URBAN HEAT ISLAND EFFECT AND ITS INFLUENCE ON TRANSFORMATIONS IN LVIV

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Abstract

Urban heat islands (UHIs) have emerged as a critical concern due to increasing global temperatures and more frequent heat waves. This phenomenon, marked by higher air and surface temperatures in urban areas compared to surrounding rural regions, has been intensified by rapid urbanisation and the replacement of natural landscapes with artificial materials. Although the UHI effect was first identified over 200 years ago, it remains under-researched, especially in Ukraine. This article presents the first detailed study of UHI in the Lviv municipality, focusing on both surface and canopy layers. The importance of such research was emphasised by the Environmental Department of the Lviv City Council, whose representatives participated in discussions about the study and its findings during the city's urban festival "Misto Workshop". As part of the festival, several vegetated zones were planted based on the "pocket parks" concept, aiming to reduce the UHI effect within the city and its territorial community. The research employed satellite remote sensing to analyse the spatial distribution of UHIs during the summer of 2024 and examined how different land surface types influence temperature variation. In addition, field measurements were conducted to assess UHI intensity, its temporal dynamics, and potential mitigation strategies. The findings offer valuable data on the scale of UHIs in Lviv and provide a scientific basis for urban planning initiatives aimed at minimising their impact. This study also lays methodological and technical grounds for the further development of this type of urban spatial analysis. For Lviv, a city committed to achieving climate neutrality by 2050, conducting such research is a significant step forward.

Key words: urban heat island, transformations, Lviv, climate change, city, urban planning.

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МІСЬКИЙ ЕФЕКТ «ОСТРОВА ТЕПЛА» ТА ЙОГО ВПЛИВ НА ТРАНСФОРМАЦІЇ У ЛЬВОВІ

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Анотація

Міські теплові острови (МТО) стали критично важливою проблемою через зростання глобальних температур та активізацію хвиль спеки. Це явище характеризується високими температурами повітря та поверхні в міських територіях у порівнянні з навколишніми сільськими територіями, а також посилюється швидкою урбанізацією та заміною природних ландшафтів міською забудовою. Попри те, що ефект МТО вперше було виявлено понад 200 років тому, його дослідження залишається недостатньо висвітленими, особливо в Україні. Ця стаття представляє перше детальне дослідження МТО в межах Львова, зосереджуючи увагу як на поверхневих МТО, так і МТО приземного шару атмосфери. Важливість проведення такого типу дослідження була підкреслена управлінням екології Львівської міської ради, представники якого брали участь у обговорення проведення та результатів дослідження під час міського урбаністичного фестивалю «Майстерня міста». У контексті проведення фестивалю було також висаджено декілька ділянок рослин з використанням концепції “pocket parks”, які зможуть допомогти зменшити вплив теплового острову в межах міста та його територіальної громади. В межах дослідження було використано супутникове дистанційне зондування для аналізу просторового розподілу МТО влітку 2024 року та досліджено, як різні типи поверхні впливають на температурні варіації. Крім того, були проведені польові вимірювання для оцінки інтенсивності МТО, його змін з часом та можливих стратегій пом'якшення. Результати пропонують дані про масштаби МТО у Львові та надають наукову основу для міських планувальних ініціатив, спрямованих на мінімізацію його впливу. Дослідження також дозволить отримати методологічну та технічну базу для подальшого розвитку такого типу аналізу міської території в майбутньому. Для Львова,як міста яке ставить собі максимальні цілі в контексті досягнення статусу «Кліматично-нейтральне місто 2050», проведення такого роду досліджень є дуже великим кроком уперед.

Ключові слова: міські острови тепла, Львів, трансформації, зміна клімату, місто, містопланування

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Introduction

In recent years, the urgency of addressing global warming has intensified due to the increasing frequency and severity of heat waves and extreme heat days. This issue is especially evident in urban areas, where the urban heat island (UHI) effect exacerbates the problem. While the UHI effect is not directly caused by climate change, the rising temperatures associated with it amplify its impact. The urban heat island effect refers to the phenomenon where cities experience higher air and land surface temperatures compared to surrounding rural areas. This effect was first studied by the English scientist Luke Howard, who documented it in his work, "The Climate of London" (1818–1820). He found that night-time temperatures in London were 2.1°C higher than in rural areas, although daytime temperatures were cooler. As urbanisation and city growth have accelerated, the intensity of the UHI effect has also increased significantly. In large cities with populations over one million, average annual air temperatures can be 1–3°C higher than in rural areas, with night-time differences reaching up to 12°C. The variation in surface temperatures within urban areas can be even more striking. For instance, remote sensing data from the summer of 2023 indicated that surface temperature differences in Lviv reached as high as 18 °C at 9 a.m. (Oke, 1997).

This article presents the first comprehensive study of the urban heat island (UHI) phenomenon in the Lviv municipality. Although the UHI effect was identified long ago, it remains under-researched, particularly in Ukraine. In Lviv, Professor Bogdan Muha examined temperature differences across various districts, but his work did not specifically address the UHI effect (Muha, 1996). Furthermore, studies on surface urban heat islands (S-UHI) had been limited due to a lack of large-scale measurement capabilities. However, advancements in satellite technology have made such research possible, yet no scientific investigations of S-UHI have been conducted in Lviv to date. This study aims to explore the S-UHI phenomenon during the summer of 2024 by utilising satellite imagery, analyzing the relationship between land cover types and temperature, and identifying temperature hotspots within the municipality. Additionally, field studies were carried out to evaluate the classic UHI (CL-UHI) effect, examining its intensity, temporal dynamics, and potential measures to reduce its impact. Surface temperature measurements further enhanced our understanding of UHI and provided valuable insights for developing strategies to mitigate its effects.

Structure of UHI

The UHI effect is divided into 3 main types: surface UHI (S-UHI) urban canopy layer (CL-UHI) and boundary layer UHI. In this study, we examined S-UHI and CL-UHI, as the impact of these types of UHI is most significant for residents and the city. CL-UHI is defined as the volume of air from the ground to the top of buildings and trees in other words that is, a space where a phenomenon can be directly experienced by a human. While CL-UHI is characterised by air temperature and peaks after sunset, S-UHI represents the difference in surface temperature and reaches its maximum during midday. Despite these temporal differences, CL-UHI and S-UHI are closely related in their genesis.

Thanks to the research conducted in the late 20th century and early 21st century, the causes of the UHI effect are now quite well known (Oke, 1987).

The primary cause of the urban heat island (UHI) effect is the disruption of the urban energy balance due to the replacement of natural surfaces with artificial materials. Vegetation, especially trees, plays a crucial role by providing shade and facilitating evaporative cooling, which helps lower both surface and air temperatures. In contrast, urban areas dominated by artificial surfaces – like roofs, roads, parking lots, and pavement – tend to accumulate significant heat. These materials absorb solar radiation and, because they have low moisture content, do not cool effectively through evaporation. As a result, they re-radiate stored heat, contributing to elevated temperatures (Aram et al., 2020). Consequently, buildings become major sources of heat, leading to a considerable temperature difference between green spaces and built-up areas, underscoring the vital role of greenery in urban thermoregulation. For instance, a previous study in Lviv found that the surface temperature difference between the built-up area and Znesinnya Park reached 11.2 °C at 9:13 a.m., and this difference would likely be even greater at noon (Koynova & Kukhar, 2024b).

