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Exploring Spatial Patterns of Urban Heat Islands in Zagreb

Dino Bečić, Alen Pažur

(Dino Bečić, M.Sc. Geography, Institute for physical planning of the City of Zagreb, Republike Austrije 18, 10000 Zagreb, Croatia, dino.becic@zagreb.hr)
(Alen Pažur, M.Sc. Geography, Institute for physical planning of the City of Zagreb, Republike Austrije 18, 10000 Zagreb, Croatia, alen.pazur@zagreb.hr)

1 ABSTRACT

Urban heat islands are a spatial phenomenon characterized by increased temperatures in urban areas compared to their suburban and rural surroundings, driven by spatial patterns of built-up areas, land use, and land cover, as well as the absence of vegetation and variations in land surface temperature (LST). This study examines the relationship between built-up intensity, planned land use, and LST in the City of Zagreb, focusing on its core urban area. Utilizing Landsat-9 satellite data for LST extraction and urban spatial planning documents for vegetation classification, the study explores key spatial factors influencing the intensity and spatial distribution of urban heat islands. The methodological approach integrates Exploratory Spatial Data Analysis (ESDA), regression models, and spatial autocorrelation to determine the spatial dependencies between land use and temperature variation, conducted using the R programming language. The analysis identifies specific areas where built-up land use categories contribute most to temperature increases, while planned green zones have a significant cooling effect. Spatial regression highlights the varying impact of different planned land-use categories on local thermal conditions, particularly the role of designated green areas in mitigating urban heat accumulation. Spatial autocorrelation techniques confirm the presence of clustering effects in heat island distribution, emphasizing the spatial dependency of UHI formation. These results emphasize the need for an integrated urban planning approach to mitigate the negative effects of urban heat islands and improve the quality of life.

Keywords: Urban Heat Islands, Zagreb, R, Spatial Analysis, Land Use

2 INTRODUCTION

The Urban Heat Island (UHI) phenomenon, characterized by increased temperatures in urban areas compared to their rural counterparts, is a major issue in urban climate research. This temperature disparity arises due to a combination of factors, including land-use changes, impervious surface expansion, anthropogenic heat emissions, and reduced vegetation cover. As urbanization intensifies, cities across the world are experiencing heightened UHI effects, which pose significant environmental challenge thus making UHI mitigation an essential component of sustainable urban planning.

Recent advancements in remote sensing and geographic information systems (GIS) have provided valuable insights into the spatial and temporal distribution of UHI. Researchers have employed multi-temporal satellite analyses, thermal imaging, and statistical modeling to assess the impact of different land-use types on urban thermal environments. Studies on cities worldwide have consistently emphasized the role of vegetation in mitigating UHI effects, highlighting the importance of integrating green infrastructure into urban landscapes.

For Zagreb, the capital of Croatia, several studies have investigated the impact of urban expansion and land-use transitions on the city's thermal environment. This review synthesizes findings from recent research on UHI in Zagreb and other comparable cities, with a focus on land-use patterns, vegetation cover, remote sensing methodologies, and mitigation strategies.

3 LITERATURE REVIEW

Land use and urban morphology play a crucial role in influencing land surface temperature (LST) and the intensity of UHIs. The spatial distribution of built-up areas, green spaces, and water bodies significantly affects temperature variations. Research in Wuhan, China, revealed that industrial and commercial zones contribute extensively to elevated surface temperatures due to anthropogenic heat emissions (Lu et al., 2021). Similarly, a study in Izmir found that areas with high street network centrality exhibited intensified UHI effects, whereas increased street connectivity mitigated heat buildup (Erdem et al., 2021). Functional zones such as commercial and industrial areas have been identified as UHI hotspots due to heat absorption by impervious surfaces and limited vegetation (Chen et al., 2022). Studies in European cities reinforce these findings. In Berlin, Germany, research demonstrated that densely built-up areas exhibit the highest temperatures, while green spaces provide cooling effects (Dugord et al., 2014). An assessment of urban temperature distributions across Europe found that industrial and commercial areas consistently exhibit higher LSTs than vegetated areas (Hellings & Rienow, 2021). In Seville, Spain, urban expansion and a reduction in agricultural land over 30 years have significantly increased LST (Halder et al., 2022). Nighttime UHI intensity has risen in Istanbul due to continuous urban expansion and reduced green cover (Ünal et al., 2020), while a study in Prishtina demonstrated a strong correlation between built-up intensity and increased surface temperatures (Isufi et al., 2021). Additionally, the growing urbanization of rapidly developing regions has exacerbated heat island effects, making mitigation efforts more urgent.

These findings underscore the strong relationship between urban development patterns and temperature variations, highlighting the need for effective mitigation strategies. One of the most effective approaches to counteracting the UHI effect is the integration of vegetation, which plays a crucial role in cooling urban environments.

