COMPARING URBAN HEAT ISLANDS IN ERBIL CITY-IRAQ: INVESTIGATING VEGETATION RESPONSE THROUGH DAY AND NIGHT THERMAL INFRARED DATA AND NDVI VALUES

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Abstract. Land surface temperature (LST) is crucial in understanding urban environments, climate dynamics, hydrology, ecology, and agriculture. While daytime thermal infrared (TIR) data from satellites have been extensively used to analyze LST and the urban heat island effect in arid regions, exploration of nighttime LST data over semi-arid urban areas using high-resolution TIR data is lacking. This study aims to investigate spatial and temporal Land Surface Temperature (LST) variations in Erbil City, located in the Northern part of Iraq, utilizing high-resolution Landsat-8 data for daytime analysis and ECOSTRESS data for nighttime evaluation. The research reveals distinct daytime Urban Cooling Intensity (UCI) and significant nighttime Urban Heat Island (UHI) effects, with UCI primarily driven by early morning Landsat imagery. Notably, a prominent UHI effect occurs at night, particularly in May and June. Daytime LST values show no significant differences among land cover categories, while nighttime LST decreases in areas with Normalized Difference Vegetation Index (NDVI) > 0.5. The study emphasizes the importance of high-resolution nighttime TIR data in investigating UHI in arid and semi-arid regions, addressing a gap in prior research that overlooked this aspect. The prevailing hot and arid climate weakens vegetation's thermal buffering capacity during warmer months, resulting in the absence of distinct temperature variations in the study area.
Keywords: *ECOSTRESS, Landsat-8, hotspot analysis, urban cool island and urban heat island*

Introduction

Land Surface Temperature (LST) is undeniably a cornerstone in the study of climate and biology. Its far-reaching influence on terrestrial ecosystems and the well-being of living organisms is nothing short of remarkable, spanning from local microenvironments to the global stage (Li et al., 2013). Within the extensive spectrum of earth data collected by eminent institutions like NASA, LST takes a paramount position, reflecting its pivotal role in deciphering the intricate web of interactions that underpin our planet's ecological equilibrium. In essence, LST refers to the measurement of thermal radiance emitted from the Earth's surface when it is heated by solar energy and interacts with various elements, including thermal radiation from vegetation or man-made structures. Consequently, monitoring and measuring LST find application in various environmental contexts. It plays a pivotal role in energy partitioning at the land surface-atmosphere boundary and serves as a sensitive indicator for assessing changes in land surface conditions (Abdullah, 2012). Furthermore, LST data can provide

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valuable insights into the physical processes governing surface energy and water balances across different ecosystems and spatial scales (Noilhan and Planton, 1989).

In recent decades, Land Surface Temperature (LST) retrieval from remote sensing platforms has gained significant popularity, especially through the utilization of remotely sensed Thermal Infrared (TIR) data. Nowadays, a variety of remote sensing platforms and sensors offer TIR data at different scales. For instance, the Landsat mission has been providing TIR data since 1972, with a spatial resolution of 30 m per pixel. Similarly, ASTER TIR data provides a spatial resolution of 90 m, allowing data acquisition during both nighttime and late afternoon hours. In contrast, the MODIS satellite offers TIR data for both day and night times at a resolution of 1 km, making it a widely used choice for regional-scale studies. The retrieval of LST data from remotely sensed TIR data yields spatially continuous LST measurements with global coverage. This method has found extensive application in examining the thermal variations across the Earth's surface and studying the effects of natural and human-induced changes on surface temperatures (Li et al., 2013).

One of the common applications of remote sensing TIR (Thermal Infrared) data, which has been known and studied since the 20th century, is the examination of Urban Heat Islands (UHI). The UHI phenomenon refers to a condition in which there is a significant increase in urban area temperatures in comparison to the surrounding suburban and rural neighborhoods (Imhoff et al., 2010). It is essential to note that, in contrast to UHI, there is another phenomenon known as Urban Cool Islands (UCI). Both UHI and UCI are sensitive conditions influenced by environmental factors such as daylight duration, the season of the year, and wind speed (Zhou et al., 2013). In other words, when using remote sensing TIR data for such applications, it is crucial to consider these factors to assess the conditions accurately.

Previous studies have consistently shown that the impact of UHI is most pronounced during the summer and warmer periods (Emmanuel and Krüger, 2012; Schlünzen et al., 2010). Additionally, within a daily cycle, UHI tends to be most intense at night (Abdullah et al., 2020; Yuan et al., 2021). Furthermore, the intensity of UHI diminishes as cloud cover and wind speed increase (Ngarambe et al., 2021), and it is most pronounced during anticyclonic conditions (Morris and Simmonds, 2000). Similarly, when it comes to utilizing remotely sensed TIR data for studying UHI or UCI, it is crucial to consider the acquisition time of that data. For instance, if the TIR data has been collected during midday, this represents an ideal condition for studying UHI (Stathopoulou et al., 2006). In contrast, when the data is captured early in the morning, the radiance emitted from surface structures, including vegetation, has not yet reached its peak due to the sunlight, which has not fully interacted with these structures on the land surface (Zhou et al., 2013). Consequently, the calculated Land Surface Temperature (LST) data from such a dataset will not accurately depict the UHI or UCI conditions.