Urban geometry significantly contributes to rising temperatures in cities. The shape and height of buildings impact air circulation: taller and narrower structures can restrict airflow, limiting the cooling effects of the wind (Voogt, 2022). In Lviv, this factor heightens the city's susceptibility to the urban heat island (UHI) effect, particularly in the central area, which features narrow streets that hinder air movement. Additionally, the city's topography exacerbates this issue. The central part of Lviv is located in the valley of the Poltva River – now flowing through an underground channel – while surrounding areas are at higher elevations. This elevation difference creates a natural barrier that further restricts air circulation, intensifying the UHI effect. The properties of materials used in urban environments also play a significant role in temperature increases. Key factors include heat capacity, thermal emission, and albedo, which influence how materials absorb, emit, and reflect solar energy. Lighter-colored surfaces reflect more sunlight, while darker surfaces, such as asphalt and tar-covered roofs, absorb more heat, contributing to higher temperatures. Urban materials generally have a higher heat capacity than natural surfaces, allowing them to retain heat long after sunset, which prolongs warming effects. Thermal emission is also crucial, as it affects how effectively materials release stored heat as infrared radiation. Together, these factors intensify the UHI effect, emphasising the need for careful material selection in urban climate adaptation strategies. Additionally, anthropogenic heat – generated by vehicles, factories, and other sources – also contributes to the formation of the UHI effect.

The urban heat island (UHI) effect presents significant risks to public health. Increased air temperatures and inadequate nighttime cooling can result in physical discomfort, breathing difficulties, heat exhaustion, and, in severe cases, heat stroke, which can be fatal. Overheating also adversely impacts people's performance and can lead to insomnia. Vulnerable groups, such as the elderly, the homeless, and low-income individuals lacking access to air conditioning, are especially at risk (Astell-Burt & Feng, 2020).

Increased urban temperatures drive higher air conditioner use, straining the power grid. Studies indicate that when temperatures exceed 18°C, electricity consumption rises by 0.5% to 8.5% per degree, with peak demand increasing by 0.45% to 12.5%. On average, cooling demand in urban areas is 12% higher than in rural areas due to the UHI effect (Santamouris, 2020).

Methodology of remote sensing analysis

Satellite data from Landsat 8 and 9, accessed through the UGSC geoportal, were utilised to analyse the surface heat island effect. To obtain reliable land surface temperature (*LST*) data for the summer, we acquired two different satellite images. Due to technical challenges such as temporal resolution and weather conditions, the availability of cloudless satellite images is quite limited. Consequently, we successfully gathered reliable data for June 21, 2024, and July 31, 2024. The Landsat 8 and 9 sensors captured images of the study area at 9:13 a.m. to retrieve *LST* in the Red (band 4, 0.64–0.67 µm), Near-Infrared (NIR) (band 5, 0.85–0.88 µm) that have spatial resolution – 30 m and thermal infrared band (TIRS) (band 10, 10,60–11.19 µm), the spatial resolution which is 100 m (USGS. Landsat Satellite Misions).

LST was calculated from band 10 using the following algorithm. First of all the Digital number were converted into top of atmosphere spectral radiance by using following equation:

$$L = ML * Qcal + AL$$

where L is spectral radiance ($W / (m2 * sr * \mu m)$), ML – radiance multiplicative scaling factor for the band, AL – Radiance additive scaling factor for the band and $Qcal$ – pixel value in DN.

Next equation turns L (or top of atmosphere) into brightness temperature conversion (BT):

$$BT = \frac{K2}{ln\frac{K1}{L} + 1} - 273.15$$

where the value for $K1$ and $K2$ is a band-specific thermal conversion constant from the metadata. Therefore, to obtain the results in Celcius, the radiant temperature is adjusted by adding the absolute zero which approximately to -273.15° Celsius.

The next stage was the calculation of the Normalised Difference Vegetation Index (*NDVI*), which is a quantitative indicator of the photosynthetically active biomass of plants. This index is calculated based on band 4 and 5.

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

The proportion of vegetation (*Pv*) is highly related to the *NDVI* and emissivity (*ε*). So next equation is calculating *Pv* based on *NDVI* (Sobrino & Raissouni, 2000):

$$e = 0.004 * Pv + 0.986$$

where 0.004 corresponds to the average emissivity value of bare soil, 0.986 the average emissivity values of the vegetated areas, and *Pv* is the proportion of vegetation.

Finally, the *LST* was derived using the following equation (Jimenez-Munoz et al., 2014):

$$LST = \frac{BT}{1 + \frac{w * BT}{p} * Ln(\varepsilon)}$$

where *BT* is the brightness temperature, w is the effective wavelength (10.89 mm for band 10 in Landsat 8 data), *p* = *h**c/j* (*h*: Planck's constant, *c*: speed of light, *j*: Boltzmann constant), *e* is the surface emission.

After Land Surface Temperature was derived, obtained result was using to determine the level of correlation between *LST* value and land cover (*LC*). The *LC* information was obtained by calculating normalised difference built-up index (*NDBI*) and normalised difference vegetation index (*NDVI*) this dataset was calculated by using the same satellite images as was used for *LST* calculation. To obtain *NDBI* the following equation was used:

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR}$$

Spectral characteristic of Short-wavelength infrared (SWIR) sensor in Landsat 8/9 is 1.57-1.65 µm (USGS, Landsat Satellite Misions).

Relationship LST with NDBI and NDVI

To investigate the level of correlation between *LC* and its temperature, a map of the vegetation index and a map of the built-up index were created using the satellite images for 21.06.2024 and 31.07.2024 (Fig. 1). The vegetation index (Normalised Difference Vegetation Index, *NDVI*) is a simple quantitative indicator of the amount of photosynthetically active biomass, in other words, it shows the density of vegetation at a certain point. The value of the vegetation index varies from -1 to +1, where a higher value corresponds to a higher density of vegetation, a value below 0.3 corresponds to an area with a very low density of vegetation. The built-up index (Normalised Difference Built-up Index, *NDBI*) is an indicator that expresses the concentration of artificial surfaces, and the range of values can be from -1 to +1, where a higher value corresponds to a greater number of artificial surfaces.