Vegetation plays a crucial role in mitigating the UHI effect by providing shade, enhancing evapotranspiration, and reducing heat absorption. The correlation between the Normalized Difference Vegetation Index (NDVI) and LST has been widely studied, with consistent findings that higher vegetation cover results in lower temperatures (Guha & Govil, 2018). A study in Bochum, Germany, confirmed a strong negative correlation between LST and green volume, indicating that increasing urban greenery can effectively mitigate heat stress (Schmidt & Lawrence, 2022). Research in Andalusia, Spain, further supports these findings, emphasizing that urban planning strategies incorporating green spaces are essential for maintaining a balanced thermal environment (Hidalgo García & Díaz, 2023). Case studies in Naples and Florence found that UHIs predominantly formed in built-up and bare land areas, while regions with dense vegetation exhibited significantly lower temperatures (Guha et al., 2018). Similarly, research in Dubrovnik, Croatia, revealed a rising trend in maximum summer temperatures from 1961 to 2019, with urbanized surfaces heating up more than vegetated areas (Boras et al., 2022). The cooling effect of tree cover is further highlighted in studies conducted in Italy, where increased impervious surface density led to higher UHI intensity, while inland cities suffered more than coastal cities due to a lack of cooling from nearby water bodies (Morabito et al., 2020). The findings highlight the necessity for large-scale tree planting initiatives, green corridor development, and the protection of existing green infrastructure.

These studies collectively emphasize the critical role of vegetation in regulating urban temperatures, reinforcing the need for strategic urban planning focused on expanding green infrastructure. To accurately assess and monitor these thermal dynamics, remote sensing and GIS methodologies have emerged as essential tools, enabling researchers to analyze UHI patterns with greater precision and develop targeted mitigation strategies.

Remote sensing and GIS methodologies have become indispensable tools for analyzing UHI spatial patterns. The use of Landsat satellite imagery and geospatial indices like NDVI and the Normalized Difference Built-up Index (NDBI) enables researchers to quantify UHI intensity and identify mitigation strategies. A study in Hefei, China, used Landsat 8 OLI_TIRS data to explore how spatial scale impacts UHI intensity, finding that smaller spatial scales provide more precise insights into the urban thermal environment (Lin et al., 2024). The integration of spatial regression models, clustering techniques, and spatial autocorrelation has been effective in identifying heat island clusters and their driving factors (Erdem et al., 2021). European studies confirm the efficacy of remote sensing in UHI analysis. In Skopje, North Macedonia, Landsat 8 data revealed a strong negative correlation between NDVI and LST, reinforcing the cooling effect of vegetation, while built-up areas significantly intensified UHI (Kaplan et al., 2018). In Andalusia, Sentinel-3 satellite data demonstrated that daytime urban heat hotspots are primarily located in rural areas with minimal vegetation, whereas nighttime hotspots cluster in highly impervious urban zones (Hidalgo García & Arco Díaz, 2023). In Ahvaz, Iran, bare lands and built-up areas were directly correlated with UHI intensity (Amindin et al., 2021). The continued advancement of satellite-based analysis provides increasingly accurate assessments.

Addressing the UHI effect requires a multi-faceted approach, including increasing green spaces, implementing high-albedo surfaces, and enhancing urban ventilation. Studies show that increasing albedo through reflective surfaces significantly reduces surface temperatures (Hidalgo García, 2023). The strategic placement of water bodies and green corridors enhances local microclimates and reduces urban heat stress.

Urban planning policies should prioritize sustainable design principles, such as tree canopies, green roofs, and urban parks, to counteract UHI effects.

Research in Granada, Spain, emphasizes that increasing impervious surfaces has led to a significant rise in LST, highlighting the need for proactive land-use planning (Hidalgo-García & Arco-Díaz, 2022). Studies in various European cities indicate that UHI mitigation strategies must be tailored to local climatic and urban conditions, considering factors such as wind flow, surface permeability, and spatial planning frameworks (Hellings & Rienow, 2021). In Sivas, Turkey, urban expansion and the reduction of barren land contributed to rising LST over a 26-year period, with urbanized areas exhibiting the highest temperatures (Karakuş, 2019).

Urban green infrastructure (UGI) has been widely recognized as a key strategy for reducing urban temperatures. A study on European functional urban areas found that UGI can lower city temperatures by an average of 1.07°C, with tree cover playing a crucial role in microclimate regulation (Marando et al., 2022). The study recommended that at least 16% of urban land should be covered by trees to achieve effective temperature reduction. Green infrastructure investments not only mitigate temperature extremes but also contribute to improved air quality and public health outcomes (Chen et al., 2022). Additionally, the implementation of green roofs and vertical gardens has proven effective in high-density urban areas where open green space is limited.

