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ECOLOGICAL AND ECONOMIC ASSESSMENT OF THE COOLING ECOSYSTEM SERVICES OF GREEN INFRASTRUCTURE CONSIDERING FUNCTIONAL RESILIENCE IN URBAN LAND MANAGEMENT

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Abstract. *Urbanization and climate change reduce the effectiveness of the cooling regulating ecosystem services of urban green infrastructure; however, their ecological and economic assessment considering functional resilience—especially for suburban urban ecosystems under conditions of armed conflict—remains insufficiently developed. The aim of this study is to provide an ecological and economic assessment of urban green infrastructure as climate-regulating natural capital and to develop an approach for assessing cooling regulating ecosystem services considering functional resilience using the case of Irpin during 2015–2024. The analysis was based on summer median Landsat 8/9 composites, ERA5-Land climate data, and pixel-based regression analysis in Google Earth Engine using*

NDVI, LST, NDBI, the Cooling Efficiency Index (CEI), and thermal hotspot dynamics analysis. A stable cooling effect of vegetation throughout the study period was identified (NDVI–LST regression coefficients ranging from −13.27 to −18.96), alongside a pronounced thermal impact of built-up areas (NDBI–LST ranging from +44.08 to +64.24). Despite relatively stable NDVI values (0.260–0.300), the area of thermal hotspots increased sharply after 2020, reaching 25.63% of the territory in 2024, while CEI indicated the maximum decline in cooling efficiency. The scientific novelty of the study is the proposed Functional Resilience Index (FRI), which integrates vegetation cooling performance, greenness level, cooling efficiency, and spatial thermal vulnerability. The critical decline of FRI from 1.72 in 2015 to 0.11 in 2024 empirically demonstrates that quantitative vegetation indicators alone are insufficient for assessing the functional resilience of regulating ecosystem services. The proposed resilience-adjusted approach provides a more differentiated ecological and economic assessment of the natural capital of urban green infrastructure compared to the classical avoided cost method and may serve as an instrumental basis for decision-making in climate adaptation and urban land management.

Key words: *urban heat island, avoided cost method, regulating ecosystem services, cooling efficiency.*

Relevance

Global climate change and increasing urbanization intensify the effects of the urban heat island, particularly through rising land surface temperatures, increased energy consumption, and the deterioration of living conditions [13, 14, 15, 20]; particularly in cities characterized by high building density, a large proportion of impervious surfaces, and a fragmented structure of green spaces [6, 31]. The problem becomes particularly acute in suburban urban areas experiencing urbanization pressure, climate change, and in the case of Ukraine — armed conflict, which transforms the structure of the urban environment and its thermal characteristics [5, 10]. The ecological and economic efficiency and functional resilience of the regulating ecosystem services provided by urban green infrastructure under such conditions remain insufficiently assessed, limiting scientifically grounded urban land management in the context of climate adaptation [25].

Analysis of recent research and publications

The spatial distribution of green spaces is one of the key factors influencing the formation of urban heat island [24, 26, 28]. However, even under relatively stable vegetation cover conditions, cooling efficiency remains highly variable and depends on the spatial structure of built-up areas, climatic pressure, and the level of thermal vulnerability [2, 27, 30]. The spatial heterogeneity of thermal load and its relationship with land use have been confirmed using remote sensing methods across different types of urban ecosystems [12, 17]. The ecological and economic assessment of cooling regulating ecosystem services has traditionally been based on the avoided cost method [3, 7, **Ошибка! Источник ссылки не найден.**]; however, this approach does not account for the functional reliability of regulating ecosystem services under increasing thermal and urbanization pressure. The conceptual foundations of ecosystem resilience assessment [4, 16] and quantitative methods for the spatial analysis of urban heat islands [1, 11, 23] provide the theoretical basis for integrative approaches combining the functional and economic components of urban green infrastructure assessment. At the same time, comprehensive methods for assessing the functional resilience of cooling regulating ecosystem services with an ecological and economic interpretation remain underdeveloped, which constitutes the scientific gap addressed in this study.