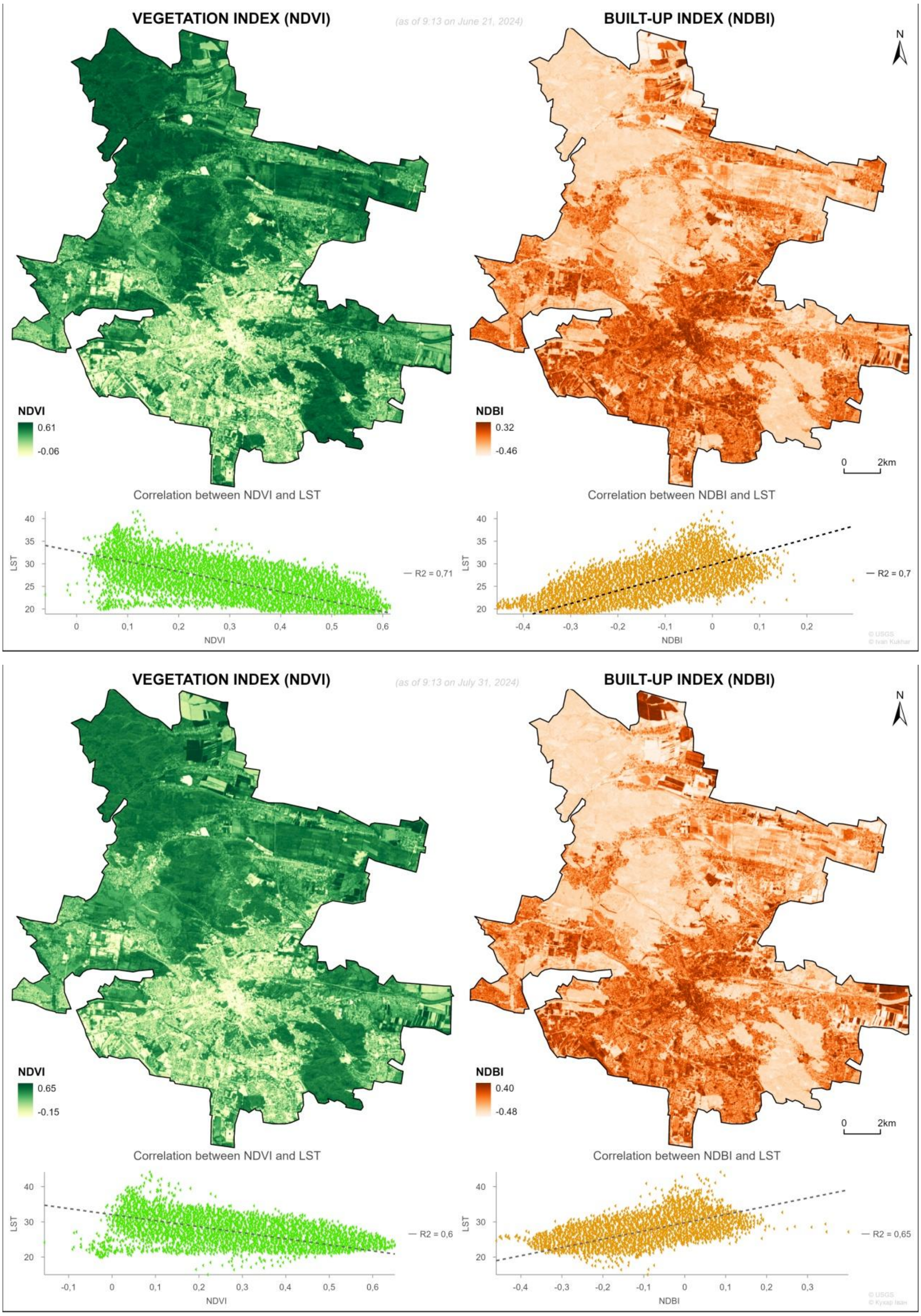

Figure 1. Correlation between LC and its temperature: 21.06.2024 (top) and 31.07.2024 (bottom). Elaborated by the authors

The overall results, presented on two maps on Fig. 1, are quite similar, except for a few agricultural fields that were harvested by July 31, 2024, resulting in lower *NDVI* (Normalised Difference Vegetation Index) and higher *NDBI* (Normalised Difference Built-up Index) values. In both cases, the graphs illustrate a strong relationship between these indices and land surface temperature (*LST*). The first graph shows a clear inverse correlation between *NDVI* and *LST*, with correlation coefficients of r = -0.71 for June 21, 2024, and r = -0.60 for July 31, 2024. Areas with a higher vegetation index – typical of forests, meadows, and parks – exhibit lower temperatures. Specifically, in regions where *NDVI* exceeds 0.5, indicating dense vegetation, temperatures range from 19°C to 28°C. The second graph reveals a strong linear relationship, showing that higher *NDBI* values correspond to higher temperatures. The correlation coefficients for this index are r = 0.70 for June 21, 2024, and r = 0.65 for July 31, 2024. In areas with NDBI values between 0 and 0.1, temperatures vary from 25°C (lower values typically correspond to water bodies) up to 42°C. Both graphs on the maps indicate a value corresponding to an *NDVI* or *NDBI* close to zero, which does not follow the general trend and is associated with water bodies. The analysis confirms that green areas with dense vegetation help lower temperatures, while built-up areas contribute to temperature increases (Parison et al., 2020). Overall, the findings underscore that temperature is influenced by land cover types.

Results of mapping land surface temperature

The resulting maps which you can see on Fig.2 show a significant difference between the surface temperature in settlements and outside them. Lviv stands out in map, particularly the areas of industrial facilities, parking lots, and shopping centres. The maximum surface temperature on June 21 was 42.1°C, the minimum was 18.8°C, and the mean was 23.9°C, while on July 31, the max 44.5°C, min. 15°C, mean 25.6°C.

To determine the boundaries and intensity of urban heat islands, urban heat island maps were created for both days based on the available surface temperature data. The urban heat island is defined by the formula $LST > \mu + 0.5 * \delta$, where μ is the mean value and δ is the standard deviation.

To highlight territories that belong to UHI red gradient colour was used and for NON-UHI - green gradient. When the maps were established we noticed that they resemble watermelon with red core (cover mostly city) and green peel (where natural landcover dominant) so this type of map on Fig.2 was named as “watermelon map”. Since large cities usually located in the centre of study area or administrative unit results of mapping UHI as a rule will be looks like watermelon (except arid regions).

In general, maps (watermelon maps) are similar to each other, except for the presence on the map as of 31.07.2024 of several agricultural fields in the north, near the villages of Zashkiv and Zarudtsi, as well as in the east near the village of Pidbirtsi, which were identified as heat islands due to the ability of soil not covered with plants to heat up.

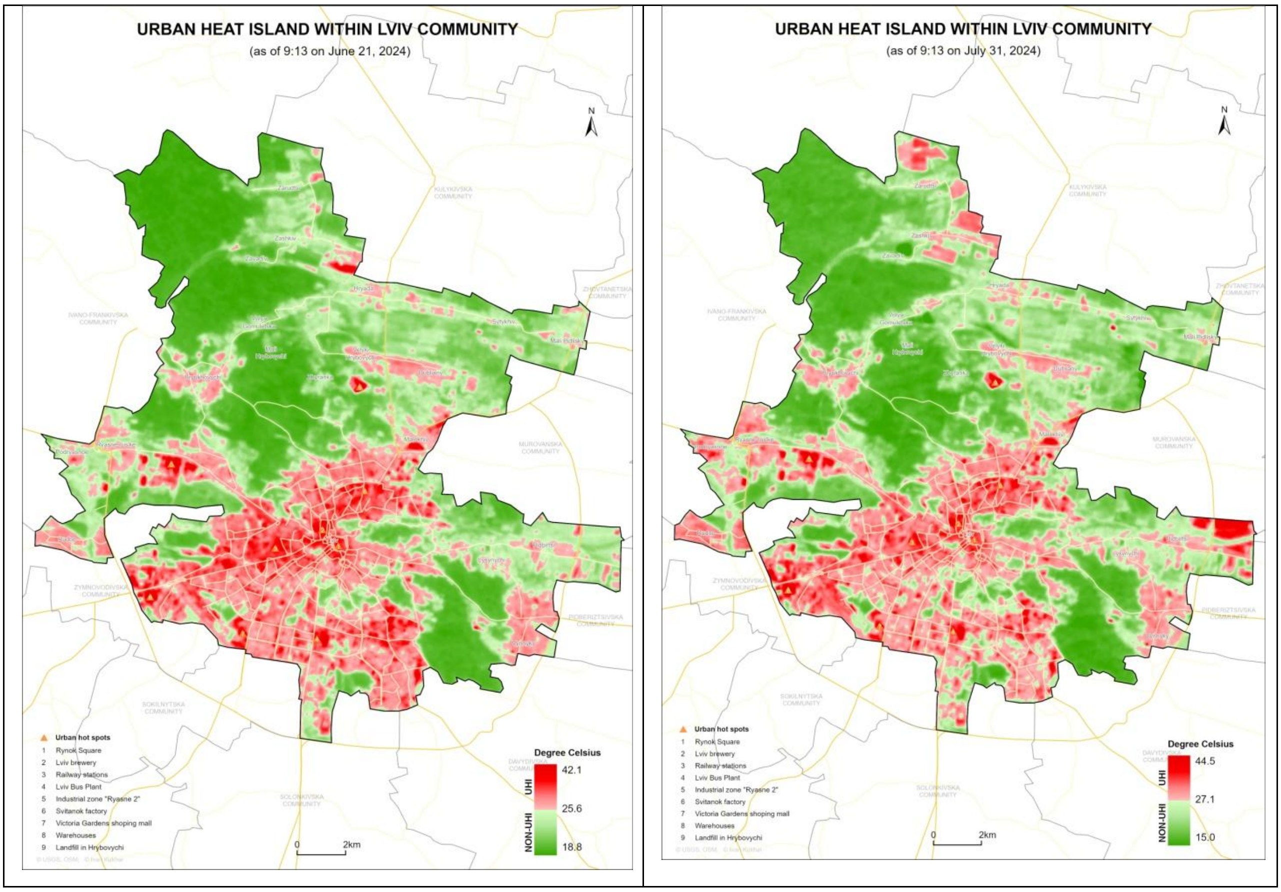

Figure 2. UHI "watermelon maps":
21.06.2024 (left) and 31.07.2024 (right). Elaborated by the authors