Building upon these broader insights, the Urban Heat Island (UHI) effect in Zagreb, Croatia, reflects similar patterns observed in other urban environments, with land use changes, urban morphology, and anthropogenic activities playing a decisive role in temperature variations. As urbanization intensifies, the spatial and temporal characteristics of UHI in Zagreb have become increasingly evident, necessitating a deeper examination of its driving factors and mitigation strategies.

Long-term satellite-based monitoring has provided valuable insights into the distribution and intensity of UHI in Zagreb. Analysis of Landsat 8 imagery from 2013 to 2022 revealed that built-up areas consistently exhibited higher land surface temperatures (LST), whereas vegetated zones, particularly forested areas, maintained significantly lower thermal anomalies. These findings underscore the importance of green infrastructure in reducing urban heat stress and maintaining thermal balance within the city (Seletković et al., 2023). Further research using multi-temporal Landsat datasets has demonstrated a strong negative correlation between LST and vegetation indices such as the Normalized Difference Vegetation Index (NDVI), reinforcing the critical role of urban greenery in mitigating heat accumulation (Krtalić et al., 2020).

Urban morphology has also proven to be a key determinant of UHI intensity in Zagreb. A temporal analysis spanning from 1984 to 2014 highlighted that densely built-up areas – including the city center and industrial districts – experience the most pronounced temperature increases. In contrast, areas with higher vegetation cover, such as parks and tree-lined streets, demonstrate a measurable cooling effect, aligning with global findings on the role of green spaces in urban heat mitigation (Krsnik, 2024). Additionally, research assessing spatial heterogeneity in UHI patterns has identified commercial hubs and transportation corridors as persistent heat hotspots, primarily due to their high concentration of impervious surfaces and anthropogenic heat emissions (Krtalić et al., 2020).

Beyond the influence of land use, remote sensing methodologies have been instrumental in evaluating Zagreb's thermal environment and identifying vulnerable areas. The Environmental Criticality Index (ECI), derived from satellite thermal data, has pinpointed districts with extreme temperature anomalies, highlighting the disproportionate impact of UHI on commercial and industrial zones. These areas, characterized by low vegetation density and high impervious surface coverage, exhibit the most significant heat retention, emphasizing the urgent need for mitigation interventions (Krsnik, 2024). Comparative analyses of different types of green infrastructure in Zagreb further confirm that urban forests, public parks, and interconnected green corridors offer the most effective cooling benefits, with temperature reductions of up to 2°C recorded in densely vegetated areas (Seletković et al., 2023).

Seasonal and diurnal variations further shape Zagreb's UHI intensity. Studies have shown that summer months exhibit the most pronounced heat buildup due to higher solar radiation and reduced evapotranspiration in built-up environments, whereas winter periods present less thermal contrast due to lower solar input and seasonal vegetation loss (Krtalić et al., 2020).

Mitigation strategies for UHI in Zagreb emphasize the need for integrating urban greenery into city planning. A study on urban green space effectiveness in climate regulation found that tree cover, green roofs, and permeable surfaces significantly contribute to reducing surface temperatures, particularly in high-density neighborhoods (Krsnik, 2024). Furthermore, the role of large-scale green infrastructure was explored through scenario modeling, demonstrating that a 16% increase in tree cover could lead to a temperature reduction of approximately 1.5°C across the city (Seletković et al., 2023). These findings are aligned with European urban sustainability studies, which advocate for policy-driven initiatives to expand urban vegetation and enhance climate resilience.

4 MATERIALS AND METHODOLOGY

4.1 Research scope

This research builds upon and extends the existing body of knowledge on Urban Heat Islands (UHIs) by providing spatially explicit analysis of UHI intensity in the city of Zagreb, focusing on the relationships between land surface temperature (LST), planned land-use categories, built-up intensity, and vegetation cover. While previous studies have examined the impact of urban form on UHI, few have integrated spatial regression modeling with high-resolution Landsat-9 imagery and urban planning data. This study bridges that gap by quantifying the statistical influence of zoning regulations on temperature variations. While they also have examined general trends in UHI formation, vegetation's cooling effects, and urban expansion's role in heat accumulation, this study takes methodological approach by integrating multiple spatial analysis techniques to identify and quantify factors driving temperature variations. Research emphasizes the importance of urban planning decisions in shaping local microclimates and investigates how different land-use types, contribute to spatial patterns of heat intensity. The spatial scope of this research is limited to the area covered by the General Urban Plan (GUP) of the city of Zagreb, rather than the entire administrative territory of the city. This delineation ensures a more precise analysis of temperature variations within the core urban area, where land-use planning and built-up intensity have the most significant impact on UHI formation. By focusing on the GUP-defined urban zones, the study effectively captures localized temperature fluctuations.

