Assessing thermal stress on cultural heritage in Limassol: A multi-scale remote sensing approach using Sentinel-3 and Landsat 9 land surface temperature data

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ABSTRACT

Cultural heritage buildings and archaeological sites in urban environments are increasingly at risk from exposure to thermal stress driven by climate change. This study examines the impact of thermal stress on heritage structures in Limassol's historic district using Land Surface Temperature (LST) images from Sentinel-3 and Landsat-9 satellite remote sensing data. Sentinel-3's broader coverage at a 1km spatial resolution allows for a city-wide survey of thermal anomalies, enabling the identification of extensive urban hotspots. Landsat 9's 30m resolution provides detailed thermal distributions that highlight localized thermal gradients around individual heritage sites, archaeological areas and listed neoclassical buildings, which are more sensitive to small-scale environmental changes. By correlating data from both satellites, this research constructs thermal risk maps, revealing the interplay between large-scale urban heat trends and site-specific vulnerabilities. The results demonstrate that areas with high concentrations of cultural heritage assets that consistently show elevated thermal stress levels face increased risks of material degradation, weathering and accelerated decay in historic structures. These findings underscore the importance of microclimate interventions to urban planning and landscaping to mitigate heat buildup. This multi-scale remote sensing approach offers a replicable framework for other Mediterranean cities facing similar climatic pressures. Integrating broader-scale monitoring with Sentinel-3 with site-focused assessments from Landsat 9 provides a robust tool for heritage preservation policies, restoration efforts, and climate-resilient urban development. Ultimately, the study highlights how the use of satellite LST data can serve as a critical resource for safeguarding historical sites against the impacts of climate change and urban heat island effect.

Keywords: Remote sensing, Sentinel-3, Landsat-9, mediterranean, urban heat island, climate change, cultural heritage, thermal stress

1. INTRODUCTION

The urban heat island (UHI) phenomenon has reached unprecedented levels in modern cities, due to extensive urbanization, reduced green spaces, and widely use of heat-retentive building materials. Contemporary research reveals urban centers now frequently experience daytime temperatures 3°C -7°C above surrounding rural areas and nighttime differences exceed 10°C in some metropolitan regions [1]. This thermal expansion sets challenges for historic structures, as traditional building materials like stone, brick and mortar reveal elevated risk to thermal stress. The continual cycles of growth and contraction induced by UHI temperature fluctuations accelerate material fatigue, leading to increased cracking, spalling and structural instability in heritage facades. Moreover, the degraded thermal performance of stressed building envelopes guides greater dependence on mechanical climate control systems in interior spaces, creating an unsustainable cycle of increasing energy consumption and additional thermal loading. Due to UHI, historic districts in Europe, consume more cooling energy than other structures on the same zones. This increasing threat demands urgent implementation of mitigation strategies, in order to reduce the heat island impact inside the cities.

Heritage buildings are invaluable cultural assets that embody historical, architectural, and social significance. However, their preservation is increasingly threatened by climate change-induced thermal fluctuations, which exacerbate material degradation, structural instability, and energy inefficiencies. Recent investigations into thermal distributions in urban fabric through diagnostic and mitigation technologies reveal how urban environment affects the climate conditions of a historic area. Pinheiro et al. (2023) applied numerical analysis (from 2023 to 2100) to project the long-term effects of temperature variations on heritage buildings [2], demonstrating that rising damp and thermal stress distributions will

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escalate significantly in the future. The case study of the Nosso Senhor do Bonfim Church in Brazil highlighted how urban microclimates increase these risks, by accelerating material fatigue.

Thermal stress can be observed through material expansion and contraction, leading to cracks and joint failures, and structural deformation, such as warping or buckling. Beyond structural impacts, thermal stress increases energy consumption in heritage buildings, which is very often crucial for the lifetime of the structure and very important to balance between preservation of heritage values, energy efficiency and thermal comfort. Aesthetic damage like peeling paint and discoloration and fire risks further underscore the need for integrated strategies in order to safeguard the heritage architecture from thermal stress inside the urban fabric. By analyzing thermal patterns in the historical center of Limassol, this paper examines the effect of thermal stress on heritage buildings, utilizing the Sentinel-3 and Landsat-9 Land Surface Temperature (LST) data and highlights the value of those tools against the impact of climate change and urban heat island.

Figure 1 Listed building located in Limassol's historic district with visible damage patterns due to thermal stress.

2. METHODOLOGY

2.1 Sentinel-3 and LandSat-9 specifications

A comparison of satellite data specifications between Sentinel-3 and LandSat-9 was conducted to determine which satellite is more suitable for this purpose, particularly in assessing land surface temperature and urban heat island (UHI) effects in Limassol district. Sentinel-3 is operated by the European Space Agency (ESA) and equipped with the Sea and Land Surface Temperature Radiometer (SLSTR), with a primary purpose for large-scale climate and marine monitoring. Although it provides frequent coverage with a revisit time of 1-2 days, its spatial resolution (500m–1000m per pixel) is relatively low, making it less ideal for detailed urban heat studies.