The S-UHI is formed not only in the largest city of the municipality, but also in smaller cities, such as Dubliany, where surface temperatures reach 30°C on 21 June and 32°C on 31 July. On both maps, there are places that are very hot, even within the heat island. These areas are called urban hot spots (UHS) and correspond to the areas that are heating up the most; they are marked with orange triangles and numbered on the map. Thus, as a result of the analysis, 9 most intense UHS were identified in the Lviv Municipal Heating District. They include: Rynok Square, the area between Kleparivska Street and Chornovola Avenue, the Main and Suburban Railway Stations including the surrounding area, the territory of the former Lviv Bus Plant, the Ryasne-2 industrial zone, the area around the Svitanok factory, Victoria Gardens shopping mall, warehouses at the end of Horodotska Street, and the unique Hrybovytske landfill site.

The reason for the significant overheating of Rynok Square is that it is a fairly large area that surrounded by buildings that forms continues wall with narrow streets, completely covered with paving stones, with a small area of vegetation. According to the map, the surface temperature here reaches 32°C, while in Vysokyi Zamok Park the surface temperature was 21.6°C on 21.06 and 22.7°C on 31.07, which indicates a significant impact of green spaces in reducing the surface temperature.

A large area of heat is the area between Kleparivska Street and Chornovola Avenue. The high concentration of buildings and the complete absence of greenery or its extremely low concentration on some streets, have a major impact on overheating here.

Another large object that is highly overheated within this area is the Forum Lviv shopping mall. Similar to Lviv Brewery, Forum Lviv covers a large area, with a roof similar to that of Lviv Brewery, but the satellite imagery shows that the surface is lighter in colour and probably made of concrete. The temperature of the roof on the studied days was 34.5 °C and 34.7 °C.

Another hotspot is the area of the Main and Suburban Railway Stations and the surrounding area, including the Lviv Locomotive Repair Plant, where the temperature on both days ranged from 31°C to 35°C, reaching the highest temperature on the roof of the Lviv Locomotive Repair Plant. The reasons for the high temperature are the same, although after the reconstruction of the Main Railway Station in 2021, there was an increase in greenery, but the canopy area is still too small to cool the area. However, the openness of the area helps to improve air circulation, which in turn reduces the effect of the heat island effect.

The Lviv Bus Plant (LAZ) is the most visible hotspot in the southern part of the city. The plant's territory consists of large premises/workshops with black tar roofs. This contributes to significant surface heating; on 21.06, the roof was heated to 38.2°C, and on 31.07 it was heated to 38.9°C.

The Ryasne-2 industrial zone, which houses Concern Electron, Lviv Forklift Plant, Lvivsilmash Plant, and Stella Foods warehouses, forms a single heat island. These enterprises occupy a large area, and the roof character is similar to the LAZ building (black tar). The temperature of the roofs ranged from 36.5°C to 37.8°C on June 21, and from 36.4°C to 38.5°C on July 31. Comparing these results with the roof temperature of the Brama enterprise, which is 28.5°C and 30°C, characterised by a light colour and probably having a hangar type of roof, we can conclude that such a roof contributes to a significant reduction in surface temperature, but in winter it has a lower ability to retain heat inside.

The area around the Svitanok factory is not characterised by significant point overheating, but forms a coherent area of elevated temperatures. This area of Pidzamche is defined by a concentration of industrial and other large facilities, often with parking lots.

Traditional parking lots covered with asphalt resemble a hot frying pan in summer. Large parking lots are usually created in places with a large concentration of people, which increases the number of people who experience the negative effects of such overheating. The territory of the Victoria Gardens shopping centre is such an example. On June 21, the surface temperature of the parking lot was 33.8°C, while the temperature of the same open area covered with grass (near the airport runway) ranged between 25°C and 25.8°C. On 31.07, the temperature of the parking lot was 33.9°C, and the temperature of the area next to the runway was 27.2°-28°C. This example clearly shows the difference between the temperature in the same conditions but with different *LC* type and shows that the integration of even low-growing grass when creating a parking lot can help reduce temperatures.

Another significant hotspot is the warehouse area at the end of Horodotska Street, where surface temperatures reached 39°C on June 21 and 40.2°C on July 31.

The Hrybovychi landfill is a unique object. Here, the maximum surface temperature of the entire municipality was recorded at 42°C and 44.2°C (21.06 and 31.07, respectively). This thermal anomaly is explained by the fact that the landfill is currently undergoing recultivation. One of the stages of recultivation is covering the landfill with geotextiles, which are black in colour and have a high heat capacity. The last stage of recultivation is the creation of a park at this site, so this area will not be considered part of the S-UHI.

The dense buildings, large artificial objects, and asphalt surfaces in Lviv lead to the formation of heat islands and hot spots. According to the surface temperature maps, the highest temperatures are recorded in such areas. Shopping centres, industrial warehouses and parking lots, occupying large areas, absorb a large amount of solar energy, which is then radiated as heat. This leads to a significant increase in temperature, particularly in summer, especially compared to green areas. Temperatures also rise significantly in areas with limited natural surfaces or trees, such as the area between Kleparivska Street and Chornovil Avenue, as well as Rynok Square, where the area of natural surfaces is very small due to compact urban development, which creates a hotspot of high temperatures.

Field research methodology

As previously mentioned, the intensity of the urban heat island (UHI) effect is evaluated by comparing temperatures within the city to those in rural areas. The purpose of this field study was to measure meteorological parameters and compare them with data from the Roztotskyi Landscape Geophysical Station (RLGS) of Ivan Franko National University of Lviv, located in Bryukhovychi, outside the densely built-up areas. This comparison aimed to assess the intensity of the classic UHI (CL-UHI) effect and evaluate the effectiveness of various adaptation measures implemented in the city to mitigate rising temperatures (Oke et al., 1991). Given the lack of a network of urban weather stations capable of continuously and automatically recording the necessary parameters throughout the year, field measurements were conducted using a Kestrel 3500 portable weather station, certified by the National Institute of Standards and Technology. In addition to measuring air temperature, surface temperature was recorded to evaluate its impact on air heating and identify the most heat-absorbing surfaces in the city. This data is essential for developing strategies to mitigate the UHI effect. Surface temperature measurements were taken using a Bosch UniversalTemp thermal detector. The study area was selected based on specific criteria, focusing on locations with high vulnerability to overheating and anticipated UHI intensity. Areas with heavy pedestrian traffic were prioritised to assess the impact of UHI on the largest number of people. Based on these considerations, the central part of Lviv was chosen for the study, and specific measurement points within this area were identified for data collection.