The primary objective is to establish statistically correlations between LST and planned urban land-use categories as well as built-up intensity parameters to assess the extent to which specific urban planning and development strategies influence temperature distribution. A crucial extension of previous research is the incorporation of a composite UHI index, constructed by integrating both LST and the Normalized Difference Vegetation Index (NDVI) to refine the identification of heat-prone areas. Unlike conventional studies that solely rely on thermal remote sensing, this research defines UHI zones based on two critical criteria: (1) LST values exceeding the daily mean temperature, which highlights localized heat anomalies, and (2) NDVI values below 0.2, which indicate areas with minimal vegetation cover and, therefore, limited natural cooling capacity. This combined approach ensures a more precise delineation of heat islands by incorporating both thermal and vegetation-based factors, offering a nuanced representation of urban heat stress zones in Zagreb.

The research further builds on previous findings by examining the spatial clustering of UHIs through spatial autocorrelation analysis, enabling a better understanding of how heat islands are distributed across the urban landscape and whether specific spatial patterns emerge due to land-use planning and built-up intensity.

4.2 Materials

Core datasets used in this research consist of high-resolution remote sensing data, urban planning documentation, and spatial statistical modeling techniques. The study relies primarily on Landsat-9 satellite imagery from July 10, 2024, which provides thermal infrared data to assess land surface temperature (LST) and multispectral data for NDVI calculations, allowing for the evaluation of vegetation cover. The integration of LST and NDVI data enables the identification of heat-prone areas where a lack of vegetation correlates with elevated surface temperatures. Additionally, the study utilizes the General Urban Plan of the City of Zagreb (GUP) and its 2024 amendments, which define planned land-use categories and provide spatial constraints for urban development. The GUP outlines different types of planned green spaces, including; protective green areas (Z), public parks (Z1), urban park-forests (Z2), thematic parks (Z3), and public green zones (Z4), which are analyzed in relation to their effectiveness in mitigating high temperature effects. Furthermore, the study incorporates urban planning regulations that specify built-up intensity parameters, allowable plot coverage, which is some of key determinants of urban density and surface heat retention. By analyzing the spatial distribution of these regulatory parameters, the study assesses how different levels of urbanization impact LST. The use of spatial datasets from official planning documents allows for an in-depth evaluation of how zoning regulations influence temperature dynamics.

4.3 Methodology

Methodological framework employed in this research represents an advancement over prior studies that relied solely on thermal remote sensing or statistical temperature analysis. Previous Zagreb-based UHI assessments, such as those by Krtalić et al. (2020) and Seletković et al. (2023), primarily focused on broad-scale thermal imagery analysis and identified general UHI patterns. By integrating Exploratory Spatial Data Analysis (ESDA), this research moves beyond descriptive analysis to establish causal relationships between land-use categories and temperature anomalies.

This research is structured around three core analytical stages:

- Correlation and regression analysis between LST, planned land-use, and built-up intensity;
- Integration of NDVI and LST to define UHI areas;
- Spatial autocorrelation analysis to assess the clustering of heat islands.

First stage involves correlation analysis which is used in this step to examine the strength and direction of relationships between temperature and urban features, helping to identify whether built-up intensity is positively associated with higher LST, while planned green areas contribute to temperature reduction. Then regression analysis is used to quantify the impact of planned land-use categories and built-up density on LST, where land surface temperature (LST) serves as the dependent variable, while independent variables include land-use type, built-up intensity, and vegetation cover.

Second stage focuses on constructing the UHI index, which is defined by combining LST values higher than the daily mean temperature with NDVI values below 0.2, ensuring that heat islands are classified based on both thermal excess and lack of vegetation. The NDVI threshold of 0.2 was selected based on prior studies that define low vegetation cover in urban settings as NDVI < 0.2 (Guha et al., 2018). This threshold ensures that areas classified as UHI zones are those with minimal vegetation cover. This approach refines conventional UHI identification by distinguishing between areas where temperature anomalies result from built-up density rather than other environmental factors.

Third stage applies spatial autocorrelation analysis to evaluate the spatial clustering of heat islands, using Moran’s I to measure global clustering patterns of UHIs across Zagreb and Local Indicators of Spatial Association (LISA) to identify localized hot spots and cold spots, highlighting districts where temperature accumulation is most pronounced. Spatial autocorrelation methods help determine whether high-temperature zones are randomly distributed or whether they form significant clusters due to specific urban planning characteristics.

This analytical approach enables a systematic assessment of how planned green spaces and built-up areas influence temperature distribution and whether heat islands are spatially clustered in areas of high-density urbanization. The combination of these methods provides a robust, evidence-based framework for urban planners and policymakers to develop targeted climate adaptation strategies, such as optimizing the distribution of green infrastructure, adjusting zoning regulations to mitigate heat retention, and improving urban design strategies to enhance thermal comfort. By integrating geospatial analysis, spatial statistics, and urban planning data, this study advances the scientific understanding of UHIs in Zagreb.