On the other hand, LandSat-9, operating by National Aeronautics and Space Administration (NASA) and the US Geological Survey (USGS), is equipped with Thermal Infrared Sensor 2 (TIRS-2), which is primary used for land surface temperature analysis. It provides a higher spatial resolution of 100m per pixel and it is more suitable for detailed applications such as in agriculture, water resource management, and urban heat island monitoring in smaller scale. However, there are limitations in real-time observations as its revisit time is 16 days, which gives a disadvantage compared to Sentinel-3.

Table 1. Thermal related specifications of Sentinel-3 and LandSat-9 satellite data.

Specifications	Sentinel-3	LandSat-9
Satellite Operator	ESA (European Space Agency)	NASA/USGS
Thermal Imaging Instrument	Sea and Land Surface Temperature Radiometer (SLSTR)	Thermal Infrared Sensor 2 (TIRS-2)
Primary purpose	Ocean and land surface temperature (climate monitoring, marine studies)	Land surface temperature (agriculture, urban heat, water resources)
Land Temperature Monitoring	Suitable for large-scale temperature trends	Suitable for detailed land temperature studies
Spatial Resolution	500m - 1000m per pixel	100m per pixel
Revisit time	1-2 days (global coverage)	16 days
Urban Heat Island (UHI) monitoring	Lower resolution, less detailed for urban areas	High resolution helps analyze city heat patterns

Focusing on studies with large-scale or wide spatial temperature patterns, Sentinel-3 is more appropriate due to the frequency of its coverage. However, if the study focuses on local districts with small-scale areas, it requires high-resolution thermal imaging in order to conduct urban heat patterns. In this case, LandSat-9 is a more useful choice, despite its less frequent revisit time. For this research, both satellite data were used in order to cross validate the results between them.

To compare and cross-validate the results between the two satellites, data from both Sentinel-3 and LandSat-9 were selected for the same date. More specifically, the comparison was conducted using data from 24th of July 2024. This date was selected because both Sentinel-3 and LandSat-9 passed over Limassol on the same day, with only a 21-minute time difference between their overpasses, which is an interval short enough not to significantly impact the results. Additionally, clear sky conditions (minimal cloud cover) on that day ensured reliable and unobstructed thermal measurements. Sentinel-3 image was conducted at 08:00 a.m. with spatial resolution of 1000m x 1000m, while LandSat-9 was conducted at 08:21 a.m. with spatial resolution of 30m x 30m.

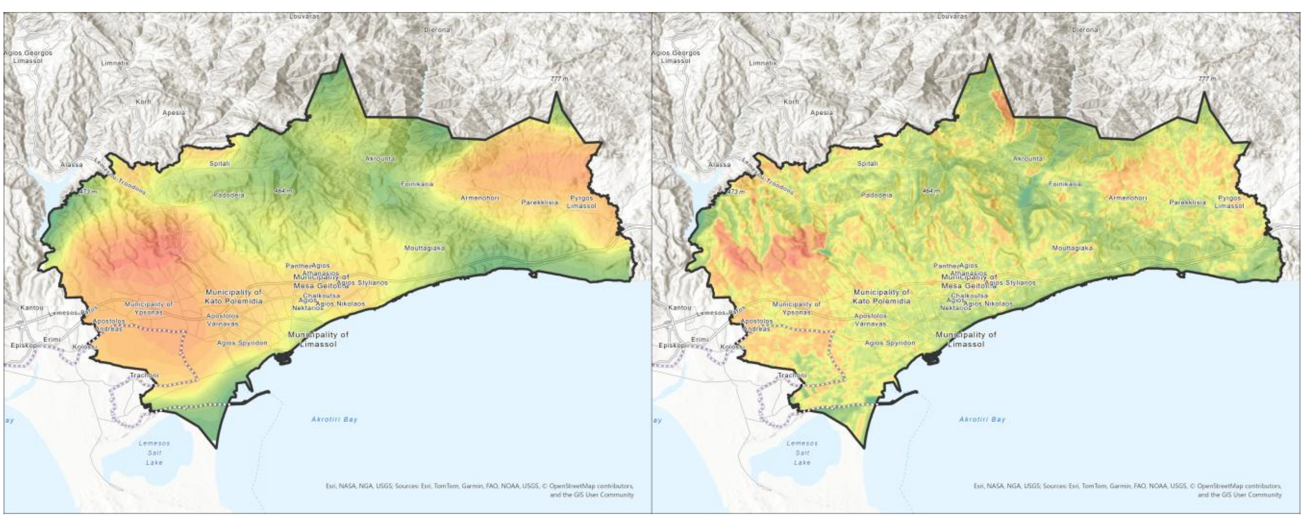

Figure 2 Remote sensing satellite data taken on the 24th of July 2024 to compare and cross-validate the results. On the left side is the image taken from Sentinel-3 at 08:00 a.m. with a spatial resolution of 1000m x 1000m and on the right side is the image taken from LandSat-9 at 08:21 a.m. with a spatial resolution of 30m x 30m.