After defining study area, the next step was select measurement points within it. They were divided into three conventional categories. The first is a "cold point", corresponding to an area with intensive greening (park, square, forest, etc.). In this study, such an observation point was Na Valakh park. Another category is a place a certain adaptation solution has been implemented ("moderate point"), which is likely to have an impact on temperature reduction. It can be any nature-based solution, so the observation point was next to the fountain in front of the Lviv National Academic and Ballet Theatre, at a distance of about 10 meters, allowing us to study the impact of the fountain on temperature reduction. The last category a "hot spot" where no adaptation measures have been taken to the temperature, and is little or no vegetation. This category includes the observation points on Rynok Square and square in front of Taras Shevchenko monument. Distribution of measurement points is explained by effectiveness of the data obtained, as they provide information on both the intensity of the UHI and the effectiveness of the implemented solutions.

It was impossible to conduct measurements at night due to the curfew. Such measurements were carried out at the following times: 9:00, 12:00, 15:00, 18:00, 21:00 at a height of 2 from the surface.

The field stage of the study took place on August 15, 2024, at the Roztotskyi Landscape Geophysical Station (LGS). The day was marked by clear weather, with an average daily temperature of 20.6 °C. Wind conditions were generally calm, averaging up to 1 m/s, except at noon when it increased to 2 m/s from the northeast. There was no cloud cover for most of the day; however, at 12:00, 21:00, and 24:00, there were brief instances of cirrus clouds, reaching a coverage of 2 oktas. No precipitation or other atmospheric phenomena were observed during the day.

Measurement points

Measurements on Rynok Square were conducted in its north-western part, near the AmphitriteFountain, at a sufficient distance from it. The underlying surface was granite paving, and the area was mostly shaded.

Na Valakh park is a green space with a main paved path lined with densely planted trees, providing continuous shade. Adjacent to the path are sports grounds surrounded by dense grass. Measurements were taken near the park's entrance, close to the intersection of Pidvalna and Lesia Ukrainka streets.

The area in front of the Taras Shevchenko monument is an open cobblestone-paved square with minimal vegetation, limited to the edges and represented by low thuja and a few trees. It remains unshaded for most of the day, with shading occurring only after 17:00, leading to significant heat accumulation. However, due to its openness, constant air movement occurs, contributing to heat dissipation. Measurements were conducted at the centre of the square.

Measurements in front of the Lviv National Academic Opera and Ballet Theatre were conducted 10 meters from the fountain, which operated continuously throughout the day. This area remained exposed to direct sunlight except during the 9:00 and 21:00 measurements when it was briefly shaded. The urban canyon effect was observed here, though its intensity was lower due to the theatre building restricting airflow.

Roztotskyi Landscape Geophysical Station is located in Bryukhovychi, on the northern outskirts of the settlement, away from the main buildings. A beech forest begins approximately 35 meters from the site. The weather station remains predominantly sunlit throughout the day.

Field research results

In order to avoid systematic errors when comparing temperatures measured at different altitudes, the air temperature values were corrected for the thermal gradient. This will eliminate the influence of altitude on temperature in the analysis. The correction is 1° per 100 m of altitude and was used for all measurement points, with the RLGS as the base station (World Meteorological Organisation, 2023).

As a result, the temperature obtained after applying the correction will differ from the actual temperature at the time of measurement, because we remove one of the factors that affects the temperature and leave only factors that depend on the environment of the measurement site (landcover type, air circulation, shading, cooling capacity of plants, etc.) (Li et al.,2011). The following analysis is based on data with this correction applied (Table 1).

Table 1. Measurement results with and without correction

	Raw data					**Correction is applied**				
	9:00	12:00	15:00	18:00	21:00	9:00	12:00	15:00	18:00	21:00
Rynok Square	19,8	25	28,9	28,6	25,9	19,4	24,6	28,5	28,2	25,5
Na Valakh park	18,2	22,9	27,3	28,7	24,8	17,9	22,6	27	28,4	24,5
Shevchenko monument	19,8	26,1	31,3	29,2	26	19,3	25,6	30,8	28,7	25,5
Theatre	19,8	27,1	29,7	29,8	26,6	19,3	26,6	29,2	29,3	26,1
Roztotskyi LGS	18,8	23,4	27,5	27,1	20,6	18,8	23,4	27,5	27,1	20,6

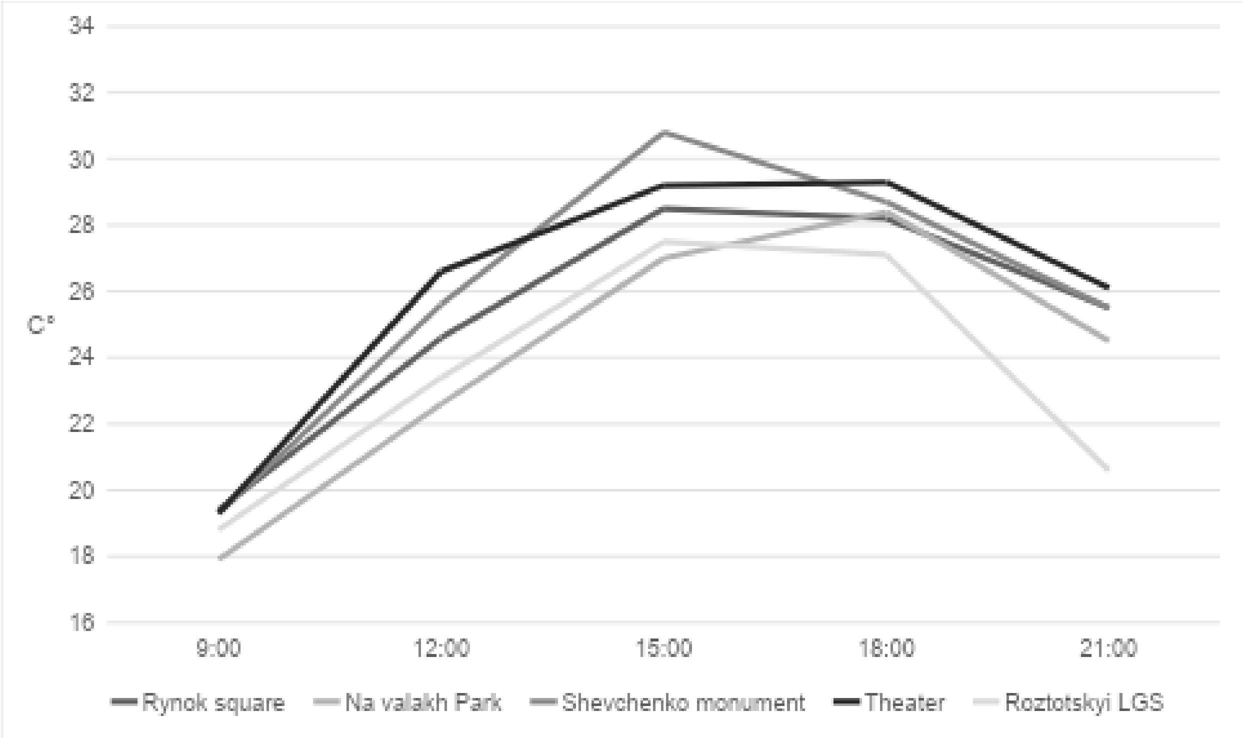

Figure 3. Temperature dynamics with correction

As you can see on Fig. 3, at 9:00 a.m., the lowest air temperature was in the Na Valakh park (17.9 C), due to shading by trees. At the RLGS, the temperature was 0.9°C higher, which is explained by the fact that the station is not shaded by trees, unlike the park, where the measurement site is completely covered by crowns. In the park, the temperature of the pavement in the shade was 19.6°C, in the sun – 23°C, and the grass remained the coolest (17.1°C), which provides a cooling effect.