5 RESULTS

Building upon the outlined methodological framework, the results of this research provide a detailed examination of the relationships between land surface temperature (LST), built-up intensity, and planned green spaces, offering insights into the drivers of Urban Heat Island (UHI) intensity in Zagreb. The first stage of the analysis focuses on statistical correlations and regression modeling to quantify how built-up areas and green spaces impact LST. By evaluating the strength and direction of these relationships, the analysis highlights the degree to which urban planning decisions influence local microclimates. This is followed by the construction of a UHI index in the second stage, integrating LST and NDVI to refine the identification of heat-prone areas and differentiate zones where elevated temperatures are primarily attributed to built-up density or lack of vegetation. Finally, the third stage applies spatial autocorrelation techniques, including Moran's I and LISA, to identify spatial clustering of high-temperature zones and assess whether these clusters align with specific urban planning characteristics. Together, these results provide a comprehensive understanding of how urban planning variables such as built-up intensity and planned green spaces affect UHI patterns, forming a basis for evidence-based urban climate adaptation strategies.

The correlation and regression analysis provide insights into relationships between land surface temperature (LST), built-up intensity, and the total area of planned green spaces. The findings reveal a moderately strong positive correlation (0.68) between built-up intensity, and mean temperature. This confirms that higher built-up intensity significantly contributes to elevated LST, emphasizing the role of impervious surfaces, such as asphalt and concrete, in retaining and amplifying heat.

On the other hand, the total area of planned green spaces demonstrates a moderate negative correlation (-0.32) with mean temperature, highlighting the critical cooling effect of vegetation in mitigating LST. Areas with greater coverage of planned green spaces exhibit lower temperatures, reinforcing the importance of greenery in reducing UHI effects.

These findings align with the hypothesis that built-up surfaces exacerbate urban heating, while green spaces serve as an effective countermeasure. From a planning perspective, the analysis underscores the urgent need for urban regulations to balance high-density development with the integration and preservation of green infrastructure. Planned green zones (Z, Z1, Z2, Z3, Z4) are essential in reducing urban heat, while high-density areas require targeted interventions, such as green infrastructure, to mitigate localized heating effects (Figure 1).

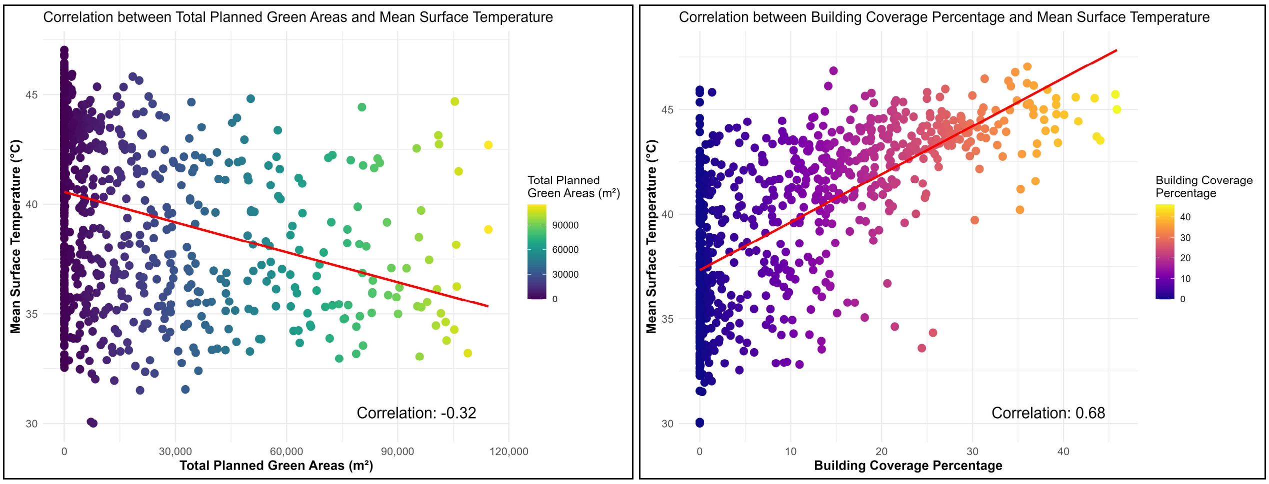

Fig. 1: Correlation analysis between planned green areas and built-up intensity and LST

Analysis provides critical insights into the relationship between land surface temperature (LST) and various land-use categories defined in the General Urban Plan (GUP) of Zagreb. The results reveal that park-forests (Z2) and protective green areas (Z) have a statistically significant cooling effect on LST, with coefficients of -3.11×10^{-6} and -3.29×10^{-6}, respectively, highlighting their effectiveness in mitigating the heat effects. The overall model is statistically significant (F-statistic = 7.25, $p < 0.001$), though it explains a modest proportion of variance in LST (adjusted R-squared = 0.064), reflecting the complexity of factors influencing urban heat dynamics.