Research Aim and Objectives

The aim of the study is to provide an ecological and economic assessment of urban green infrastructure as climate-regulating natural capital and to develop an approach for assessing cooling regulating ecosystem services considering their functional resilience in the context of urban land management, using the case of Irpin during 2015–2024. To achieve this aim, the following objectives were addressed:

1) to analyze the spatio-temporal dynamics of NDVI, LST, and NDBI based on Landsat data;

2) to assess the cooling effect of vegetation and the thermal impact of built-up areas using pixel-based regression analysis;

3) to determine the dynamics of thermal hotspots as an indicator of the spatial thermal vulnerability of urban areas;

4) to develop and test the Functional Resilience Index (FRI) for cooling regulating ecosystem services ;

5) to conduct an ecological and economic assessment of cooling regulating ecosystem services using a resilience-adjusted valuation approach as a basis for decision-making in urban land management.

Materials and Methods

Study Area

The study area is the city of Irpin, located in the northwestern part of the Kyiv agglomeration. The administrative boundaries of the city were used in the form of a vector shapefile imported into the Google Earth Engine environment. Irpin belongs to suburban urbanized territories and is characterized by intensive residential development, transformation of land-use structure, and significant dynamics of urban environmental change, which intensified particularly after 2022. The combination of residential areas with varying building density, transport infrastructure, fragmented green spaces, and natural forest massifs forms a complex spatial urban structure and determines the patterns of heat accumulation and the functioning of regulating ecosystem services. The dynamic transformation of the land-use structure of Irpin — from predominantly recreational and agricultural land to intensive residential development — creates specific challenges for urban land management in the context of preserving the climate-regulating functions of green infrastructure.

Satellite and Meteorological Data

Satellite data from Landsat Collection 2 Level-2 (Landsat 8 OLI/TIRS and Landsat 9 OLI/TIRS), obtained through the Google Earth Engine platform, were used to analyze vegetation indicators and land surface temperature [8]. Meteorological conditions were assessed using ERA5-Land Monthly Aggregated Data (Copernicus

Climate Data Store), which contain monthly mean air temperature values. The analysis was conducted for the summer season (June–August), corresponding to the period of maximum thermal stress in the urban environment [20].

Summer median composites were generated for 2015, 2018, and 2020–2024. The selection of these years was determined by two factors: the need to assess the interannual dynamics of thermal load under different climatic conditions and the availability of a sufficient number of low-cloud-cover Landsat images for producing representative composites. Clouds and cloud shadows were masked using the QA_PIXEL band of Landsat Collection 2 Level-2, and only images with minimal atmospheric interference were included in the analysis.

Calculation of Spectral Indices

For each annual summer composite, three spectral indicators were calculated: the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Built-up Index (NDBI), and Land Surface Temperature (LST).

NDVI was used to assess the condition and density of vegetation cover according to the following formula [19, 21]:

$$NDVI = (NIR - Red) / (NIR + Red), \quad (1)$$

where NIR is the near-infrared band and Red is the red band.

The intensity of built-up areas was assessed using the Normalized Difference Built-up Index (NDBI) [28]:

$$NDBI = (SWIR - NIR) / (SWIR + NIR), \quad (2)$$

where SWIR is the shortwave infrared band and NIR is the near-infrared band.

LST was calculated based on the thermal infrared band ST_B10 to the following formula [**Ошибка! Источник ссылки не найден.**]:

$$LST = ST\_B10 \times 0,00341802 + 149.0 - 273.15, \quad (3)$$

where LST − land surface temperature (°C), and ST_B10 − the thermal infrared band of Landsat.

The obtained index values were used to analyze the relationships between vegetation, built-up intensity, and thermal load within the study area.