The highest air temperature among measurement points was recorded on Rynok Square (19.4°C). In front of the theatre and the Shevchenko monument, it was 19.3°C. These areas are not shaded, and the influence of vegetation is quite low due to the small area it occupies. The temperature of the pavement here reached 24 °C in sunny areas and the theatre facade – 24°C. The hottest was the asphalt bike path (28.4°C), which was 4.4°C higher than the temperature of the pavement.

On Rynok Square, the surfaces heated up similarly to other locations: granite paving stones reached 23.2 °C in sunny areas and 16.3°C in the shade. The light-coloured facade heated up to 26°C, which further increased the temperature of the square.

At noon (12:00), the temperature difference between the warmest and coolest locations increased. The highest air temperature was measured in front of the theatre (26.6°C), and the lowest – in Na Valakh park (22.6°C). The surfaces were heated even more intensively: the temperature of the pavement in front of the theatre in the sun reached 36.8°C, while in the shade it was 18.8°C, a difference of 16.4°C. Such a difference between identical surfaces in the shade and in the sun indicates the high efficiency of shading in reducing the temperature of surfaces in the city (Lee et al., 2015). The fountain also has an effect on reducing the surface temperature: the temperature of dry tiles located next to the fountain is 32.1°C (under the sun), and the temperature of wet tiles directly in the fountain is 22.1°C. The asphalt bike path heated up to 48.1°C in the sun, which suggests that the use of this material can increase the city's vulnerability to extreme heat. At the same time, the vegetation remained much cooler: the temperature of the grass in the open area did not exceed 25.5°C, which is 11.3°C lower than the neighbouring pavement. The temperature of the grass in the park was 21.9°C (in the shade), which is 9.4°C lower than the pavement temperature in the shade nearby.

At 15:00, the air temperature peaked at almost all measurement points, at which time there is a clear difference in air temperature depending on the specifics of the location. The highest air temperature was in the square in front of the monument to Shevchenko at 30.8 °C, the lowest in the park at 27°C. The temperature difference is 3.8°C. The air temperature at the RLGS was 27.5°C, which is 3.3°C lower than the highest temperature during this hour. At this time, the effect of CL-UHI and the effectiveness of adaptation methods in the city, including parks and fountains, are already clearly visible. The temperature in front of the theatre is 29.2°C, which is 1.6°C lower than the temperature in the square in front of the monument, and these two points are located on the same street with the same type of buildings, which makes these points relevant for comparison with each other to determine the cooling effect of the fountain. Also, at this time, the two points were exposed to direct sunlight, which also brings their conditions closer together. This indicates the cooling effect of the fountain, which can be considered an effective adaptation measure. Therefore, a decrease in air temperature by 1.6°C can be considered the approximate effectiveness of this fountain as an adaptation measure. However, it should be noted that this value may fluctuate depending on weather conditions.

The temperature of almost all surfaces reached a daytime maximum, at which time the S-UHI effect is most intense. The temperature of the pavement in front of the Shevchenko monument was 49.1°C in the sun and 31.4°C in the shade, a difference of 17.7°C; in the square in front of the theatre, the temperature of the pavement in the sun was 45.7°C and in the shade was 32.1°C, a difference of 13.6°C. The fountain contributed to the cooling of the surface temperature: the temperature of the pavers near the fountain was 12.1°C lower than the identical ones located further away from the fountain, and the temperature of the tiles in the fountain itself was 22°C lower. The temperature of the pavers at the other measurement points was also very high. The average difference between the temperature of the pavers in the sun and in the shade is 14.3°C. Thus, based on these results, it can be concluded that shading surfaces and moisturising them, including with a fountain, is effective in reducing their temperature and, as a result, lowering the air temperature.

At 15:00, the theatre facade was heated to 43.1°C, and on the Rynok Square, the temperature of the building facade was 39.2°C. The temperature of the vegetation does not overheat even when exposed to direct sunlight. The surface temperature of the grass in front of the theatre was 30.2°C, compared to the temperature of the pavement in the sun, the difference is 15.5°C, the temperature of the vegetation on the Rynok Square was 32.7°C, and the temperature of the shaded grass in the park on Na Valakh was 27.6°C. Vegetation maintains a more stable and lower temperature compared to artificial surfaces, helping to mitigate the UHI effect. In contrast, building facades accumulate heat in summer, significantly contributing to air warming and further intensifying the UHI effect.

At 18:00, the highest air temperature was recorded in front of the theatre – 29.3°C, and the lowest in front of the Shevchenko monument – 28.7°C. This difference arose because at that time the area was already completely shaded by the bank building, so the surfaces had already cooled down, while the area in front of the theatre was not yet shaded. The air temperature in Na Valakh park was 28.4°C, and on Rynok Square it was 28.2°C. The lowest air temperature was recorded at base station – 27.1°C. Thus, as of 18:00, the intensity of the CL-UHI effect in front of the theatre was 2.2°C.

The temperature of the facades also gradually decreased: the theatre facade was 34.9°C, and the temperature on Rynok Square was 29.7°C. The vegetation remained much cooler than the hard surfaces: the temperature of the grass near the theatre was 29.1°C, which is 16°C lower than the temperature of the neighbouring pavement. In Na Valakh park, the temperature of the shaded grass was 25.8°C, which is 3.9°C lower than the pavement temperature, emphasising the effectiveness of vegetation in reducing overheating of urban space.

According to theoretical model (Stewart et al., 2021), the intensity of the CL urban heat island is highest after sunset. On August 15, the sunset occurred at 20:44, before the last measurements of the day. The measurement results confirmed this theory, because at 21:00 the temperature in the city and in the rural area (RLGS) is significantly lower. The highest air temperature at 21:00 was measured in the square in front of the theatre and amounted to 26.1°C. The lowest air temperature was expectedly recorded at the Roztotskyi Landscape Geophysical Station and amounted to 20.6°C. The temperature difference was 5.5°C. The temperature in Na Valakh park was 24.5°C, and in Rynok Square and in front of the Shevchenko monument it was 25.5°C, which is 4.9°C higher than the temperature at the base station.

The intensification of the CL-UHI effect at 21:00 can be attributed to the rapid cooling of natural areas after sunset. Due to their openness and lower surface temperatures, these areas cool significantly faster than urban environments, where artificial surfaces dominate. These surfaces possess a considerably higher heat capacity compared to vegetated natural surfaces, leading to a prolonged retention of heat in urban areas.

Although surface temperatures began to decline, materials that accumulated heat throughout the day remained warm. The pavement in front of the theatre, which had been exposed to direct sunlight for an extended period, retained a temperature of 29.3°C, whereas the adjacent grass exhibited a significantly lower temperature of 19.7°C, resulting in a 9.7°C difference. Even in shaded areas, the pavement remained warmer than the grass, measuring

22.2°C compared to 19.7°C. Near the fountain, the pavement temperature was 25.3°C, 4°C lower than in open areas, likely due to evaporative cooling. The water temperature within the fountain was 21.4°C, which was 7.9°C lower than the temperature of the surrounding heated pavement.

In front of the Shevchenko monument, the pavement retained a temperature of 27.2°C, while the nearby vegetation remained cooler at 25.1°C. In Na Valakh park, the grass maintained a lower temperature (22.1°C) compared to the adjacent pavement (25.2°C); however, the limited vegetation cover reduced the overall cooling effect.