Building upon the statistical correlation and regression analysis, the construction of the composite Urban Heat Island (UHI) index represents the second stage of the methodological framework. This composite index integrates land surface temperature (LST) and Normalized Difference Vegetation Index (NDVI) to refine the identification of areas most affected by hight temperature effects. The threshold for LST > 39°C, chosen based on the average land surface temperature on the day the satellite images are dated, which ensures that regions experiencing significant heat accumulation are highlighted. Simultaneously, the threshold of NDVI < 0.2 identifies zones with minimal vegetation cover. This dual-filtering approach enables the differentiation of heat-prone areas primarily driven by built-up intensity from those influenced by the absence of vegetation (Figure 2).

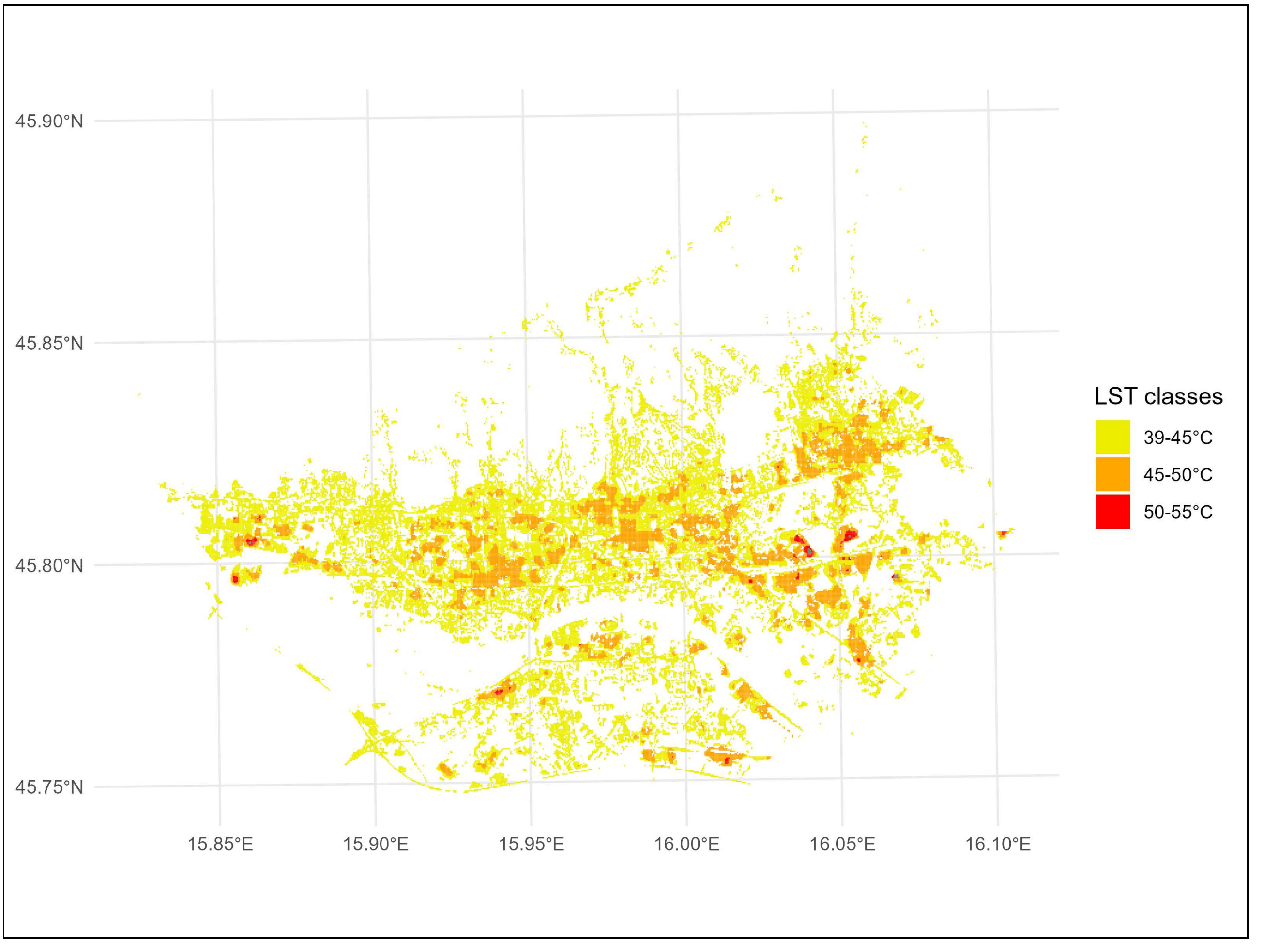

Fig. 2: Distribution of Land Surface Temperature

Building upon the statistical correlation and regression analysis, the spatial autocorrelation analysis represents a critical step in identifying and understanding the spatial clustering of Urban Heat Island (UHI) hotspots. Utilizing Moran's I and Local Moran's I (LISA), this stage examines the spatial patterns of high land surface temperature (LST) values to determine whether they are randomly distributed or form statistically significant clusters. The key focus of this analysis is to identify hotspots, or areas where elevated temperatures are spatially concentrated.