In light of findings from previous studies, it has come to our attention that some related research on the use of remote sensing TIR data in relation to Urban Heat Islands (UHI) did not account for the acquisition time of the satellite data used for Land Surface Temperature (LST) calculations and UHI assessments (Faqe Ibrahim, 2017; Rasul, 2016; Rasul et al., 2015). In our earlier investigation, we explored the impact of different land use and land cover on LST in Erbil city using Landsat TIR data. This city is situated in a semi-arid region, characterized by scorching summers and cold, wet winters. In our previous study we found and underscored that the study area experienced an Urban Cool Island (UCI) rather than a UHI. This discrepancy is

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attributed to the early morning acquisition time of the Landsat data, which was collected at 7:32 am. Therefore, the identified UCI is not a result of the inherent characteristics of the area but rather stems from the choice of TIR data (Abdullah, 2012)

In general, daytime TIR data closely aligns with the radiative and thermodynamic characteristics of the Earth's surface, surpassing standard air temperature measurements (Guillevic et al., 2018). Consequently, daytime LST measurements exhibit heightened sensitivity to changes in vegetation density and provide additional insights into the biophysical controls on surface temperature, including surface roughness and transpirational cooling (Fan et al., 2015; Still et al., 2019)

On the other hand, nighttime TIR data offers a distinct perspective, furnishing information on radiative cooling, urban heat islands, and vegetation stress (Abdullah et al., 2020; Fricke, 2019; Still et al., 2019). Both daytime and nighttime TIR data are complementary, offering a comprehensive understanding of Earth's surface conditions and processes. Therefore, in this study, temporal TIR data was utilized for the first time at both daytime and nighttime to compute LST over the city of Erbil. To achieve this, we take into account seasonal variations and acquisition times, utilizing day time Landsat TIR data from January to June 2023, covering the transition from winter to summer conditions. Additionally, for nighttime TIR data, we employ the LST product from the ECOSTRESS satellite. The ECOSTRESS (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station) mission is a NASA project aimed at monitoring the Earth's thermal and water-related processes. ECOSTRESS was launched to the International Space Station (ISS) on June 29, 2018, as part of the SpaceX CRS-15 mission. This unique instrument measures TIR from the Earth's surface to provide valuable insights into various environmental parameters, with a primary focus on vegetation health, land surface temperature, and evapotranspiration. ECOSTRESS data is collected at a spatial resolution of approximately 70 m, allowing for detailed observations of surface temperature and vegetation conditions (Chang et al., 2021). This fine spatial resolution makes it particularly useful for studying small-scale environmental changes, agricultural practices, and the effects of urban heat islands.

In this study, our main objectives were to investigate the diurnal temperature fluctuations in Land Surface Temperature (LST) across various land cover classes within the city of Erbil using normalized difference vegetation index (NDVI) and thermal infrared data from satellite data. Our research focused on two primary aspects: the spatiotemporal changes in key LST parameters spanning from the cold to the hot season and, of particular significance, the response of vegetation cover in this challenging environment to temporal variations in thermal infrared radiation, both during the daytime and at night.

Materials and methods

Study area

The research was conducted in Erbil city, a prominent urban center situated in Northern Iraq known for its substantial size and expansive geography. Erbil is geographically positioned between the coordinates of 36° 080 N–36° 140 N latitude and 43° 570 E–44° 030 E longitude, as illustrated in *Figure 1*. This region experiences two distinct climatic conditions: a dry and hot climate prevails from April to the end of September, while the period from October to March is characterized by a wet and cold climate (Hussein et al., 2018). The topography of the area is relatively flat, with the

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highest elevation point reaching approximately 412 m above sea level. Notably, Erbil has undergone significant economic growth and development, particularly following the liberation of Iraq in 2003. As a result, it has emerged as one of the most densely populated and developed cities in Northern Iraq, housing approximately 2 million residents (Abdullah, 2012). In parallel with its expansion and urbanization, the region has faced a pressing issue of severe drought over the past two decades. This drought has led to a dramatic reduction in precipitation and a corresponding increase in temperatures, posing considerable challenges for the local environment and its inhabitants (Al-Quraishi et al., 2021).