Cross-validation between the two satellites confirms the accuracy of their observational data and thus, the reliability of their results. On the west side of the city, are observed high values of temperatures due to high dry hilly lands with hard soil surface. This hotspot exhibits a spatial extension that propagates toward the urban core of Limassol, gradually diminishing in intensity until it eliminates along the coastal walkway. It is observed that the results exported from Sentinel-3 are more generalized in terms of spatial resolution, whereas those derived from Landsat-9 exhibit a higher degree of spatial localization.

2.2 Area of Interest

The investigation process was focused on the center of Limassol and more specifically, to the “area of special character”, as defined by the department of Town Planning and Housing of Limassol. This area, which is located into the urban fabric of the city, is rich in heritage buildings, characterized by a diverse classification of listed structures and significant archaeological monuments that reflect its historical and cultural importance.

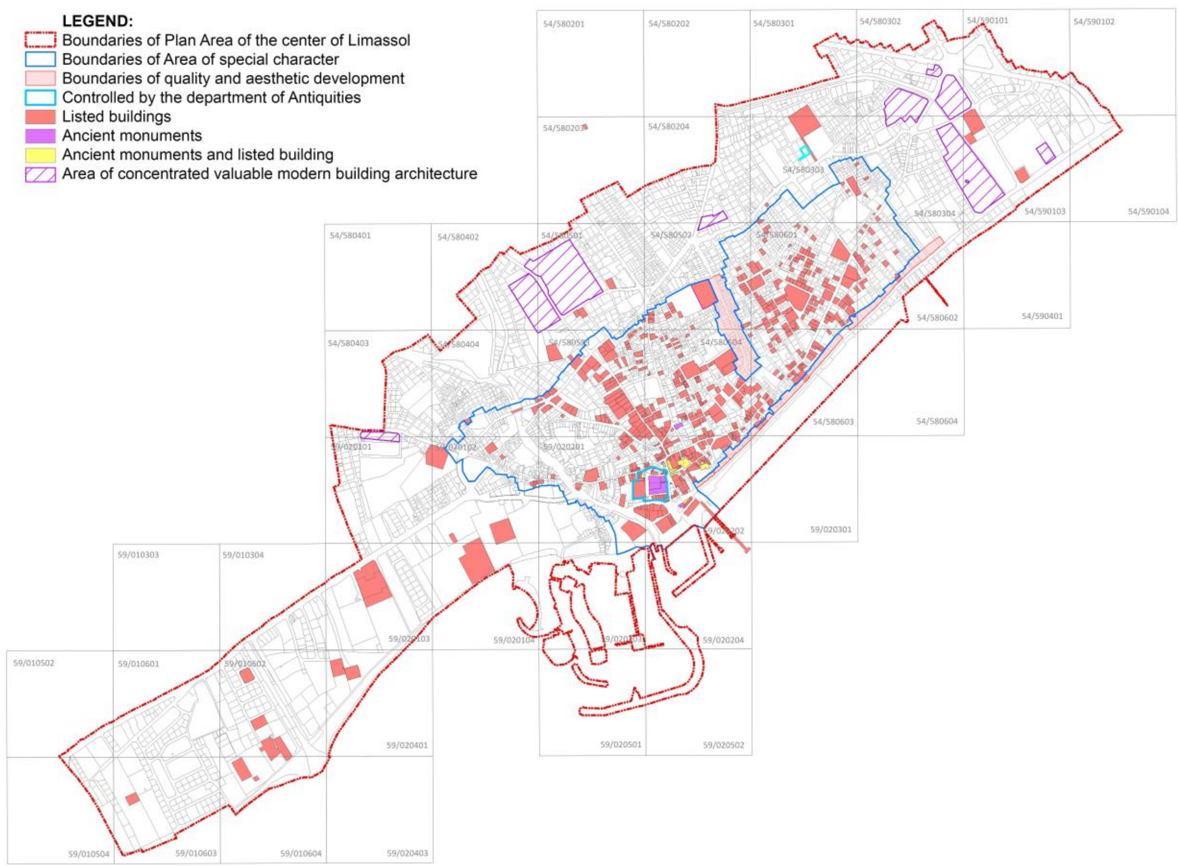

Figure 3 Map provided by the department of Town Planning and Housing of Limassol, indicating the boundaries of Plan area of the center of Limassol (red dotted line), boundaries of the Area of special character (blue line), boundaries of quality and aesthetic development (orange color), listed buildings (red hatch), Ancient monuments (purple color), Ancient monuments and listed buildings (yellow color), and Area of concentrated valuable modern building architecture (hatched purple). Retrieved from https://shorturl.at/8rIW5