Analysis of Relationships Between Indices

The cooling effect of vegetation was assessed using pixel-based regression analysis between NDVI and LST according to the following model [24]:

$$LST = a + b_{NDVI} \times NDVI, (4)$$

where a – intercept; b_{NDVI} – coefficient representing the cooling effect of vegetation. Negative values of b_{NDVI} were interpreted as a decrease in land surface temperature with increasing greenness levels.

Similarly, the influence of urbanized surfaces on heat accumulation was assessed through NDBI–LST regression, an approach widely applied in urban heat island studies [26, **Ошибка! Источник ссылки не найден.**]:

$$LST = a + b_{NDBI} \times NDBI, (5)$$

where b_{NDBI} – coefficient representing the thermal impact of built-up areas. Positive values of b_{NDBI} indicate an increase in thermal load with the expansion of impervious and urbanized surfaces.

Analysis of Thermal Hotspots

Areas with land surface temperatures exceeding 38 °C during the summer period (“thermal hotspots”) were identified within the study area to assess spatial thermal vulnerability. The area of hotspot zones was calculated as a proportion of the total study area and used as an indicator of thermal load.

Cooling Efficiency Index

The relationship between land surface temperature and vegetation condition is widely used in studies of urban heat mitigation and cooling ecosystem services [24, 30]. The functional efficiency of cooling regulating ecosystem services was assessed using the Cooling Efficiency Index (CEI), proposed on the basis of the above-mentioned concept:

$$CEI = LST / NDVI (6)$$

An increase in CEI values was interpreted as a decline in cooling efficiency under conditions of increasing thermal load on the urban ecosystem.

Ecological and Economic Assessment of Cooling Regulating Ecosystem Services

The ecological and economic assessment was conducted using the avoided-cost approach, according to which the cooling effect of vegetation reduces potential costs associated with thermal stress and air conditioning in the urban environment. The nominal economic valuation of cooling regulating ecosystem services was determined using the following formula:

$$E = \Delta T \times \beta \times Ce, \quad (7)$$

where E – nominal economic valuation of cooling; ΔT – temperature mitigation, °C; β – oefficient of energy consumption sensitivity to temperature; Ce – electricity tariff.

A standardized tariff of Ce ≈ 0.07 EUR/kWh was used in the calculations, corresponding to the average electricity tariff for households in Ukraine during 2023–2024. The coefficient β was determined according to Santamouris (2015), who reported that a 1 °C increase in temperature may raise cooling-related energy costs by 0.5–8.5%, depending on climatic and urban conditions.

Development of the Functional Resilience Index (FRI) and Assessment of Ecosystem Service Functional Resilience

To provide a comprehensive assessment of the functional resilience of cooling regulating ecosystem services, a Functional Resilience Index (FRI) was proposed, integrating vegetation cooling performance, the level of spatial vegetation provision, cooling efficiency, and spatial thermal vulnerability. The methodological framework for the development of the FRI, including mathematical expressions and the ecological and economic interpretation of each component, is presented in Table 1.

1. Methodological Framework for the Development of the Functional Resilience Index (FRI)

Stage	Component	Mathematical Expression	Ecological and Economic Interpretation
I	Vegetation Index NDVI	NDVI	Natural Capital Stock
II	Cooling Performance	|b_NDVI|	Vegetation Cooling Potential
III	Cooling Efficiency Index CEI	LST/NDVI	Cooling Inefficiency
IV	Thermal Vulnerability	H	Spatial Thermal Vulnerability
V	Functional Resilience Index	(|b_NDVI| × NDVI) / (CEI × H)	Functional Resilience of Regulating Ecosystem Services
VI	Resilience-Adjusted Economic Valuation	Avoided Cost × FRI	Resilience-Adjusted Ecological and Economic Valuation

Source: Developed by V. V. Strashok.