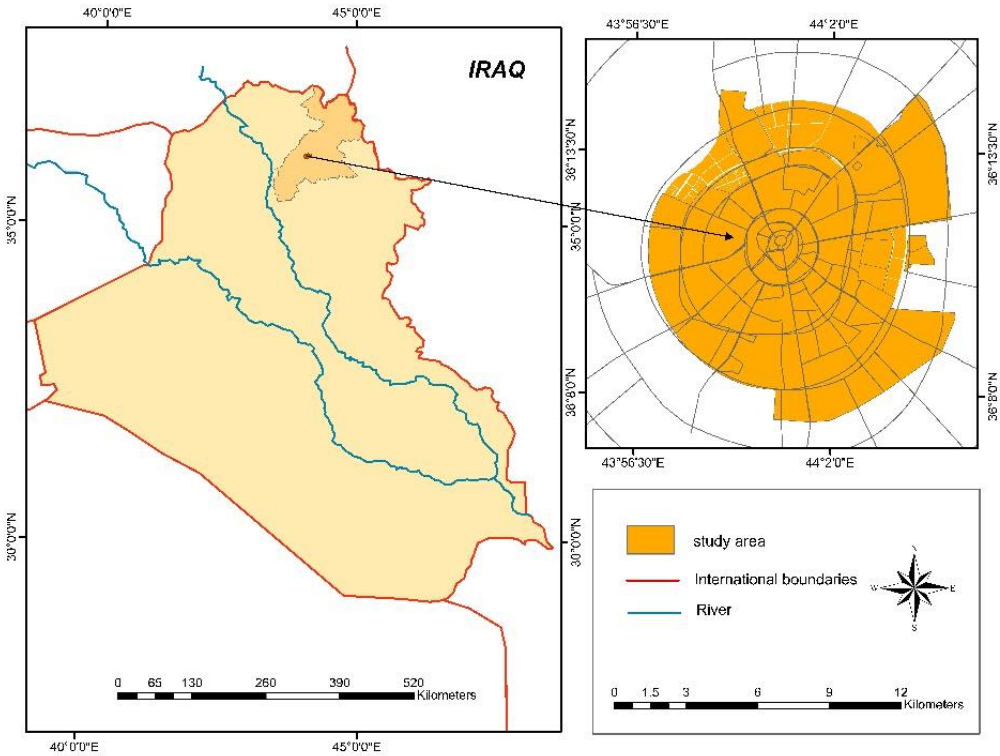

***Figure 1.** The location of Erbil City in Iraq*

Satellite data

Figure 2 depicts the methodology workflow embraced in this study for assessing urban heat islands and the responses of vegetation cover during both daytime and nighttime using thermal infrared data. The following subsections elaborate on the specifics of satellite data and the methodologies implemented within this study.

PlanetScope

One of the primary objectives of this study is to comprehend how vegetation cover responds to urban heat islands during both day and night. Therefore, it is crucial to identify vegetation cover using high spatial-resolution satellite data. To achieve this, we employed PlanetScope Dove satellite data for the date May 14, 2023. The PlanetScope Dove product consists of eight spectral bands, ranging from coastal blue at 431 nm to near-infrared at 885 nm. To identify vegetation cover, we utilized a spectral vegetation

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index, namely the Normalized Difference Vegetation Index (NDVI), using the following equation:

$$\text{PlanetScope Dove NDVI} = (B8 - B6) / (B8 + B6) \qquad \text{(Eq.1)}$$

Here, B8 and B6 represent the near-infrared and red spectral bands, respectively. Subsequently, we used the NDVI product to classify vegetation cover into three distinct classes (*Fig. 3*):

- Non-vegetated areas (e.g., built-up land and barren land) are identified if the NDVI value is lower than 0.2
- Sparse vegetation cover (e.g., grasslands and open green spaces) is recognized if the NDVI value falls between 0.2 and 0.5
- Dense vegetation cover (e.g., green spaces with tree cover) is delineated if the NDVI value is greater than 0.5