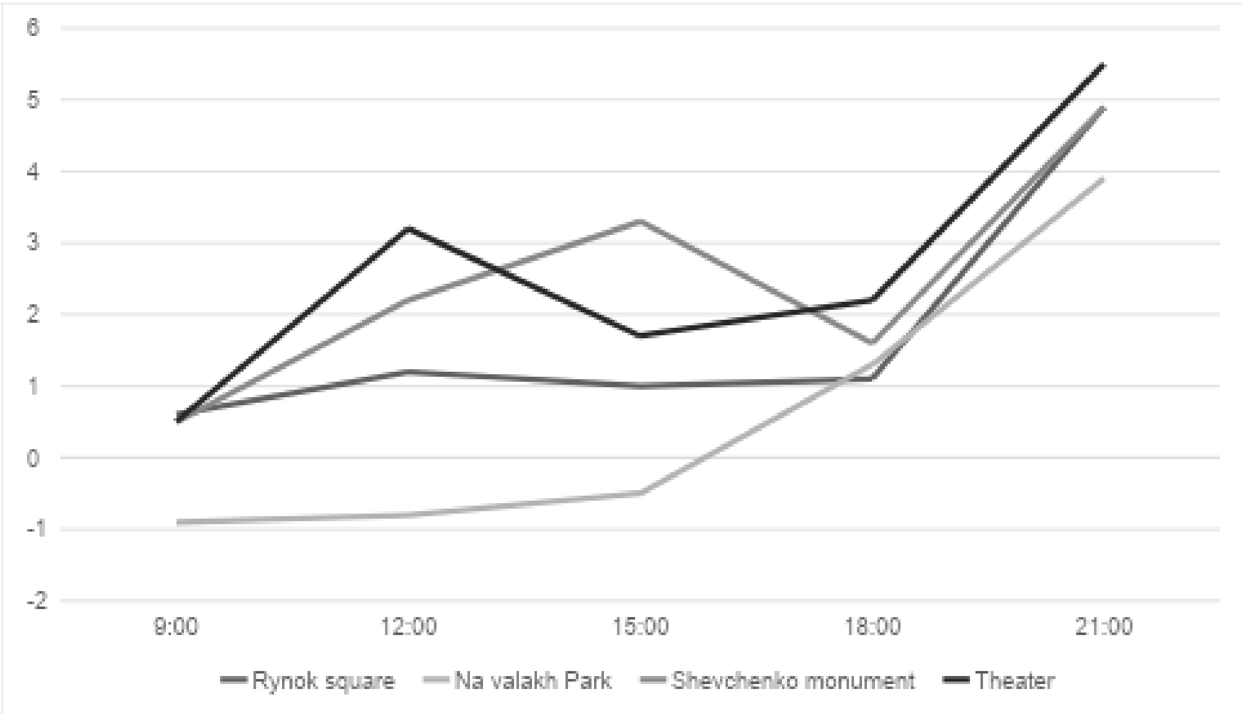

Figure 4. The intensity of the CL-UHI effect

On Rynok Square, surface temperatures were higher due to dense urban development and minimal greenery. The shaded pavement measured 26.8°C, the building facade reached 27.2°C, and the polished pavement, which effectively accumulated heat, retained 32.9°C. The high concentration of heat-emitting surfaces and insufficient vegetation contributed to a CL-UHI intensity of 5.5°C, highlighting the critical role of green spaces in mitigating urban overheating.

Fig. 4 shows the dynamics of the intensity of the CL-UHI effect, which is the temperature difference at a certain point and the results of measurements at the Roztotskyi landscape geophysical station, i.e., the base station for comparing temperature and determining UHI. Thus, this graph shows that at 9:00 a.m., the intensity of CL-UHI at almost all measurement points was 0.5°C, and at the Rynok Square it was 0.6°C. However, in the Na Valakh park, the intensity of the UHI is negative, which is explained by the high shade of the park, unlike the weather station located in an open area; this trend persists until 18:00, when the CL-UHI effect also begins to appear in the park. At lunchtime, at 12:00 and 15:00, this effect is already more pronounced, but it is most intense after sunset. The sunset on the day of the study occurred at

20:44, i.e. before the final measurement. At 21:00 intensity of CL-UHI was the highest in the theatre point (5.5°C) on the Rynok Square and next to monument intensity of this effect was the same (4.9°C). Expectedly the lowest intensity was in the park and was 3.9°C.

Urban Heat Island mitigation solution

When the intensity and geospatial distribution of the UHI effect is known the main issue that remains is the reducing of such effect. The most logical approach is to reduce reasons that contribute for UHI formation. According to study the main cause is replacing nature surface and structures with artificial surface. Therefore, the most effective method to reduce UHI is to increase in the area green zones. Increasing the area of green space within urban environments can be approached through three primary strategies. The first approach involves incorporating green areas into urban planning processes. However, this method proves ineffective for already densely built-up areas, particularly in city centres where the UHI effect is most pronounced. The second approach focuses on converting existing surfaces to natural ones by establishing green spaces on the sites of buildings. While this is generally impractical, it can be effectively applied to abandoned or underutilised areas, such as former industrial sites. In such cases, the creation of green spaces not only addresses the UHI effect but also mitigates the negative social and environmental consequences associated with urban decay and marginalisation, while at the same time enhancing thermal comfort and overall quality of life for nearby residents. As a compromise between these two strategies, a third approach has emerged, which aims to integrate vegetation into existing urban structures without necessitating large-scale demolition or redevelopment. This is the integration of vegetation (nature) into an existing city (buildings, infrastructure) through nature-based solutions (NBS), which in many cases involve a certain degree of reconstruction of existing facilities, thereby not changing their main functionality but only expanding it, adding ecosystem services (temperature reduction, air purification, noise barriers, etc.) for the city.

Integration nature into the city through NBS might be the most effective approach to increasing the ratio of natural surfaces in the structure of the city’s land cover. This approach is especially relevant for Lviv, whose urban development in the central part of the city is represented by a common for Europe urban geometry style with narrow streets, where is a lack of space for greenery. But NBS approach is especially useful in such densely built-up areas.

There is a wide variety of such solutions, for example, green roofs, green walls, green parking lots, green tracks, pocket parks, etc. To maximise the cooling effect, it is important to choose the right place for greening; vegetation located in a densely built-up area, where the intensity of overheating is the highest, has the greatest cooling effect, while greening around the city has a lesser effect. Choosing a location for implementing such solutions is an important step and requires a comprehensive approach to take into account many factors, including the architectural complex of the territory, the strength of existing facilities if the solution involves additional weight (vertical gardening, green roof) and local climate conditions such as street orientation or natural lighting of the area (Kabisch et al., 2017).

An effective solution for mitigating the UHI effect in Lviv could be the creating of pocket parks. Pocket parks are small public green spaces with an area of less than 0.5 hectares, significantly smaller than conventional urban parks. These parks are created in areas where high building density prevents the allocation of large spaces for traditional parks. Despite their limited size, pocket parks can be designed with diverse configurations and enhanced with various small architectural elements (Faraci, 1967).

To maximise the result, i.e. cooling, it is important to carefully choose a location for the park, because there is no one-size-fits-all solution. It is necessary to take into account the local climate zone in each district of the city, street orientation, height difference, shading, and other factors. The planning of the park itself, including the selection of species composition and spatial configuration, plays a crucial role in its effectiveness. Properly chosen plant species can enhance cooling through shading and evapotranspiration, while the park's configuration should promote natural air circulation (Houet al., 2022).

In Lviv, there are quite a few places for pocket parks, even in the central part. The advantage of the block development is that a courtyard is formed inside the block, unfortunately, these courtyards in Lviv are often abandoned, sometimes serving as parking for several cars, or are completely empty(Hou et al., 2022). There are also positive examples, for instant, in the central part of the city, cafes and restaurants operate in such courtyards. It is important to use this territory rationally, as such courtyards have the potential to become public spaces with greenery, which will help cool down and have many social benefits (Koynova & Kukhar, 2024c).

