reduction ecosystem services from urban BGI —  $E_{Scooling_{(BGI)}}$

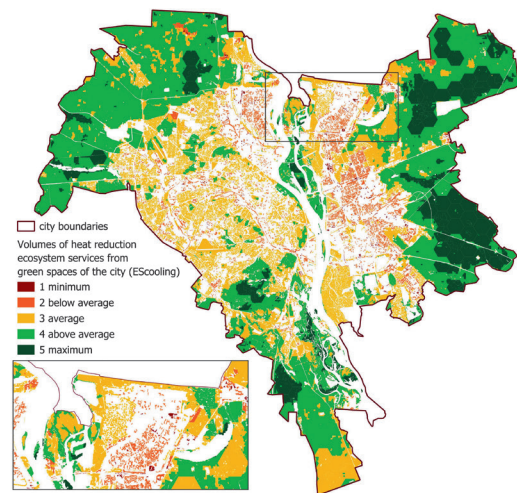


Fig. 6. The volumes of heat reduction ES from individual green spaces of the city —  $E_{Scooling_{(g_a)}}$

**Table 1. Data on average surface temperature for a set of model polygons for the study area within the city and suburbs of Kyiv**

	min	max	mean	median
Average surface temperature of the suburban area	22.976	41.875	33.780	34.003
Average surface temperature of the urban area	26.673	42.706	34.099	33.704

**Table 2. Average surface temperature data for green spaces within the city and a set of model polygons**

	min	max	mean	median
Average surface temperature within green spaces	25.460	46.489	35.72	35.905
Average surface temperature of model polygons of the urban area	26.673	42.706	34.099	33.704

The next step should be the conversion of the obtained cooling effectiveness values into quantities of ecosystem services related to heat mitigation. The formalization of calculation indicators, similar to previous works [30–33], is based on the empirically generalized desirability scale by E. Harrington [34], which involves transforming (normalizing) all measured indicators (in this case, indicators of the cooling function effectiveness  $E_{cooling(BGI)}$ ,  $E_{cooling(g,a)}$ ) into dimensionless values. This study employs a function where 0 represents the lowest quality of a UGS (or BGI) (minimal ecosystem services provision), and 1 represents the highest.

#### Implementation of the methodology

According to sections 1.1.1 and 1.1.2 of the methodology, the study calculates the average temperature within the constructed model polygons using a series of images (Table 1) and the cooling function performed by BGI (Fig. 1). Figure 1 reveals that in the northwestern, northeastern, and southern parts of the city, within polygons fully covered by tree vegetation of the BGI, the cooling effect is most pronounced, and heat manifestations are entirely absent. Over the major waterway, the Dnipro River, which runs through the city center, the temperature is even lower than the average temperature outside the city.

At the same time, in polygons with maximum urban development, surface temperatures exceed the temperatures outside the city by more than 9°C, which further emphasizes the impact of the BGI in mitigating heat effects.

According to sections 1.2.1 and 1.2.2 of the methodology, the indicators of average surface temperature —  $t_{g,a}$ , and the cooling function in individual green spaces of the city,  $Cooling_{g(a)}$ , were calculated and mapped (Table 2, Fig. 2).

This result confirms that the model polygons with a large percentage of the area covered by green spaces at the citywide level or individual large green spaces at the local level are those whose functioning neutralises the UHI (temperature difference is “0” or “minus”). Also, Figure 2 shows that even within the same landfill, the surface temperatures of green spaces are more than 10°C lower than the average in the model polygon. At the same time, the temperatures in some green spaces are higher by 10°C than the average temperature in the polygon, which indicates their different efficiency and is obviously related to their characteristics.

The next step was to determine the effectiveness of the cooling function. According to section 2.1.1 of the methodology, the maximum surface warming in the model polygons of Kyiv —  $t_{plg(max)}$  was 42, 7°C

Using section 2.1.2 of the methodology, the percentage of areas covered by different types of green vegetation —  $P_s$  was determined. To establish the relationship between the areas of green vegetation, their types, and surface temperatures in the polygons, a correlation analysis was conducted.

A correlation analysis was conducted to find the relationship between the area of green spaces, their type and surface temperatures in the model polygons. This analysis indicates that there is a relationship between these indicators. The correlation coefficients between the average surface temperature in the polygons and the percentage of the city’s tree and total vegetation areas show a rather strong (–0.57) correlation between the area covered by vegetation and surface temperature. Also confirmed that herbaceous vegetation has very weak correlation with temperature (0.119). According to the results of the correlation analysis, the influence of the Dnipro River on the cooling processes in the city is noticeable. The correlation coefficient in the distribution of surface

**Table 3. The volume of heat reduction ecosystem services**

<i>Ecooling</i> <sub>(BGI)</sub> , °C	<i>Ecooling</i> <sub>(g.a)</sub> , °C	Assessment score	Volume of ES Ecooling
[ -12,649 — -15,811 ]	[ 0 — 4,206 )	5	maximum
[ -9,961 — -12,649 )	[ 4,206 — 7,780 )	4	above average
[ -5,850 — -9,961 )	[ 7,780 — 13,248 )	3	average
[ -3,162 — -5,85 )	[ 13,248 — 16,823 )	2	below average
[ 0 — -3,162 )	[ 16,823 — 21,029 ]	1	minimum

**Table 4. The volume of heat reduction ecosystem services, provided by BGI in Kyiv**

EScooling(BGI)	The model polygons of the city	
	amount	%
maximum	78	12
above average	192	30
average	210	33
below average	99	16
minimum	60	9
<b>Total</b>	<b>639</b>	<b>100</b>

**Table 5. The volumes of heat reduction ecosystem services provided by green spaces in Kyiv**

EScooling(BGI)	The model polygons of the city	
	amount	%
maximum	8,914	16.7
above average	26,780	50.2
average	14,920	27.97
below average	2,588	4.85
minimum	151	0.28
<b>Total</b>	<b>53,353</b>	<b>100</b>

temperature and green space, taking into account the cooling effect of the Dnipro water area, is  $-0.43$ .