The FRI was calculated using the following formula:

$$FRI = (|b\_NDVI| \times NDVI) / (CEI \times H), \quad (8)$$

where |b_NDVI| – absolute value of the vegetation cooling-effect coefficient; NDVI – mean greenness level of the study area; CEI – cooling inefficiency index; H – proportion of hotspot zones expressed as a decimal fraction (0–1). Higher FRI values correspond to greater functional resilience of regulating ecosystem services and higher stability of the climate-regulating functions of urban green infrastructure. To standardize the assessment, an original classification of resilience levels was proposed (Table 2).

The conceptual cause-and-effect relationships between input factors, index components, and the ecological and economic consequences of declining functional resilience of RES are presented in Figure 1.

2. Classification of Functional Resilience Levels of Climate-Regulating Natural Capital Based on the FRI

FRI index value	Level of functional resilience
≤ 0.2	Critical
0.2-1,0	Vulnerable
≥ 1.0	Stable

Source: Developed by V. V. Strashok.

The scheme illustrates how climatic pressure, urbanization stress, war-related destabilization, and vegetation availability shape the integrated Functional Resilience Index (FRI) of regulating ecosystem services through intermediate indicators (cooling performance, cooling inefficiency, and thermal vulnerability), thereby determining the level of thermo-economic vulnerability of the urban area.