The area of interest is situated on the western side of the special character’s boundaries. This specific zone was selected due to the higher concentration of listed buildings exhibiting signs of thermal stress, which have been observed in numerous structures across the site. The prevalence of these thermally affected heritage assets suggests potential vulnerabilities linked to environmental factors, material degradation, or microclimatic conditions. Further investigation into this area could provide valuable insights into preservation challenges and adaptive strategies for mitigating thermal damage in historically significant buildings.

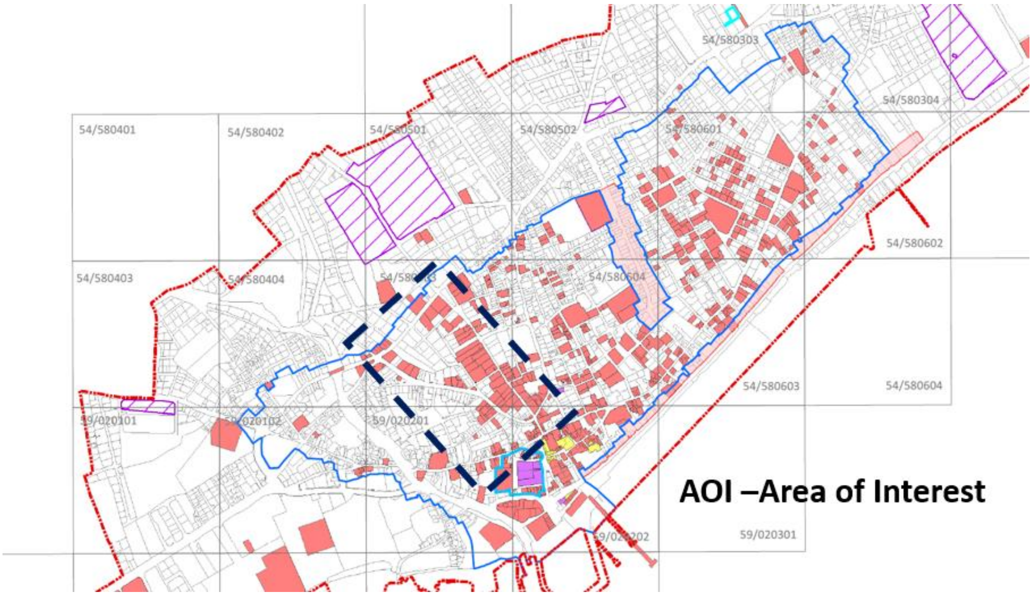

Figure 4 Area of Interest indicated with black dotted lines.
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2.3 Urban hotspots analysis

Landsat-9 remote sensing data were utilized for this investigation to assess urban heat island (UHI) effects at a high level of spatial detail. The original thermal data, with a resolution of 100 meters, were resampled to a finer 30m × 30m grid enhancing the precision of the analysis and making it particularly suitable for localized urban studies. The resampling of Landsat-9's thermal bands (Bands 10 & 11) from 100m to 30m happens automatically during the Level-1 data processing before distribution to users. The Thermal Infrared Sensor (TIRS-2) equipped on Landsat-9 originally captures thermal data at 100 meters. However, the United States Geological Survey (USGS) processes the raw data into Level-1 products (e.g., L1TP, L1GT) and resamples the thermal bands to 30 meters to match the resolution of the OLI-2 multispectral bands, ensuring consistency across all bands for easier analysis. This resampling methodology is applied to the distributed data, though the true thermal resolution which remains limited by the sensor's original 100m capability. The improved resolution allows for better identification of micro-scale thermal variations across diverse urban landscapes, including built-up areas, green spaces, and water bodies.

Given that UHIs are most pronounced during the summer months due to increased solar radiation and reduced vegetation moisture, the analysis was focused on this period to capture peak thermal intensity into the city’s center. To ensure methodological reliability and enable meaningful temporal comparisons, datasets from two consecutive years were selected. Specifically, imagery from the 6th of July 2023, 22nd of July 2023, 8th of July 2024, and 24th of July 2024 were analyzed. These dates were chosen to represent typical mid-summer conditions in Cyprus, avoiding anomalous weather events while capturing diurnal and seasonal thermal extremes. July is consistently the hottest month in Cyprus, with historical records from the Cyprus Meteorological Department indicating average maximum temperatures exceeding 36°C during this period.