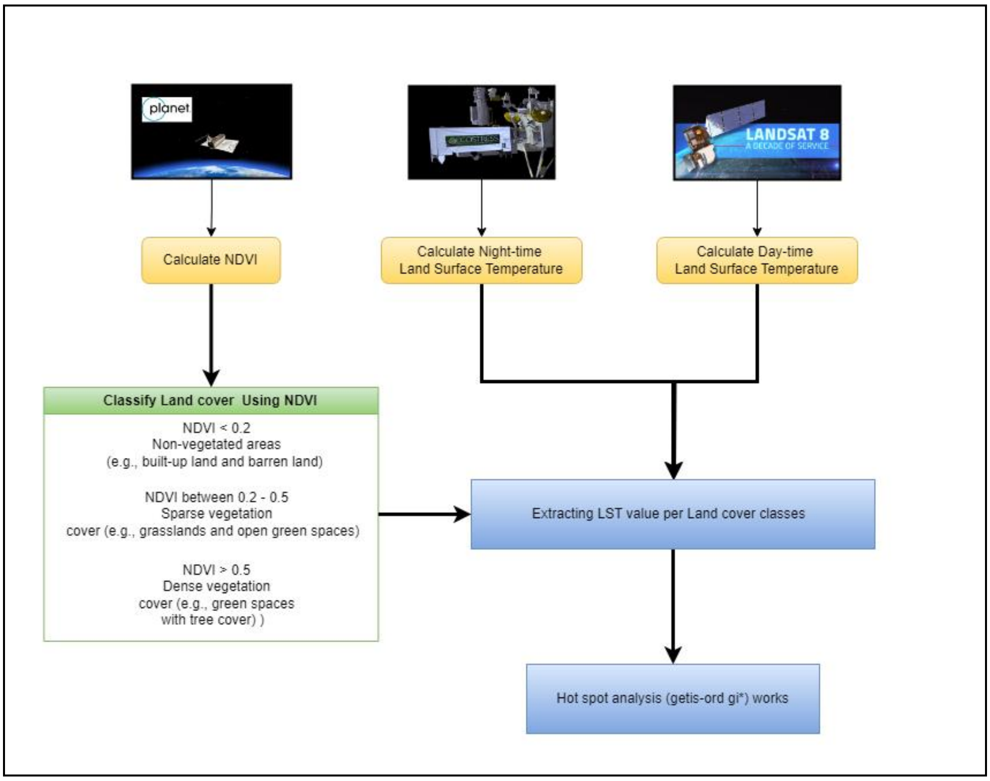

Figure 2. *Graphical workflow adopted in this study*

Calculating daytime and nighttime land surface temperature

The primary objective of this study was to assess the response of vegetation cover to the UHI phenomenon during both daytime and nighttime conditions. To achieve this goal, we utilized thermal infrared (TIR) data from the LANDSAT-8 Operational Land Imager (OLI) product to calculate land surface temperatures (LST) during the daytime and the ECOSTRESS LST product for nighttime measurements. For daytime LST calculations, TIR data were acquired from Landsat-8 TIR, with an acquisition time at 07:38:21 (early morning) as documented in *Table 1*. Landsat-8 TIR sensor provides data

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from two thermal bands (band 10 and band 11). However, band 11 is no longer operational for quantitative analysis, as reported by the US Geological Survey (USGS) (source: https://landsat.usgs.gov/using-usgs-landsat-8-product). Therefore, in this study, we exclusively utilized band 10, which has wavelengths ranging from 10.60 to 11.19 nm, to derive daytime land surface temperatures using the mono-window algorithm (MWA). The MWA has been proven to be effective and suitable for the semi-arid region and climate conditions in our study area (Qin et al., 2001). To apply the MWA, a set of climatic variables was required, including surface emissivity, air transmittance, and effective mean atmospheric temperature. The climatic variables, such as air temperature and wind speed, were obtained from the Erbil meteorological station, situated within the city of Erbil at coordinates (lat 36.171765° and long 44.014511°). Both air temperature and wind speed data were collected simultaneously with the satellite data acquisition (*Table 2*). In addition, the estimation of air transmittance and mean atmospheric temperature involved the consideration of two additional parameters: air surface temperature and water vapor content. Detailed procedures for retrieving these climatic variables and their application in the MWA can be found in our previous studies (Abdullah, 2012; Abdullah et al., 2019, 2020).

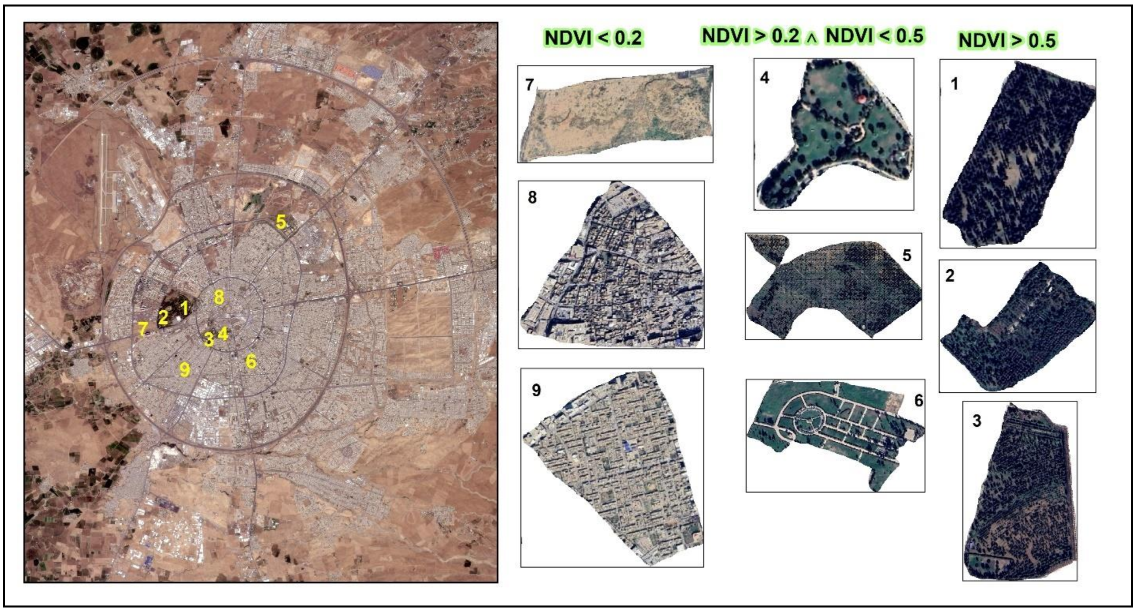

Figure 3. *Examples of various land cover classes are identified using different thresholds of NDVI data*