The Moran's I test under randomization indicates a highly significant positive spatial autocorrelation (Moran I = 0.920, p-value $< 2.2 \times 10^{-16}$), confirming that high LST values are strongly clustered rather than randomly dispersed. This result validates that UHI effects in Zagreb are driven by systematic spatial processes rather than random temperature variations, underscoring the role of urban planning and land-use patterns in shaping heat accumulation. The Moran I statistic's standard deviation deviate (394.04) further supports the strength of this clustering, highlighting the robustness of the identified patterns.

Local Moran's I (LISA) refines this global insight by pinpointing the exact locations of statistically significant hotspots. These hotspots are areas where high LST values are not only concentrated but are also surrounded by other high-temperature zones, creating pockets of intense heat accumulation (Figure 3).

The ability of the spatial autocorrelation tools to statistically identify these clusters makes them indispensable for understanding UHI dynamics. Hotspot detection enables urban planners to spatially delineate the areas most vulnerable to heat accumulation, providing a clear foundation for targeted mitigation strategies..

By focusing exclusively on hotspots, this analysis emphasizes the power of spatial modeling in addressing urban heat challenges. The integration of Moran's I and LISA with high-resolution LST data provides a comprehensive tool for modeling heat distribution and highlighting areas of concern. This approach moves beyond descriptive analyses to deliver statistically validated insights, reinforcing the need for evidence-based interventions in urban planning. In doing so, it not only enhances the scientific understanding of UHI effects but also equips stakeholders with precise spatial intelligence to prioritize climate adaptation measures effectively.