Another effective solution to increase the green space in the city is vertical gardening, as it does not require a territory, but only a vertical object – a wall or some kind of barrier. This is an effective solution for reducing indoor and outdoor temperatures, and it does not require high costs. Plants can climb up the wall or along the frame, or grow in the open ground or in containers. Studies indicate that the implementation of green walls and facades can effectively reduce indoor temperatures by up to 2.25°C, thereby decreasing electricity consumption for cooling. Notably, the surface temperature of vegetated walls remains approximately equal to or slightly below ambient temperature during the day, whereas bare walls can reach temperatures up to 20°C higher than the surrounding air. The effectiveness of these solutions depends on various factors, including the regional climate, the selection of plant species, and the orientation of the wall. Optimal cooling is achieved with western and southern orientations, where the greatest exposure to sunlight occurs. In addition to temperature reduction, green walls and facades can lower energy consumption by up to 16%, improve outdoor air quality, trap dust and other microparticles, and contribute to oxygen production (Safikhani et al., 2014; Azkorra-Larrinaga et al., 2023; Bakhtyari et al., 2024)

Based on the study of S-UHI parking lots that often occupy a large area in front of a shopping centre or enterprise contribute to the formation of UHI. Such parking lots are usually completely covered with asphalt without any greenery (Zheng et al., 2023). Thus, in summer, such parking lots feel like a hot frying pan, and even after sunset, one can feel the surfaces give off heat. The study compared the surface temperature of the parking lot in front of the Victoria Gardens shopping centre with the surface temperature of the grass next to the runway of Lviv Airport. The difference in temperature was 8.8°C on June 21 and 6.7°C on July 31, which is quite significant given that the measurements were taken in the morning. At lunchtime, this difference is even greater. Thus, this comparison suggests combining the parking function with a natural surface. Such a solution is already widely used in the EU, and such parking lots are called green. This solution is to use a lawn grate or porous paving stones instead of asphalt or traditional paving stones for parking spaces, in the space between which grass grows. Examples of such implementation already exist in Lviv, but not on a large scale and need to be scaled up (Koynova & Kukhar, 2024a).

Replacing existing parking lots with green parking lots will help reduce the intensity of UHI in the city, as well as retain water during precipitation, which will increase evaporation and lower temperatures.

The research of S-UHI has shown that roofs are one of the most noticeable overheated surfaces. These are mostly roofs of commercial and industrial facilities. A lot of the industrial buildings were constructed during the Soviet occupation of Ukraine, including buildings that now belong to the Electron Concern, Lviv Forklift Plant, Lvivsilmash, and others. The specificity of these buildings is that during their construction, resin was used to insulate the roof, which is a heat-intensive black material. The same coating was used in buildings for other purposes - residential, administrative, etc. The characteristics of this coating contribute to intense surface heating in summer, which increases the temperature indoors and outdoors.

An effective solution to combat extreme heat is to create green roofs. Green roofs are a nature-based solution that involves partially or completely covered roofs with vegetation. Depending on the height of the plants, green roofs are divided into intensive and extensive. Intensive roofs are roofs with high and sparse vegetation cover, where bushes and even trees can grow. Whereas, extensive green roofs are characterised by low vegetation cover, it can be grass, moss, lichens (Gao et al., 2020).

The choice of a green roof type depends on the budget and the strength of the roof, as vegetation and substrate add significant weight to the structure. Despite the higher efficiency of an extensive green roof, most existing roofs are not able to support its weight without additional reinforcement, but an extensive type with grass or succulents can be an effective way to reduce temperatures and energy use for cooling in summer and heating in winter.

This is especially true for large enterprises and warehouses. A study modelled the energy savings on heating and cooling for a one-story commercial building in Toronto with a green roof area of 2,980 m^2. According to the results, a green roof can save about 6% of total energy consumption for cooling and 10% for heating, respectively. Another study showed that turning 50% of the roofs of central Toronto into green roofs would reduce the city's air temperature by 0.1-0.8°C, and additional watering would reduce the temperature by another 2°C (Liu & Bass, 2005).

Thus, the implementation of such solutions can reduce the intensity of the UHI effect and reduce energy consumption. In addition, vegetation purifies the air and retains rainwater, which saves on wastewater treatment systems, as less of it will go into the sewer system.

Within Lviv, such a solution can be implemented on the roofs of warehouses and enterprises, creating full-fledged parks or simply planting low vegetation. Also, green roofs can be created on already built flat-roofed residential houses, which make up a large part of the housing stock in Lviv. Also, most municipal institutions and enterprises are suitable for creating such roofs.

In addition to NBS, water is also an effective way to cool down. Fountains can be used in cities where there are no large natural reservoirs. Despite their spatially limited cooling effect, they are effective in reducing air temperatures. The field study demonstrated that fountains can effectively contribute to reducing air temperature. At 15:00, when both points were exposed to direct sunlight, the air temperature at a distance of 10 meters from the fountain in front of the Solomiya Krushelnytska Lviv National Theatre was 1.6°C lower than the temperature recorded simultaneously in the square in front of the Shevchenko monument. Additionally, the surface temperature near the fountain was 12.1°C cooler than the same surface located further away (Dorst et al., 2019).

These findings indicate that incorporating fountains into urban environments can positively influence climate adaptation efforts by reducing the intensity of the urban heat island effect.

To summarise, the best way to reduce the intensity of UHI is to increase the area of greenery in the city's land cover structure. The integration of NBS in the city can be a key method for this, but requires a comprehensive approach to take into account the conditions of each site to select the best solution and configuration to maximise the cooling effect. In addition to NBS, 2 other approaches are also important – prioritising greening in urban planning and replacing some facilities with green areas where justified.

Conclusions

This study provides a comprehensive analysis of the UHI effect within the Lviv municipality, highlighting its spatial distribution and the impact of land cover types. For the first time, S-UHI maps were created, allowing for the identification of heat islands and hot spots, assessment of their geospatial patterns and intensity, and investigation of the correlation between surface temperature and land cover characteristics.

Field measurements conducted as part of this research helped to characterise CL-UHI, supplementing the S-UHI analysis and offering deeper insights into urban heat dynamics. Additionally, the study examined the role of green spaces and nature-based solutions, such as fountains, in mitigating the UHI effect.

The study results indicate that the most overheated areas are open spaces with minimal vegetation. Remote sensing analysis identified heat hotspots primarily on the roofs of large enterprises, parking lots, and densely built-up areas. Field measurements confirmed that the CL-UHI effect is most pronounced after sunset, with a maximum intensity of 5.5°C recorded in front of the theatre.

Artificial surfaces, such as asphalt and concrete paving stones, exhibit high heat retention, intensifying the UHI effect, while shaded and green areas remain significantly cooler. Vegetation plays a crucial role in mitigating localised overheating, as grass temperatures were found to be 10–15°C lower than those of neighbouring artificial surfaces. Fountains also provide a cooling effect, though their influence is limited to their immediate surroundings.

The study also highlights several effective approaches to reduce the intensity of the urban heat island effect in Lviv. These include prioritising green areas in urban planning, replacing some degraded and abandoned areas with green areas, and implementing nature-based solutions. These include the creation of pocket parks, green parking lots, green facades, fountains, and green roofs. All of these solutions contribute to lowering the ambient temperature through shading, evaporation, and cooling through water bodies (Castleton et al., 2010). Moreover, most of these measures also reduce energy consumption, reducing the need for air conditioning. Implementing such nature-based solutions can significantly increase a city's resilience to climate change, improve thermal comfort, and promote energy efficiency.

Overall findings underscore the need for targeted climate change mitigation actions, such as increasing vegetative cover, especially in open spaces with low vegetation, incorporating high-albedo materials, and expanding the implementation of nature-based solutions. Future research should focus on the seasonal variability of UHI, the long-term effectiveness of mitigation strategies. The insights from this study can contribute to evidence-based policymaking aimed at enhancing climate resilience in urban environments.

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