On the other hand, in this study, the ECOSTRESS data was used to calculate nighttime Land Surface Temperature (LST). ECOSTRESS, which stands for Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station, is a NASA mission designed to measure the temperature of the Earth’s surface. It was launched on June 29, 2018, as part of the SpaceX CRS-15 resupply mission to the International Space Station (ISS). ECOSTRESS is equipped with a specialized instrument known as a thermal radiometer, which measures the thermal infrared radiation emitted by the Earth’s surface. This data is used to calculate Land Surface Temperature (LST) with high spatial and temporal resolution. The key specifications of ECOSTRESS in regards to LST include its ability to capture LST data with a spatial resolution of approximately

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70 m and a revisit time of every two to five days. This high-resolution and frequent data collection is valuable for monitoring various environmental processes, such as droughts, heatwaves, and the health of vegetation. In this study, the ECOSTRESS LST Level-2 product was obtained from the NASA Land Processes Distributed Active Archive Center (NASA-LPDAAC). The spatial resolution of ECOSTRESS LST L2 product is 70 m × 70 m, and it includes estimated uncertainties for each retrieved quantity, along with a quality control (QC) bit field (Hulley et al., 2019).

Table 1. *List of utilized Landsat-8 and ECOSTRESS data*

No	Landsat-8 OLI (day-time)	ECOSTRESS (night-time)
1	18-January-2023 7:39 am	19-January-2023 9:45 pm
2	19-February-2023 7:38 am	24-February-2023 11:58 pm
3	2-May-2023 7:38 am	1-May-2023 9:46 pm
4	11-June-2023 7:38 am	3-June-2023 4:06 pm

Table 2. *Metrological data (air temperature and wind speed) collected from the Erbil meteorological station during the exact time of the thermal data taken by Landsat-8 and ECOSTRESS*

Daytime				Nighttime	
Date & time	Air temperature °C	Wind speed (s avg m/s)	Date & time	Air temperature °C	Wind speed (s avg m/s)
18-January-2023 7:39 am	15.9	0.001	19-January-2023 9:45 pm	9.9	0.005
19-February-2023 7:38 am	20.2	0	24-February-2023 11:58 pm	4.4	0.051
2-May-2023 7:38 am	28.7	0.32	1-May-2023 9:46 pm	27.1	0.27
11-June-2023 7:38 am	50.7	0.25	3-June-2023 4:06 pm	45.4	0.44

Statistical analysis

To evaluate the temporal variation in LST data across different vegetation and land cover types, we initially extracted the LST values for both daytime and nighttime using the NDVI approach (see *Fig. 2*). Following this, a hotspot analysis was conducted to understand the spatial patterns and variations of LST during both daytime and nighttime across the study area. To do this Hot Spot Analysis (Getis-Ord Gi*) was utilized, which is a spatial statistics technique and analytical approach that serves as a valuable tool for understanding and interpreting spatial patterns of temperature variations across landscapes (Jana and Sar, 2016). In the realm of LST studies, Hot Spot Analysis plays a significant role in uncovering and quantifying areas with significant ($p < 0.05$) temperature differences. It accomplishes this by examining the spatial distribution of temperatures and determining whether certain locations stand out as “hot spots” (areas with higher temperatures) or “cold spots” (areas with lower temperatures) compared to their surrounding areas. Therefore, using Hot Spot Analysis (Getis-Ord Gi*) It enables us to swiftly identify regions experiencing abnormal temperature behavior, such as extreme heat in urban areas (hot spots) or unusual cooling patterns (cold spots) attributed to factors like vegetation cover, urban heat islands, or the impacts of climate change (Sánchez-Martín et al., 2019). Additionally, as Hot Spot Analysis provides statistical significance to the identified hot and cold spots, and therefore this statistical rigor ensures that the observed temperature patterns are not merely random occurrences but hold meaningful implications.

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Results

Diurnal and nocturnal temporal changes in land surface temperature across various land use categories

The temporal variability of Land Surface Temperature (LST) across different months and various land cover categories is depicted in *Figure 4*. Notably, there is a pronounced disparity in LST values between daytime and nighttime observations, with this contrast being particularly conspicuous during the colder months, namely January and February. It is imperative to highlight that the variance in LST within distinct land cover categories is not statistically significant during the daytime hours. In contrast, a statistically significant disparity in LST data is observed between three land cover categories during nighttime observations. Notably, land cover characterized by dense vegetation (NDVI > 0.5) consistently exhibits significantly lower LST during nighttime throughout the four months under investigation. During daytime observations in the cold months (January and February), the LST pattern across all three land cover categories is nearly uniform. However, during the hotter months, specifically May and June, a significant reduction in LST is evident in the dense vegetated land cover category, as opposed to the other two categories during nighttime observations.