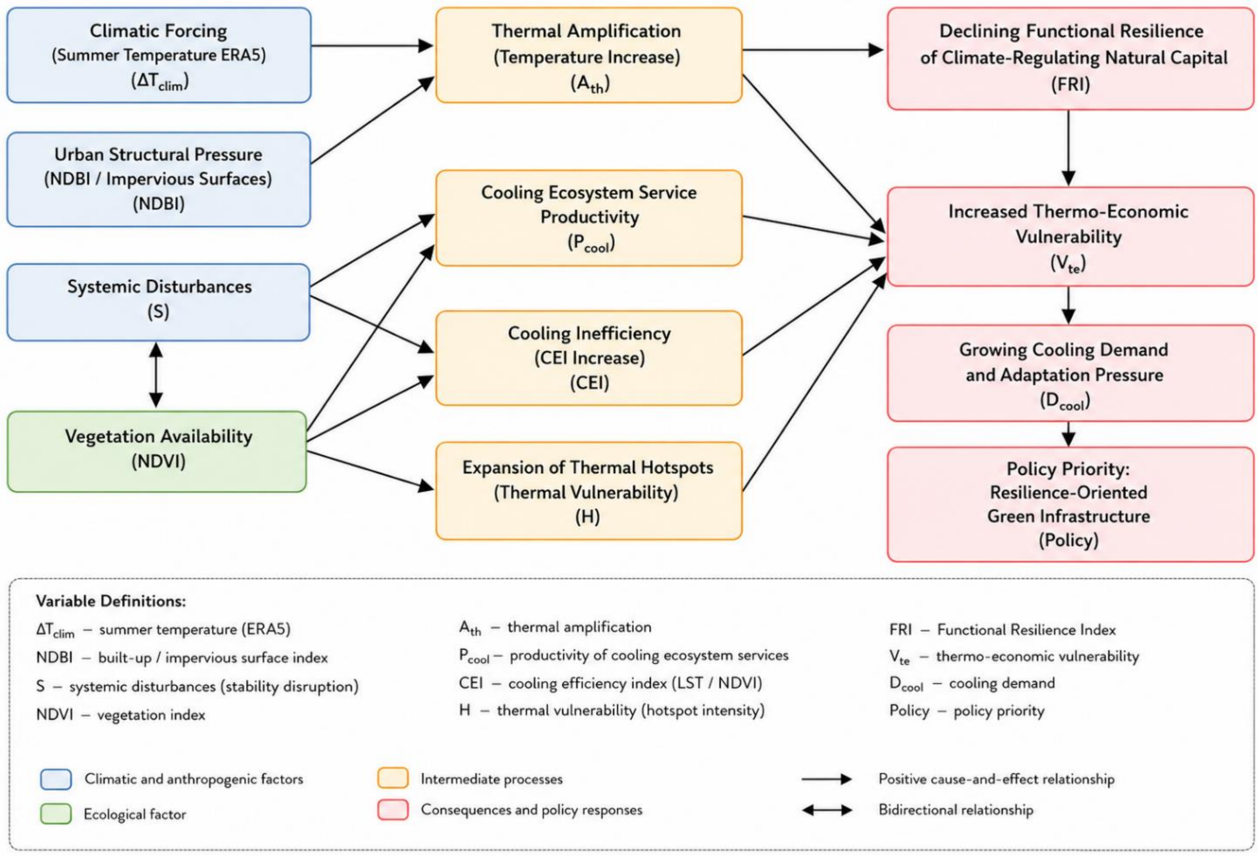

Figure 1. Conceptual Framework for the Development of the Functional Resilience Index (FRI) of Cooling Regulating Ecosystem Services Provided by Urban Green Infrastructure and Its Ecological and Economic Implications

Source: Developed by authors.

To account for functional resilience in the ecological and economic assessment, a resilience-adjusted valuation approach was proposed:

$$\text{Adjusted Cooling Value} = \text{Avoided Cost} \times \text{FRI} \quad (9)$$

This approach makes it possible to reflect not only the nominal economic value of cooling regulating ecosystem services, but also their functional reliability under conditions of thermal and urbanization pressure.

Results and Discussion

The summarized results of the spatio-temporal analysis of all calculated indicators are presented in Table 3. A detailed interpretation of each group of indicators is provided in the corresponding subsections.

Table 3. Spatio-Temporal Dynamics of Vegetation Indicators, Thermal Regime, Cooling Efficiency, and Functional Resilience of Regulating Ecosystem Services in Irpin (2015–2024)

Year	NDVI ± SD	LST ± SD, °C	b_NDVI	b_NDBI	CEI ± SD	Hotspot, %	FRI	Avoided Costs, €
2015	0.260 ± 0.083	32.51 ± 2.65	−13.27	+44.08	141.09 ± 67.96	1.42	1.72	−137.00
2018	0.283 ± 0.090	32.22 ± 3.02	−14.53	+49.13	134.05 ± 75.79	2.38	1.29	−164.26
2020	0.277 ± 0.096	33.93 ± 3.51	−15.30	+58.44	143.36 ± 83.74	14.76	0.20	0.00
2021	0.300 ± 0.097	35.11 ± 3.54	−18.96	+61.77	137.41 ± 80.12	23.89	0.17	+113.71
2022	0.295 ± 0.103	33.41 ± 3.53	−16.55	+64.24	137.47 ± 82.44	12.28	0.29	+50.34
2023	0.292 ± 0.098	32.41 ± 3.34	−17.78	+55.32	129.51 ± 78.10	3.48	1.15	−145.87
2024	0.279 ± 0.094	35.76 ± 2.74	−15.41	+59.08	151.74 ± 85.33	25.63	0.11	+176.60

Note: Avoided costs were calculated relative to the baseline year 2020. Negative values indicate lower levels of thermal load compared to the baseline year rather than economic losses.

Source: Developed by V. V. Strashok.

Spatio-Temporal Dynamics of Vegetation and Land Surface Temperature

The analysis of summer Landsat composites for 2015–2024 revealed significant spatial heterogeneity in the distribution of vegetation and land surface temperature within the city of Irpin. The highest NDVI values were characteristic of areas with tree vegetation and forest massifs, whereas the lowest values were associated with dense built-up areas, transport infrastructure, and impervious surfaces. Throughout the study period, mean NDVI values remained relatively stable (0.260–0.300), indicating the overall persistence of vegetation cover despite active urbanization.