The results derived from Landsat-9 thermal imagery clearly demonstrate the spatial distribution and temporal variability of urban heat islands (UHIs) across the study area. The data reveals distinct hotspot patterns that fluctuate in intensity and extent between different summer days, highlighting the dynamic nature of thermal stress in urban environment of the city’s center. Analysis of these thermal signatures reveal that the western sector of the Special Character Area exhibits significantly higher surface temperatures compared to other zones, indicating it experiences the most severe thermal stress conditions.

Heat accumulation in the western part can be attributed to several urban factors, including extensive use of heat-absorbing materials and reduced green space coverage. The persistence of these hotspots across multiple observation dates suggests this is not merely a transient phenomenon but rather a systemic thermal vulnerability in the area's urban fabric. Such findings have important implications for urban planning strategies and are more important in heritage conservation areas where thermal stress may accelerate material degradation in historically significant structures.

The Landsat-9 thermal images were acquired at approximately 8:20 a.m. local time during the satellite's morning overpass over Limassol district. The thermal data reveals striking temperature variations across the urban landscape, ranging from a moderate 24°C in coastal areas influenced by sea breezes to extreme highs of 48°C in the densely built urban core. This 24-degree differential between coastal and central urban zones highlights the dramatic intensification of urban heat island effects within relatively short distances.