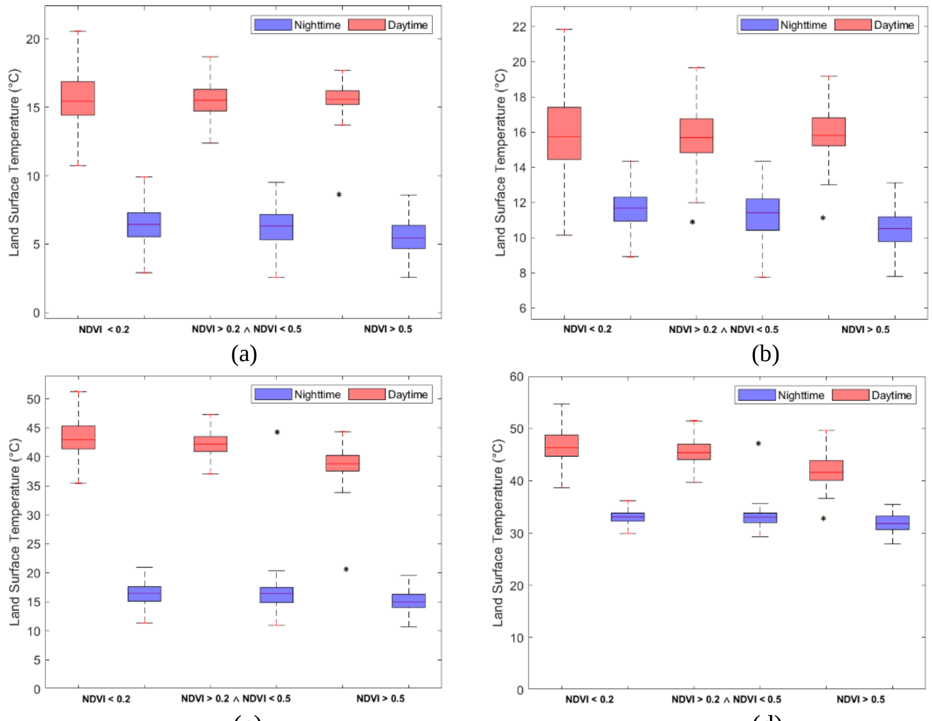

***Figure 4.** Temporal variation of land surface temperature for different land cover categories using NDVI threshold approach. A, B, C, and D represent the months of January, February, May, and June, respectively. The asterisk (*) indicates whether the LST is significantly different between the two-land use categories*

Moreover, it is noteworthy that the distinction in LST between daytime and nighttime observations diminishes during the hot month of June, in contrast to the cold months of January and February. For instance, in January, the mean LST during daytime hours

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across all three land cover categories was approximately 16°C, whereas during nighttime, it ranged from 6°C to 5°C. Conversely, in June, the mean LST during nighttime reached approximately 35°C, and during daytime, it ranged from 40°C to 45°C.

Temporal dynamics of hot and cold spots in land surface temperature throughout day and night

Figures 5 and *6* display the area coverage and spatial distribution of hot, cold, and statistically insignificant spots within the study area during the four months under investigation. Notably, there was a moderate to high spatial autocorrelation (clustering) of hot spots with statistical significance at $p < 0.05$ in Land Surface Temperature (LST) during the nighttime for the months of January and February. In contrast, during May and June, a majority of LST data clustered around the “not significant” spots.