Temperature characteristics demonstrated considerably higher interannual variability. After 2020, a sharp increase in the area characterized by elevated LST values was observed, coinciding with the intensification of urban development and, since 2022, with the spatial transformation of the urban environment caused by war-related destruction. Similar patterns have been reported by Weng et al. (2004), Yuan and Bauer (2007), and Zhou et al. (2011).

The obtained results confirm that assessing vegetation quantity alone does not allow for a comprehensive characterization of the functional condition of cooling regulating ecosystem services in the urban environment.

Relationship Between Vegetation and Land Surface Temperature

Pixel-based regression analysis between NDVI, NDBI, and LST confirmed the opposite effects of vegetation and urbanized surfaces on the thermal regime of the urban environment (Table 4).

4. Regression Coefficients Between NDVI, NDBI, and LST (Irpin)

Year	b_{NDVI}	b_{NDBI}
2015	−13.27	+44.08
2018	−14.53	+49.13
2020	−15.30	+58.44
2021	−18.96	+61.77
2022	−16.55	+64.24
2023	−17.78	+55.32
2024	−15.41	+59.08

Source: Developed by V. V. Strashok.

The NDVI–LST regression coefficients remained consistently negative throughout the study period, reflecting the methodologically expected cooling effect of vegetation: an increase in NDVI by one unit was associated with a decrease in LST by the value of |b_NDVI|. In contrast, the NDBI–LST coefficients were consistently positive, confirming intensified heat accumulation on urbanized surfaces.

The strongest cooling effect was recorded in 2021 (b_NDVI = −18.96), whereas the greatest thermal impact of built-up areas was observed in 2022 (b_NDBI = +64.24). he increase in the absolute values of b_NDVI after 2020 indicates a growing thermal contrast between vegetated and urbanized areas under intensified thermal pressure. The noticeable decrease in b_NDBI in 2023–2024 compared to 2022 may partially reflect a reduction in active construction surfaces during the period of war-related disturbances and subsequent recovery processes, which affected the spatial structure of urbanized surfaces and the nature of their thermal impact, consistent with the findings of previous studies [24, 26, 31].

After 2020, a simultaneous intensification of the thermal impact of built-up areas, expansion of hotspot zones, and decline in the functional resilience of cooling regulating ecosystem services was observed, indicating that even under relatively stable NDVI values, urbanization pressure may substantially limit the climate-regulating functions of urban green infrastructure.

Dynamics of Thermal Hotspots and Spatial Thermal Vulnerability

The analysis of thermal hotspots demonstrated a sharp increase in areas characterized by elevated thermal load after 2020 (Table 3). The largest extent of hotspot zones was recorded in 2024, reaching 25.63% of the study area, whereas in 2015 this indicator accounted for only 1.42%. Thermal hotspots were formed predominantly within densely built-up areas, transport infrastructure, and territories with low levels of vegetation cover.

The dynamics of hotspot zones after 2020 exhibited a pronounced nonlinear pattern: the sharp increase observed in 2021 (23.89%) was followed by a noticeable decline in 2022–2023 (12.28% and 3.48%, respectively), with a subsequent peak reached in 2024 (25.63%). The reduction observed in 2022–2023 may be explained by several interrelated factors, including the suspension of active construction activities during wartime conditions, decreased land-use intensity in certain areas, and partial changes in the spatial structure of built-up areas caused by destruction [9, 18]. At the same time, the recovery of construction activity after 2023 and the continued spatial transformation of the urban environment once again intensified the thermal vulnerability of the territory, which was reflected in the maximum extent of hotspot zones recorded in 2024.

Notably, in 2021 and 2024, the sharp expansion of hotspot zones occurred despite the persistence of a strong negative relationship between NDVI and LST. This confirms the conclusions of Chakraborty et al. (2020) regarding the uneven spatial distribution of thermal load and indicates that the spatial thermal vulnerability of urban areas is determined not simply by vegetation deficiency itself, but by the interaction between built-up structure, fragmentation of green spaces, and climatic pressure.