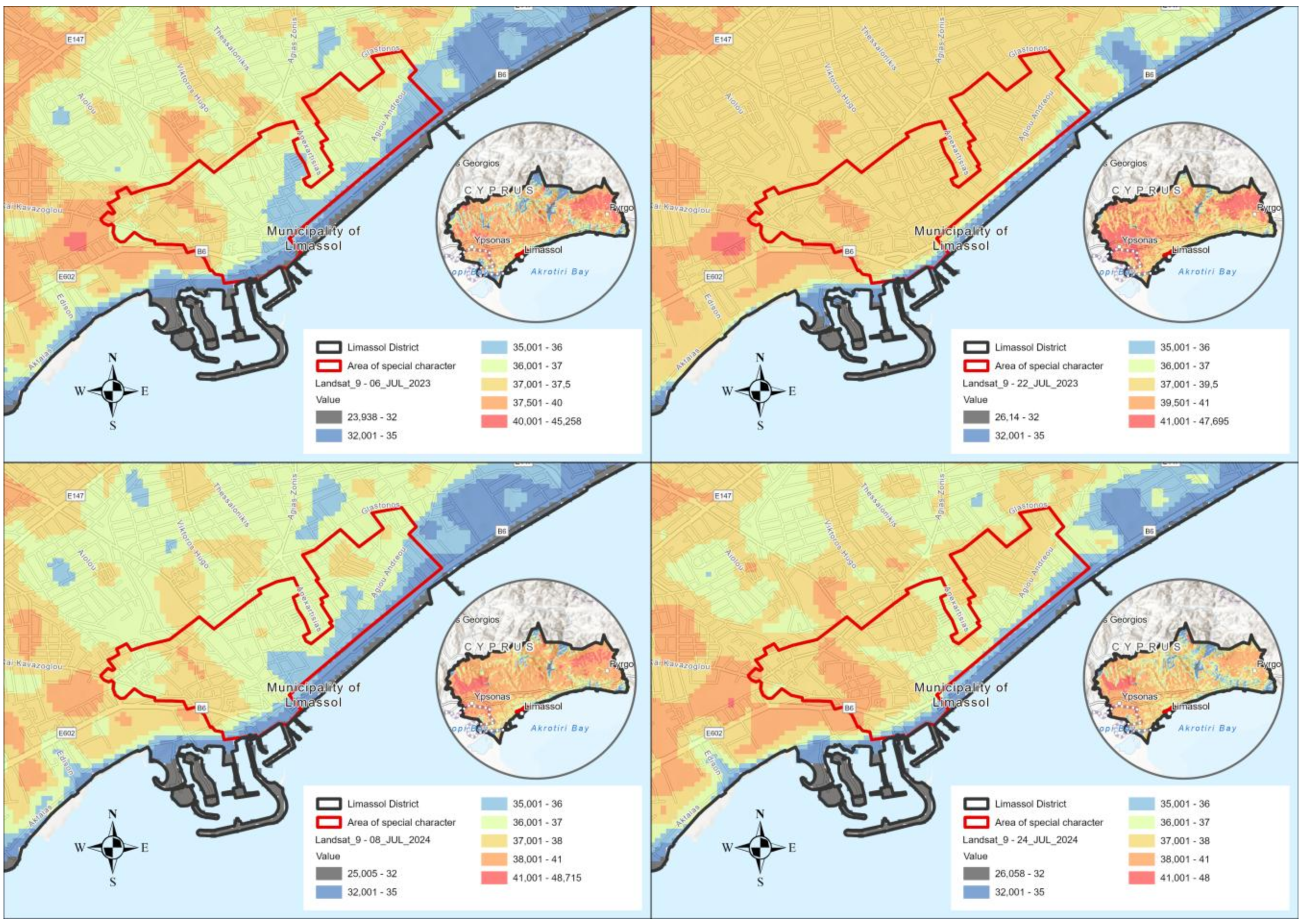

Figure 5 On the left upper side is the image captured by the Landsat-9 satellite on July 6th, 2023, and on the top right side is the image captured by the LadnSat-9 satellite on 22nd of July 2023. On the left lower side is the image captured by the Landsat-9 satellite on July 8th, 2024. On the right lower side is the image captured by the LadnSat-9 satellite on 24th of July 2024.
Red color indicates the borders of the "area of special character", as characterized by the department of Town Planning and Housing.

A microscale thermal analysis was conducted on the western part of the 'Area of Special Character' using high-resolution Landsat-9 satellite imagery acquired on 9th July 2024 at 08:20 local time. The thermal infrared data revealed critical temperature variations across the study area, with surface temperatures ranging from 38°C to 48°C. Notably, the highest thermal signatures (peaking at 48°C) were recorded in urban neighborhoods which are characterized by high-density built environments with extensive use of heat-retentive construction materials (concrete, asphalt) and limited vegetation cover with minimal evapotranspiration cooling effects.

These conditions aggravate the urban heat island (UHI) effect, creating a discomfort microclimate with temperatures up to 12°C warmer than adjacent vegetated areas. The pronounced thermal differential observed during early morning hours is particularly concerning, as it indicates significant overnight heat capacity in urban materials which consists of long-term heat stress conditions to existing buildings. The sustained thermal loading, places listed buildings at significant risk, as traditional construction materials are especially vulnerable to accelerated degradation from extended thermal stress. Ongoing heat-induced expansion and shrinkage cause cracks in historic structures, while intense temperatures break down traditional mortars and protective layers over time.

Figure 6 Thermal satellite image from LandSat-9 in Limassol with spatial resolution 30m x 30m acquired on 8th of July 2024 at 08:20 a.m.

To understand and evaluate the micro-climate impact of the city's Special Character Area on the aggressive degradation of cultural heritage structures, a detailed investigation was undertaken, focusing on three key aspects: the physical deterioration of historic buildings, the role of existing built environment in micro-climate modification, and the influence of localized environmental parameters. Field observational assessments conducted within these neighborhoods demonstrate that sustained thermal stress imposes a degradative effect on heritage materials.

The most dominant observations of thermal degradation include widespread cracking and spalling of exterior plaster, accelerated material breakdown due to thermal expansion-contraction cycles, and discoloration resulting from chronic ultraviolet (UV) exposure. Additionally, visible signs of spalling paint, surface buckling in metal fixtures, and microfractures in load-bearing elements further highlight the long-term consequences of seasonal temperature fluctuations. These observed deterioration mechanisms which include characteristics of chronic heat accumulation in urban fabric of Limassol, highlight the sensitivity of heritage structures to micro-climate extremes, particularly in areas with insufficient ventilation or thermal-expansion green infrastructure.