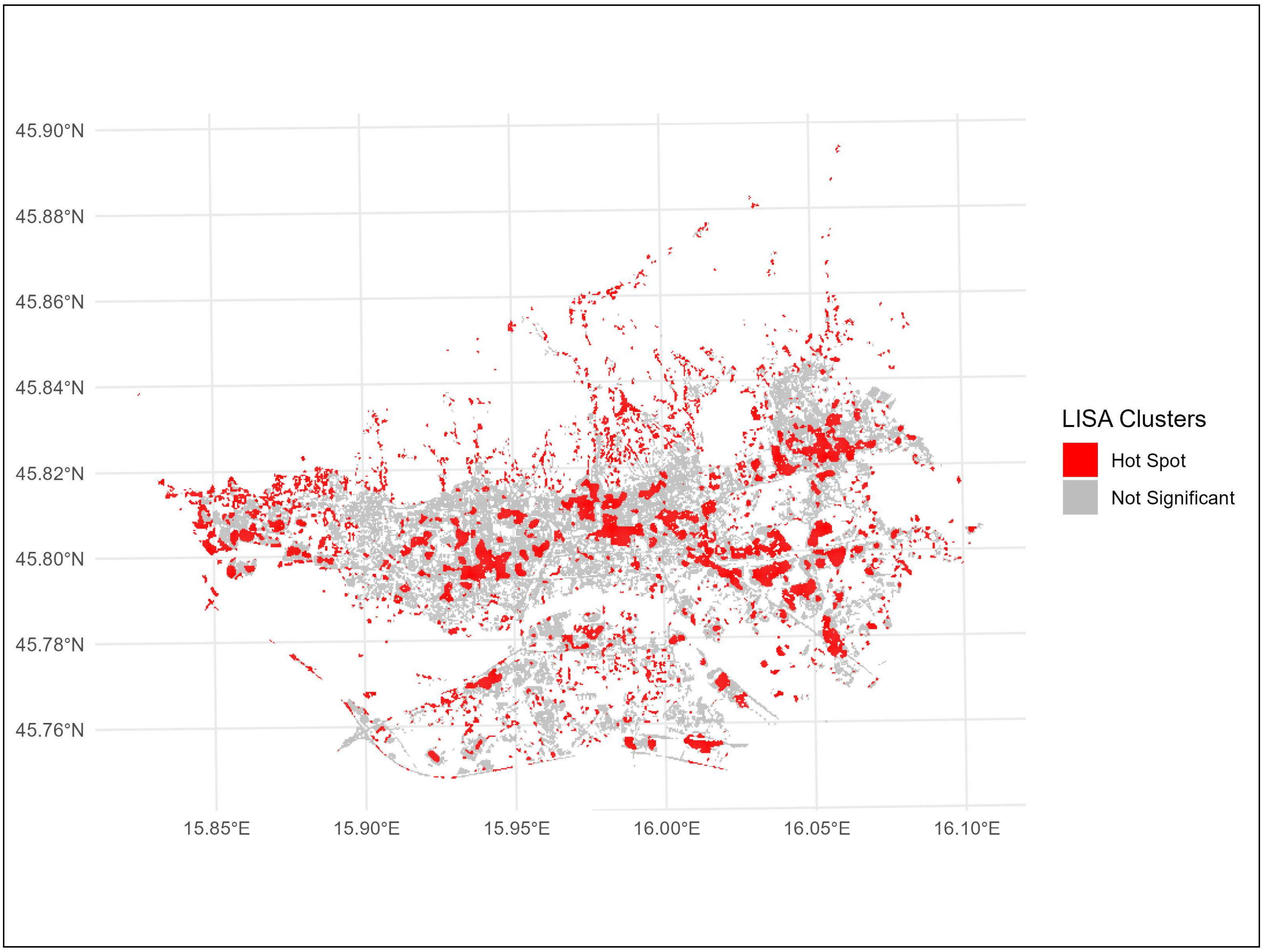

Fig. 3: Spatial Autocorrelation of UHI

6 CONCLUSION

This study provides significant insights into the spatial dynamics of Urban Heat Islands (UHIs) in Zagreb by employing a methodological framework that integrates correlation, regression, and spatial autocorrelation analyses. The findings reveal that built-up intensity is a key driver of elevated land surface temperature (LST), while planned green spaces, such as park-forests (Z2) and protective green areas (Z), play a critical role in mitigating UHI effects.

The spatial autocorrelation analysis, using Moran's I (Moran I = 0.920, p-value $< 2.2 \times 10^{-16}$) and Local Moran's I (LISA), identifies statistically significant UHI hotspots that are spatially clustered in high-density urban zones characterized by impervious surfaces and minimal vegetation. This precision in hotspot detection underscores the spatial dependency of UHI formation and validates the influence of urban planning and land-use patterns on the thermal environment.

The study advances UHI research by moving beyond traditional descriptive methods, employing spatial autocorrelation techniques to validate clustering patterns and incorporating regulatory zoning frameworks (GUP) to contextualize thermal patterns. By integrating high-resolution Landsat-9 satellite imagery from July 10, 2024, the research provides a snapshot of UHI intensity on an extreme temperature day, ensuring accurate identification of heat-prone areas. However, this single-day analysis does not capture seasonal or annual variations, and future research could incorporate multi-temporal analysis to assess UHI evolution over time and the effectiveness of mitigation strategies. Additionally, expanding the methodological framework to include broader climatic influences, such as wind circulation, humidity levels, and anthropogenic heat emissions, could further refine the understanding of UHI drivers in an urban environment.

The identification of UHI hotspots in high-density zones provides a foundation for targeted urban interventions, such as expanding green infrastructure, increasing vegetation density, and implementing reflective surfaces, particularly in areas most affected by heat accumulation. Furthermore, the preservation and enhancement of planned green spaces (Z1, Z2, Z3, Z4) emerge as vital components for sustainable urban design, reinforcing the importance of climate-adaptive policies in city planning.

However, the primary objective of this study was not necessarily to propose direct solutions for mitigating UHI effects but rather to conduct a systematic spatial analysis to identify the zones most vulnerable to negative temperature impacts and to assess the extent to which planned land-use categories influence temperature variations. By establishing a spatially explicit understanding of UHI formation, the findings serve as a foundation for integrating urban heat mitigation strategies into spatial planning frameworks. Based on these analyses, conclusions can be incorporated into urban planning policies and regulatory documents, ensuring the protection of green areas, strategic tree planting, and improved zoning regulations to enhance climate resilience.

Future research should incorporate multi-temporal analysis to assess long-term trends in UHI intensity and evaluate seasonal variations in land surface temperature. Expanding the study to include meteorological factors such as wind patterns, humidity, and anthropogenic heat emissions would provide a more comprehensive understanding of UHI drivers. Additionally, refining statistical models by integrating urban geometry indices (e.g., building height, albedo, sky view factor) could enhance the explanatory power of UHI predictions. Further investigation into the effectiveness of different types of green infrastructure – such as tree canopy density, water bodies, and rooftop gardens – would offer targeted strategies for mitigating urban heat. These advancements would strengthen the link between geospatial analysis and urban planning, ensuring more effective climate adaptation strategies.

This research contributes to UHI analysis by:

- Advancing the methodological framework for UHI studies by integrating remote sensing, regression modeling, and spatial autocorrelation techniques.
- Providing statistically validated evidence for the role of built-up intensity and green spaces in temperature regulation.
- Utilizing spatial clustering methods to precisely identify UHI hotspots, strengthening the case for targeted mitigation efforts.
- Aligning findings with urban planning regulations (GUP), bridging the gap between geospatial analysis and policy implementation.

Overall, this research highlights the critical role of spatial modeling in addressing urban heat challenges and offers a replicable framework for integrating geospatial data with urban planning to support climate-resilient cities. By leveraging advanced spatial statistical tools, this study provides a robust evidence base for designing effective UHI mitigation strategies, ensuring that urban policies align with climate adaptation objectives to enhance the long-term sustainability of urban environments.

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