Efficiency of Cooling Regulating Ecosystem Services

The calculated CEI values demonstrate substantial interannual variability with an overall tendency toward declining cooling efficiency under increasing thermal pressure (Table 3). The highest CEI values (indicating the lowest cooling efficiency) were recorded in 2024 (151.74), coinciding with the maximum extent of hotspot zones. In contrast, the lowest CEI values were observed in 2023 (129.51), corresponding to the lowest thermal load recorded during the study period.

The results of this study indicate that the decline in the efficiency of cooling regulating ecosystem services under intensified thermal pressure became most pronounced in 2024, when the highest CEI values were recorded.

The obtained results confirm that even under conditions of preserved vegetation cover, the functional efficiency of cooling may decline under the influence of external thermal pressure. This is consistent with the principles of ecosystem resilience theory, according to which the structure of a system may remain relatively stable while its functional efficiency gradually decreases [4], and substantiates the need to shift from a static assessment of vegetation quantity toward an analysis of the functional efficiency of climate-regulating ecosystem services.

Ecological and Economic Assessment of the Functional Resilience of Cooling Ecosystem Services

Based on the results of the study, a Functional Resilience Index (FRI) was proposed, integrating vegetation cooling performance, greenness level, cooling efficiency, and spatial thermal vulnerability (Table 3). The lowest FRI values were recorded in 2024 (0.11) and 2021 (0.17), reflecting a critical decline in the functional resilience of cooling regulating ecosystem services under conditions of maximum thermal pressure. Notably, in 2021, despite the strongest vegetation cooling effect (|b_NDVI| = 18.96), the FRI value remained low due to the extensive spread of hotspot zones (23.89%), directly confirming the main hypothesis of the study: vegetation quantity alone is not a sufficient indicator of the functional resilience of climate-regulating ecosystem services.

The resilience-adjusted valuation was calculated as the product of avoided costs and the FRI. Negative values of avoided costs in 2015, 2018, 2022, and 2023 reflect lower levels of thermal load compared to the baseline year 2020 rather than actual economic losses, and therefore represent a computational artifact of the selected reference baseline. The highest resilience-adjusted valuation recorded in 2024 (€176.60) was driven by maximum thermal pressure; however, the simultaneously low FRI value (0.11) indicates a critically reduced functional reliability of regulating ecosystem services during that year.

Thus, even under relatively stable vegetation cover conditions, the functional efficiency and reliability of cooling regulating ecosystem services may substantially decline under the influence of thermal pressure, urbanization stress, and the spatial fragmentation of the urban environment. The dynamic transformation of the land-use structure of Irpin — from predominantly recreational and agricultural land to intensive residential development — creates specific challenges for urban land management in the context of preserving the climate-regulating functions of green infrastructure.

Conclusions and Prospects for Further Research

It was established that the urban green infrastructure of Irpin provided a stable cooling effect throughout 2015–2024 (b_NDVI ranging from −13.27 to −18.96); however, its functional efficiency was determined not only by the level of greenness, but also by the interaction between vegetation cooling capacity, built-up intensity, and the spatial thermal vulnerability of the territory.

It was shown that despite the relative stability of mean NDVI values (0.260–0.300), a sharp increase in the extent of thermal hotspots was recorded after 2020 (from 1.42% in 2015 to 25.63% in 2024), accompanied by an increase in the CEI to its maximum value of 151.74 in 2024. This indicates a progressive decline in the functional efficiency of cooling regulating ecosystem services under increasing thermal and urbanization pressure. The temporary reduction of hotspot zones in 2022–2023 is associated with the spatial transformation of the urban environment caused by war-related events.

A Functional Resilience Index (FRI) was proposed, integrating vegetation cooling performance, greenness level, cooling efficiency, and spatial thermal vulnerability. It was empirically confirmed that the critical decline of FRI in 2021 (0.17) and 2024 (0.11), despite simultaneously high |b_NDVI| values, indicates that vegetation quantity alone is insufficient as an indicator of the functional resilience of cooling regulating ecosystem services.