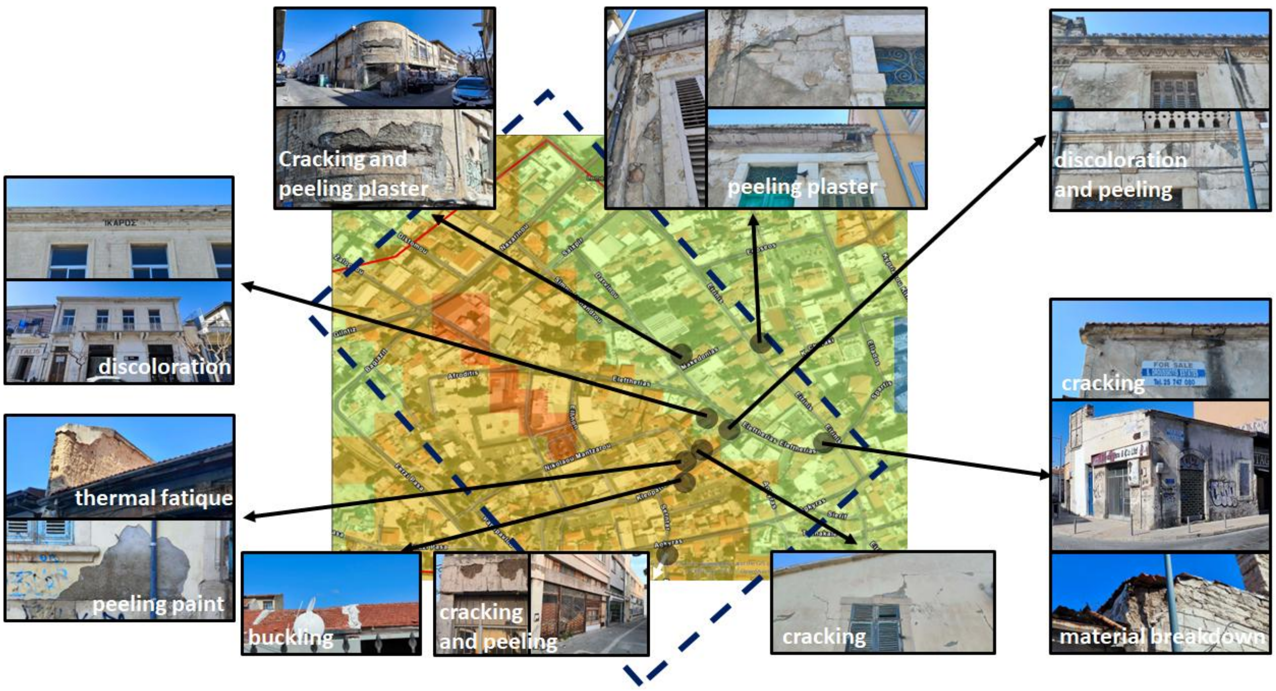

Figure 7 Observations of cultural heritage buildings deteriorate by thermal stress. Map allocation of temperature fluctuations distributed in the city's center.

3. RESULTS

As climate change is expected to intensify the UHI in the future, implementation of green infrastructures inside the cities core's is essential and a very powerful mitigation measure against the UHI effect [4],[5],[6],[7]. An environmental investigation was undertaken to analyze the correlation between urban landscaping patterns and thermal distribution characteristics within the built environment, by applying remote sensing satellite data. Landsat-8 satellite imagery was acquired on 25 February 2025 to calculate the Normalized Difference Vegetation Index (NDVI), which utilized as a type of measure of vegetative cover density across the urban landscape. An important Furthermore, spatial analysis involved the integration of NDVI data with thermal infrared imagery from LandSat-9 to examine the mitigating effects of vegetation on localized microclimate conditions. The correlation between NDVI and LST is a very valuable and essential methodology in assessing the effect of green infrastructure against the Urban Heat Island inside the city's core [8].

The results visualize an inverse relationship between vegetation presence and surface temperature distribution. Areas with higher NDVI values, reflective of chlorophyll concentration, continuously demonstrate reduced thermal signatures, with temperature differences of up to 4-6°C compared to neighboring non-vegetated zones. On the other hand, urban neighborhoods with limited or deficient vegetation are indicating critically elevated values of temperature patterns, especially in dense built-up areas which are characterized by high emissivity material surfaces and limited green infrastructure. These findings highlight the importance of urban greenery in mitigating thermal heat waves and emphasize the need for strategic implementation of landscape planning in climate-resilient city development.