In the implementation of point 2.1.3 of the methodology, the effectiveness of the city's BGI was determined as *Ecooling*(BGI). Given the proportion of gray and green infrastructure areas and the composition of vegetation species, it is not surprising that the BGI in the city, where it covers over 90% of the area, significantly reduces surface temperatures. The temperature difference can reach up to  $16^{\circ}\text{C}$  (Fig. 3). However, for the majority of areas in Kyiv, with the existing ratio of built-up and green spaces, the average cooling is around  $3\text{--}5^{\circ}\text{C}$  (Fig. 3).

As a result of the implementation of section 2.2.1 of the methodology, the efficiency of the functioning of UGS — *Ecooling*<sub>(g.a)</sub> it was determined that most green spaces in typical urbanized areas differ from the minimum temperature indicators by  $16^{\circ}\text{C}$  due to

their characteristics (Fig. 4). We conducted calculations and observed a clear relationship between the areas occupied by green spaces, their permeability (perimeter-to-area ratio), and their effectiveness in performing the cooling function. Most commonly, if the green spaces occupy  $0.23\text{--}0.29$  of the polygon's area and have a permeability of  $70\text{--}80\text{ km}^2/\text{km}^2$ , they are the least effective in cooling and differ from the minimum value by  $15\text{--}19^{\circ}\text{C}$ . The most efficient cooling occurs when the green spaces cover more than 90% of the area and have a permeability of up to  $10\text{ km}^2/\text{km}^2$ .

The next step in implementing the methodology was to standardize the cooling efficiency indicators into dimensionless values, which will characterize the volumes of ecosystem services in mitigating heat effects. The results of standardizing the indicators are presented in Table 3.

The cartographic representation of the modeling results is presented in **Fig. 5, 6**. Specifically, Figure 5 illustrates the volumes of ecosystem services provided by the BGI within each polygon, while Figure 6 — by the each UGS.

### Conclusions

The methodology and remote sensing data presented in this study were used to calculate the effectiveness of the cooling function BGI in Kyiv. This effectiveness was understood as the ability to reduce temperatures compared to the most intensely heated polygon in the city. The modeling results revealed that the BGI of Kyiv, in its current state, can cool surfaces by up to 16°C. This cooling effect is most pronounced in large forested areas and along the Dni-pro River. The most effective cooling occurs in UGS when they occupy more than 90% of the polygon and have a permeability (perimeter-to-area ratio) of up to 10 km/km<sup>2</sup>. By determining the efficiency in this manner, it was possible to assess the volumes of heat reduction ecosystem services (**Tables 4, 5**).

The urban BGI in Kyiv, in its current state, provides a significant level of heat reduction in most cases, with 33% and 30% of the polygons showing average and above-average levels, respectively (**Table 4**).

The data in **Table 5** demonstrate that among the analyzed green spaces of the city, in 16.7% of cases,

they provide their maximum ES. At the same time, it becomes evident that the rest of the areas require changes to enhance their efficiency in cooling the city.

### The novelty of the study

The data obtained regarding the impact of the urban BGI on the mitigation of heat islands and individual UGS on the microclimate formation in specific city areas represent valuable information that can assist urban planners in minimizing the effects of UHI throughout the entire city and in specific districts. Additionally, identifying the effectiveness of individual green spaces serves as a useful way to demonstrate their role and value in combating heat islands. This research also aids in identifying efficient strategies for designing BGI and establishing a sequence of managerial decisions to achieve the greatest impact in combating heat effects. Undoubtedly, this is crucial for ensuring sustainable urban development.

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## Оцінка екосистемних послуг з пом'якшення впливу островів тепла, що надаються міськими зеленими зонами Києва

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Міська синьо-зелена інфраструктура (СЗІ) надає екосистемні послуги (ЕП) з охолодження (пом'якшення впливу «островів» тепла). Обсяги ЕП залежать від ефективності СЗІ у виконанні функції охолодження. Мета роботи — оцінити ЕП з пом'якшення впливу «островів» тепла, що надає СЗІ міста загалом та окремі міські зелені зони (МЗЗ) зокрема. Оцінювання включало: моделювання «функції охолодження» і визначення ефективності та обсягів ЕП, що надаються СЗІ. З'ясовано, що в м. Києві СЗІ охолоджує поверхні до 16°C. Найменш ефективними виявились зелені насадження, що займають 23–29 % площі полігону і мають перфорованість 70–80 км/км<sup>2</sup>, а найефективнішими виявились ті, що займають 90 % площі із перфорованістю до 10 км/км<sup>2</sup>. СЗІ забезпечує ЕП з охолодження в середніх (33 % випадків) та вище середніх (30 % випадків) обсягах. 16,7 % міських зелених зон надають ЕП в максимальних обсягах, у той час як інші потребують заходів з підвищення їхньої ефективності.

**Ключові слова:** міський «острів» тепла; міські зелені зони; синьо-зелена інфраструктура; екосистемні послуги; оцінка.

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