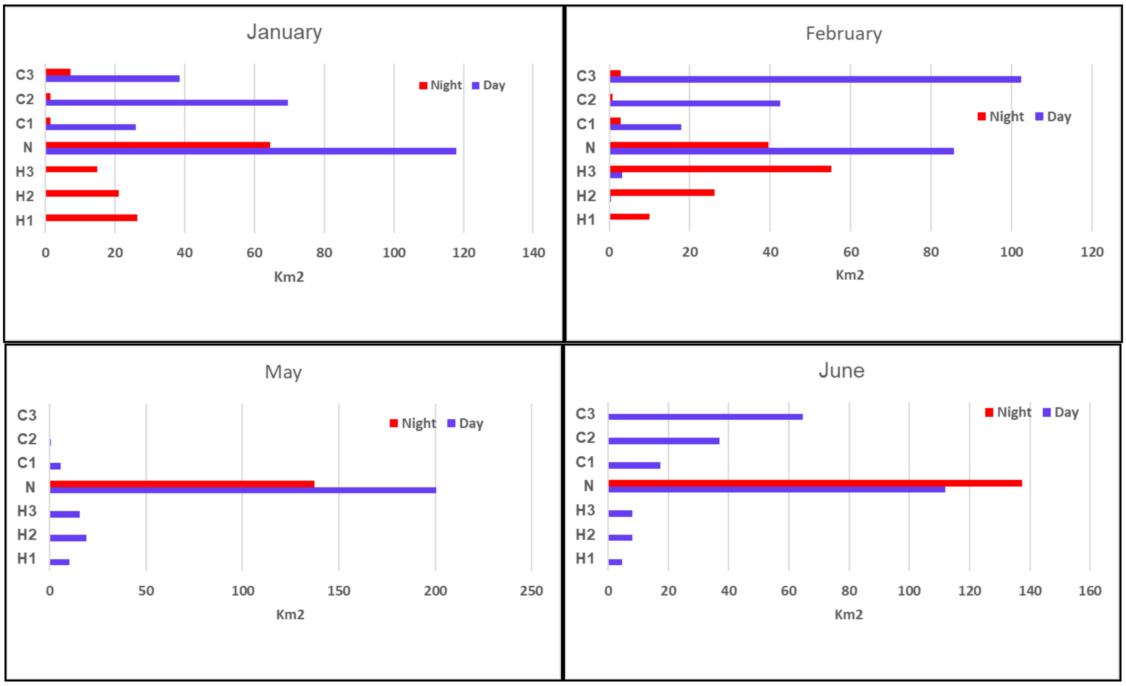

Figure 5. *Area coverage by hot, cold, and not-significant spots for day and nighttime land surface temperature (LST) from January to June 2023. The labels H1, H2, H3, N, C3, C2, and C1 correspond to hot spot confidence levels of 90%, 95%, 99%, not significant, cold spot confidence levels of 99%, 95%, and 90%, respectively*

During daytime hours, the pattern was reversed, with the majority of clustered LST values found within cold spots for all months except May, where the majority clustered around hot spots, with the highest area covered by the “not significant” category. When examining the distribution of hot spots in LST, it was observed that most of the study area exhibited hot spots with confidence levels of 99% and 95% during nighttime in January and February. However, this trend did not apply to areas of dense vegetation, as depicted in *Figures 6* and *3* (Locations 1, 2, and 3). Conversely, during daytime hours, the entire study area predominantly featured cold spots throughout the four months studied.

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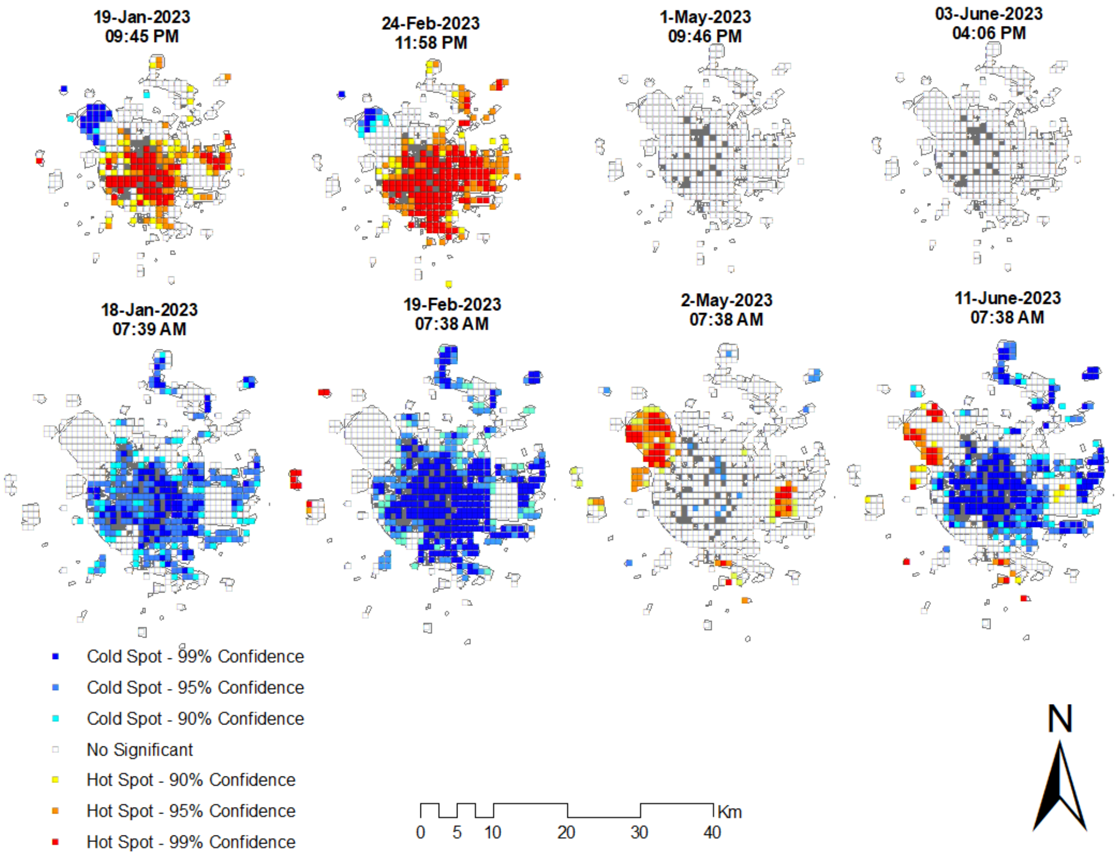

Figure 6. *Temporal maps of hot spot analysis for day and nighttime land surface temperature*

Discussion and conclusion

In this study, we embarked on an exploration of the Urban Heat Island (UHI) phenomenon within a semi-arid region Erbil city. We harnessed temporal high-resolution Thermal Infrared (TIR) data, encompassing both day and night periods. Furthermore, we delved into the interplay between vegetation cover and the UHI, examining their responses during day and night. Our findings validated that the study area predominantly experiences Urban Cooling Intensity (UCI) during daytime hours, while a pronounced UHI becomes apparent, especially during the scorching months of May and June, during nighttime. It is noteworthy that the daytime UCI is primarily attributed to the utilization of TIR data from Landsat imagery, collected during the early morning hours.