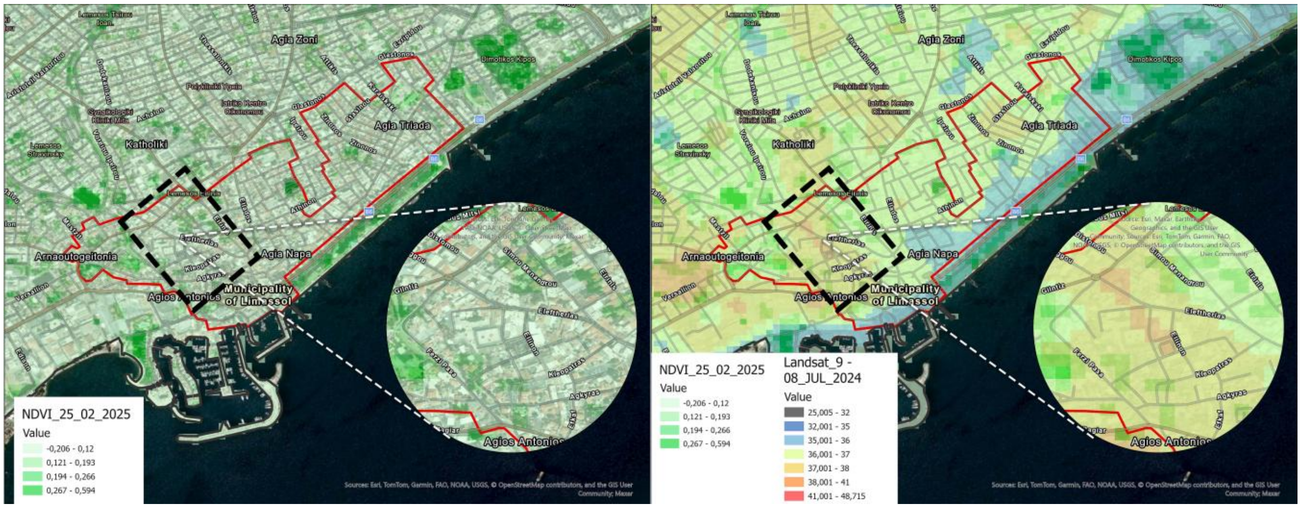

Figure 8 The left image presents the NDVI (Normalized Difference Vegetation Index) derived from Landsat-8 satellite imagery acquired on 25 February 2025. The right image displays an overlay of the NDVI and thermal data for the city center, highlighting spatial correlations between vegetation health and surface temperature distributions.

4. CONCLUSIONS

This paper presents a comprehensive investigation of thermal stress impacts on cultural heritage buildings within Limassol's urban core, with particular focus on the intensification effects of the Urban Heat Island (UHI) phenomenon. Field observations conducted across the city's historic district reveal intense thermal stress anomalies, including surface cracking, material spalling and deterioration, which collectively accelerate the structural degradation of vulnerable heritage structures. The methodology integrates remote sensing techniques, utilizing data from Sentinel-3, Landsat-8, and Landsat-9 satellites to establish an urban heat tracking framework. These satellite datasets provide advantages in monitoring and quantifying the behavior of UHI, as they are able to provide precise spatial analysis of surface temperature distributions across the city and highlight thermal anomalies which exceed critical temperature values related to their surroundings.

The analysis demonstrates that the predominant use of high-emissivity construction materials within the urban fabric significantly contributes to sustained thermal storage, creating both microclimatic discomfort and accelerated weathering of historic buildings. The combined interpretation of land surface temperature (LST) data with NDVI (Normalized Difference Vegetation Index) values points out vegetation coverage as a critical mitigation of UHI compared to adjacent built-up zones.

The results underscore the urgent need for strategic urban landscape interventions in Limassol's historic center, to reshape the urban fabric and replace high-thermal-mass surfaces with dense green infrastructure like green roofs and tree canopies, to provide shade and absorb heat from sunlight. To improve the local micro-climates and thus to relief the heat stress out of heritage buildings which will enhance the urban environment's climate resilience in climate change. Implementation requires a coordinated policy action plan to improve green infrastructures inside the urban fabric which can coexist harmonically with architectural character of the city [8],[9],[10].

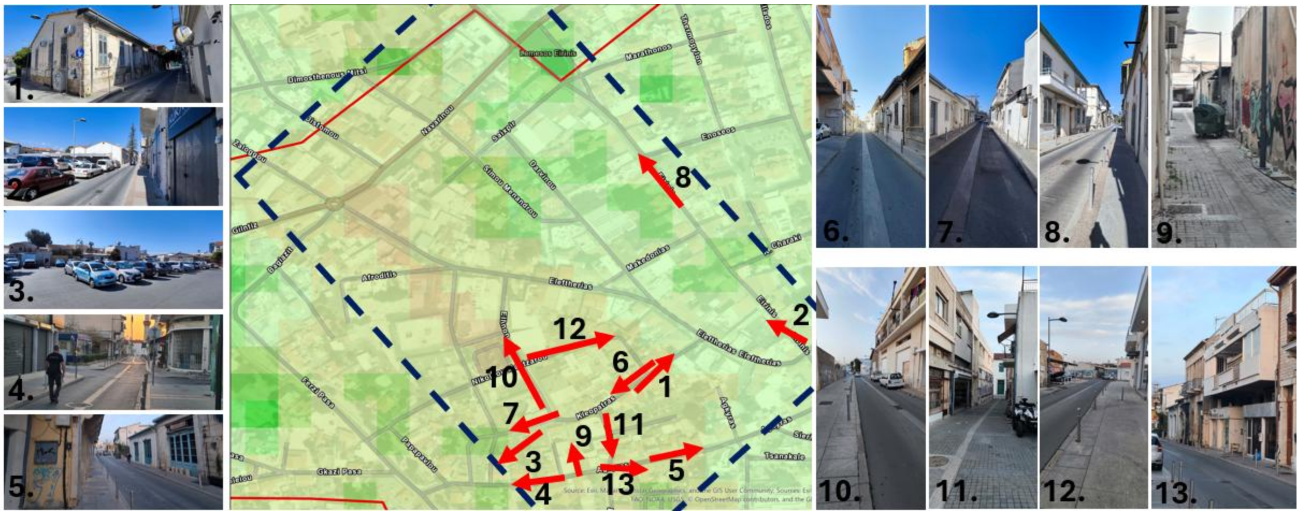

Figure 9 The built environment of city center visualizing the predominance of high-emissivity materials and the lack of green infrastructures.

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