A resilience-adjusted valuation approach — an ecological and economic assessment adjusted by the FRI was substantiated, making it possible to account for the functional reliability of regulating ecosystem services under thermal pressure and to obtain a more differentiated assessment of the natural capital of urban green infrastructure compared to the classical avoided cost method.

The necessity of shifting urban planning systems from static indicators of green area extent toward a dynamic assessment of the functional resilience of regulating ecosystem services was demonstrated, taking into account the spatial structure of green spaces, the intensity of built-up areas, and the level of thermal vulnerability of the territory. This is a necessary condition for scientifically grounded urban land management in the context of climate adaptation and sustainable urban development.

The proposed methodological approach may serve as an instrumental basis for supporting decision-making in climate adaptation, spatial planning, and the ecological and economic assessment of the natural capital of suburban urban ecosystems, particularly those simultaneously affected by urbanization pressure, climate change, and post-conflict spatial transformation.

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ЕКОЛОГО-ЕКОНОМІЧНА ОЦІНКА ОХОЛОДЖУВАЛЬНИХ ЕКОСИСТЕМНИХ ПОСЛУГ ЗЕЛЕНОЇ ІНФРАСТРУКТУРИ З УРАХУВАННЯМ ФУНКЦІОНАЛЬНОЇ СТІЙКОСТІ В УМОВАХ УПРАВЛІННЯ МІСЬКИМИ ЗЕМЛЯМИ

Анотація. *Урбанізація і кліматичні зміни знижують ефективність охолоджувальних регулюючих екосистемних послуг (РЕП) міської зеленої інфраструктури, проте їх еколого-економічна оцінка з урахуванням функціональної стійкості – особливо для приміських урбоекосистем в умовах* *збройного конфлікту – залишається недостатньо розробленою. Метою дослідження є еколого-економічна оцінка міської зеленої інфраструктури як кліматорегулюючого природного капіталу та розроблення підходу до оцінки охолоджувальних РЕП з урахуванням функціональної стійкості на прикладі м. Ірпінь у 2015–2024 рр. Аналіз ґрунтувався на літніх медіанних композитах Landsat 8/9, кліматичних даних ERA5-Land і піксельному регресійному аналізі в Google Earth Engine із застосуванням NDVI, LST, NDBI, індексу ефективності охолодження (CEI) та аналізу динаміки теплових «гарячих точок». Встановлено стабільний охолоджувальний ефект рослинності впродовж досліджуваного періоду (коефіцієнти регресії NDVI–LST від −13,27 до −18,96) за вираженого теплового впливу забудови (NDBI–LST від +44,08 до +64,24). Незважаючи на відносно стабільні значення NDVI (0,260–0,300), після 2020 р. площі теплових «гарячих точок» різко зросли, досягнувши 25,63 % території у 2024 р., а CEI зафіксував максимальне зниження ефективності охолодження. Науковою новизною є авторський Індекс функціональної стійкості (FRI), що інтегрує охолоджувальну продуктивність рослинності, рівень озеленення, ефективність охолодження та просторову теплову вразливість. Критичне зниження FRI від 1,72 у 2015 р. до 0,11 у 2024 р. емпірично доводить, що кількісні показники рослинності не є достатнім індикатором функціональної стійкості РЕП. Запропонований підхід з поправкою на резильєнтність забезпечує більш диференційовану еколого-економічну оцінку природного капіталу міської зеленої інфраструктури порівняно з класичним методом уникнутих витрат і може слугувати інструментальною основою для управлінських рішень у сфері кліматичної адаптації та міського землекористування.*

Ключові слова: *міський тепловий острів, метод уникнених витрат, регулюючі екосистемні послуги, охолоджувальна ефективність.*