The comparison of Land Surface Temperature (LST) values among three distinct land cover classes, identified through the NDVI threshold approach, reveals that during the daytime, there is no significant disparity among these classes. However, during nighttime, a pronounced reduction in LST is observed over areas with an NDVI greater than 0.5 (see *Fig. 4*). Several factors contribute to this phenomenon. Firstly, in daylight, all urban areas are exposed to similar external factors, primarily solar radiation, resulting in uniform surface heating (Lai et al., 2019; Synnefa et al., 2007). Conversely, at night, the absence of these external heat sources leads to a more substantial divergence in LST. Secondly, urban surfaces emit heat back into the atmosphere at night, with variations based on land cover types. For example, concrete surfaces,

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prevalent in building construction within the study area, exhibit a slower heat release compared to natural surfaces such as grass and green spaces (Chow et al., 2011; Erell et al., 2012; Quattrochi and Ridd, 1994). The varying thermal properties of materials like concrete, asphalt, and green spaces play a crucial role in this temperature discrepancy. Furthermore, it is important to note that urban vegetation acts as a thermal buffer during nighttime (Deardorff, 1978; Erell et al., 2012), absorbing and mitigating heat released by built surfaces, thereby reducing the intensity of the Urban Heat Island (UHI) effect (Gunawardena et al., 2017). Our study consistently supports these findings, as the lowest nighttime LST values were consistently observed over dense vegetation cover with an NDVI > 0.5 for all four months considered in this study (see *Figs. 4* and *6*).

As illustrated in *Figures 5* and *6*, the large area within the study site has located within no significant spot, particularly during the warmer months of May and June, as discerned through the Getis-Ord Gi* analysis results. This lack of statistical significance suggests that this specific area does not markedly deviate from the surrounding clustered pixels. This outcome can be primarily attributed to the prevailing regional climate, characterized by persistent hot and arid conditions that curtail the emergence of discernible Land Surface Temperature (LST) hot spots (Rasul, 2016). Essentially, the arid and high-temperature nature of the study area during these months diminishes vegetation’s nocturnal thermal buffering capabilities, resulting in the observed lack of distinct hot or cold spots. These findings corroborate previous research, emphasizing the factors influencing vegetation’s role as a thermal buffer in arid, high-temperature settings (Mahmoud, 2011). These factors include: (a) limited precipitation, such as in our study area, which results in insufficient moisture for effective transpiration, reducing vegetation’s cooling effect (Hoelscher et al., 2016); (b) extreme high temperatures, which can stress vegetation, leading to wilting, reduced photosynthesis, and cellular damage, impairing its cooling potential (Hasanuzzaman et al., 2013; McWilliam et al., 1982). In such conditions, vegetation struggles to thrive and provide its usual cooling benefits. Furthermore, in arid environments, man-made structures, soil, and rocks tend to absorb and radiate heat during the day in the absence of vegetation moderation, releasing this stored heat at night and contributing to higher nighttime temperatures (Farina, 2012). Lastly, in arid and semi-arid regions, shorter nighttime cooling periods due to extended daytime heat exacerbate the situation, resulting in an environment where nighttime cooling is less pronounced.

Our study underscores the significance of employing high-resolution nighttime ECOSTRESS Thermal Infrared Radiometer (TIR) data to investigate the Urban Heat Island (UHI) phenomenon in arid and semi-arid regions. It reveals substantial differences in Land Surface Temperature (LST) between day and night. Previous UHI studies in the same area neglected nighttime TIR data, thus their primary findings only reflected urban responses during the daytime, often relying on inadequate data. This limitation stems from their use of early morning TIR data, which does not capture the heat accumulated from solar radiation. In essence, their findings depict LST status in the early morning, which is inadequate for assessing UHI and Urban Cool Island (UCI) effects.

Our research demonstrates that high-resolution nighttime TIR data from multispectral satellites like ECOSTRESS can significantly enhance the monitoring and detection of UHI and UCI without the need for ground-level ancillary data. This innovative application of satellite TIR imagery holds great promise for studying the UHI phenomenon. An exciting extension of this discovery could involve exploring the

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use of Unmanned Aerial Vehicles (UAVs) and airborne hyperspectral measurements for enhanced thermal imagery in the study of UHI in arid and semi-arid regions, as well as investigating the upscaling effect on LST retrieval.

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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