


Urbanization and surface temperature dynamics in Fortaleza: The role of natural elements and spatial transformations

¹Francisca Dalila Menezes Vasconcelos , ² Raquel Jahara Lobosco , ³Anderson Passos Bezerra,
⁴Marx Chhay 

¹Universidade Estadual do Norte Fluminense, Rio de Janeiro - Brasil, menezes.dalila@gmail.com

²Universidade Federal do Rio de Janeiro, Rio de Janeiro - Brasil, raquelobosco@poli.ufrj.br

³Prefeitura de Fortaleza, Fortaleza - Brasil, anderson.iplanfor@gmail.com

⁴Université da Savoie Mont Blanc, França, marx.chhay@univ-smb.fr

ABSTRACT

Amid escalating environmental pressures and the accelerating impacts of climate change, integrating climatological data into urban planning has become essential for sustainable city development. This study analyzes the spatial relationship between surface temperature patterns and key urban planning variables in Fortaleza, Ceará, Brazil. Landsat 8 satellite imagery from 2014 to 2022 was processed to generate temperature distribution maps, which were cross-referenced with population density, land use and land cover, vegetation, water bodies, informal settlements, urban plot distribution, and vacant land. The results reveal a strong correlation between the reduction of natural cooling elements—particularly vegetation and surface water—and the intensification of Urban Heat Island (UHI) effects. Areas undergoing rapid urbanization, especially coastal and high-density sectors, exhibited the highest thermal values, while zones with preserved green and blue infrastructure consistently maintained lower temperatures. These findings underscore the urgent need to incorporate urban climatology into land-use policies, zoning regulations, and environmental governance, ensuring that resilience and thermal comfort are integral to the planning and design of cities.

keywords: Urban Climatology. Urban Planning. Urban Heat Islands. Resilience. Adaptation..

Urbanização e dinâmicas de temperatura da superfície em Fortaleza: o papel dos elementos naturais e das transformações espaciais

Diante das crescentes pressões ambientais e dos impactos acelerados das mudanças climáticas, integrar dados climatológicos ao planejamento urbano tornou-se essencial para o desenvolvimento sustentável das cidades. Este estudo analisa a relação espacial entre os padrões de temperatura da superfície e variáveis-chave do planejamento urbano em Fortaleza, Ceará, Brasil. Imagens de satélite Landsat 8, referentes ao período de 2014 a 2022, foram processadas para gerar mapas de distribuição de temperatura, os quais foram correlacionados com dados de densidade populacional, uso e cobertura do solo, vegetação, corpos hídricos, assentamentos informais, parcelamento urbano e áreas vazias. Os resultados revelam forte correlação entre a redução de elementos naturais de resfriamento — especialmente vegetação e corpos d'água — e a intensificação do efeito de Ilha de Calor Urbana (ICU). Áreas em rápida urbanização, particularmente setores costeiros e de alta densidade, apresentaram os maiores valores térmicos, enquanto zonas com infraestrutura verde e azul preservada mantiveram temperaturas consistentemente mais baixas. Esses achados reforçam a necessidade urgente de incorporar a climatologia urbana nas políticas de uso do solo, nos regulamentos de zoneamento e na governança ambiental, assegurando que a resiliência e o conforto térmico sejam elementos centrais no planejamento e no desenho das cidades.

Palavras-chave: Climatologia urbana. Planejamento urbano. Ilhas de calor urbano. Resiliência. Adaptação.



1 INTRODUCTION

In Brazil, Environmental Urban Planning in major cities is guided by a framework of municipal laws, (Brasil, 2001, p. 1) such as the Land Use and Occupation Law (LUOS) and the Master Plan, which aim to promote sustainable development and safeguard the well-being of urban populations, (Kloth; Staloch; Goettenr, 2024) However, the rapid pace of urbanization combined with the intensifying effects of climate change—particularly the rise in urban temperatures—demands a deeper understanding of the interplay between urban form and the phenomenon of heat concentration in cities (Jung; Haddad; Gelder, 2024).

Previous studies have demonstrated that changes in land use and land cover (LULC) significantly affect urban temperatures. For example, Maheng *et al.* (2024) used the UrbClim model to quantify the warming effect caused by converting green spaces into built-up areas, while Moreira *et al.* (2024) developed the Urban Heat Island Vulnerability Index (UHIVI) for Recife, integrating physical UHI exposure with indicators of social vulnerability to reveal spatial inequalities. Such research underscores the importance of understanding how factors like vegetation cover, population density, impermeable surfaces, and the distribution of green and blue infrastructure shape local microclimates and influence the severity of the Urban Heat Island (UHI) effect. The consequences of rising temperatures in densely built environments are manifold: reduced thermal comfort, increased health risks—especially for vulnerable groups—higher energy consumption, pressure on water resources, and accelerated environmental degradation.

Innovations in predictive modeling, such as the multimodal deep learning approach introduced by Yi, Liu e Hu (2025), have shown that integrating high-resolution thermal stress forecasting with scenario-based urban greening strategies can achieve significant cooling benefits. Similarly, recent global research reinforces the role of green infrastructure as a cost-effective and multifunctional measure for UHI mitigation, particularly in tropical cities (Santos *et al.*, 2024). Meta-analyses indicate that strategically positioned vegetation can maximize cooling effects by intercepting prevailing winds and shading impervious surfaces (Li *et al.*, 2025). Advances in remote sensing now enable more accurate detection and monitoring of thermal patterns, improving both spatial and temporal resolution in UHI studies (Diem *et al.*, 2024).

For coastal cities such as Fortaleza, the moderating effect of sea breezes is a key climatic asset. However, its potential is frequently undermined by high-density construction and the loss of permeable and vegetated spaces (Zhou *et al.*, 2019). Moreover, the burden of extreme urban heat is not distributed evenly; low-income and socially vulnerable communities often face disproportionate exposure (Chen; Bruhn; Seto, 2024). These insights align with the objectives of the present study, which seeks to integrate climatological data into urban planning to enhance resilience, equity, and livability in the face of mounting environmental challenges.

2 METHODOLOGY

This study adopts a case study approach, focusing on Fortaleza, the capital of Ceará State in northeastern Brazil, selected for its urban characteristics. According to the 2022 national census (IBGE, 2022), Fortaleza has approximately 7,775 inhabitants per square kilometer (Figure 1). In an area that encompasses 314 km², Fortaleza includes a 34-kilometer-long coastline, which subjects the city to marine influences and prevailing coastal winds. The climate is classified as tropical savanna (Aw) under the Köppen climate classification (Köppen; Geiger, 1928), characterized by consistently high temperatures and a well-defined rainy season with intense precipitation.

The city has experienced rapid and predominantly unplanned urban expansion, leading to multiple environmental and infrastructural challenges. Fortaleza also exhibits pronounced socio-spatial inequalities: approximately 42% of its population resides in informal settlements with limited access to basic services and infrastructure. These characteristics increase the city’s exposure to climate-related hazards and play a crucial role in the spatial patterns of vulnerability and thermal variation analyzed in this research.

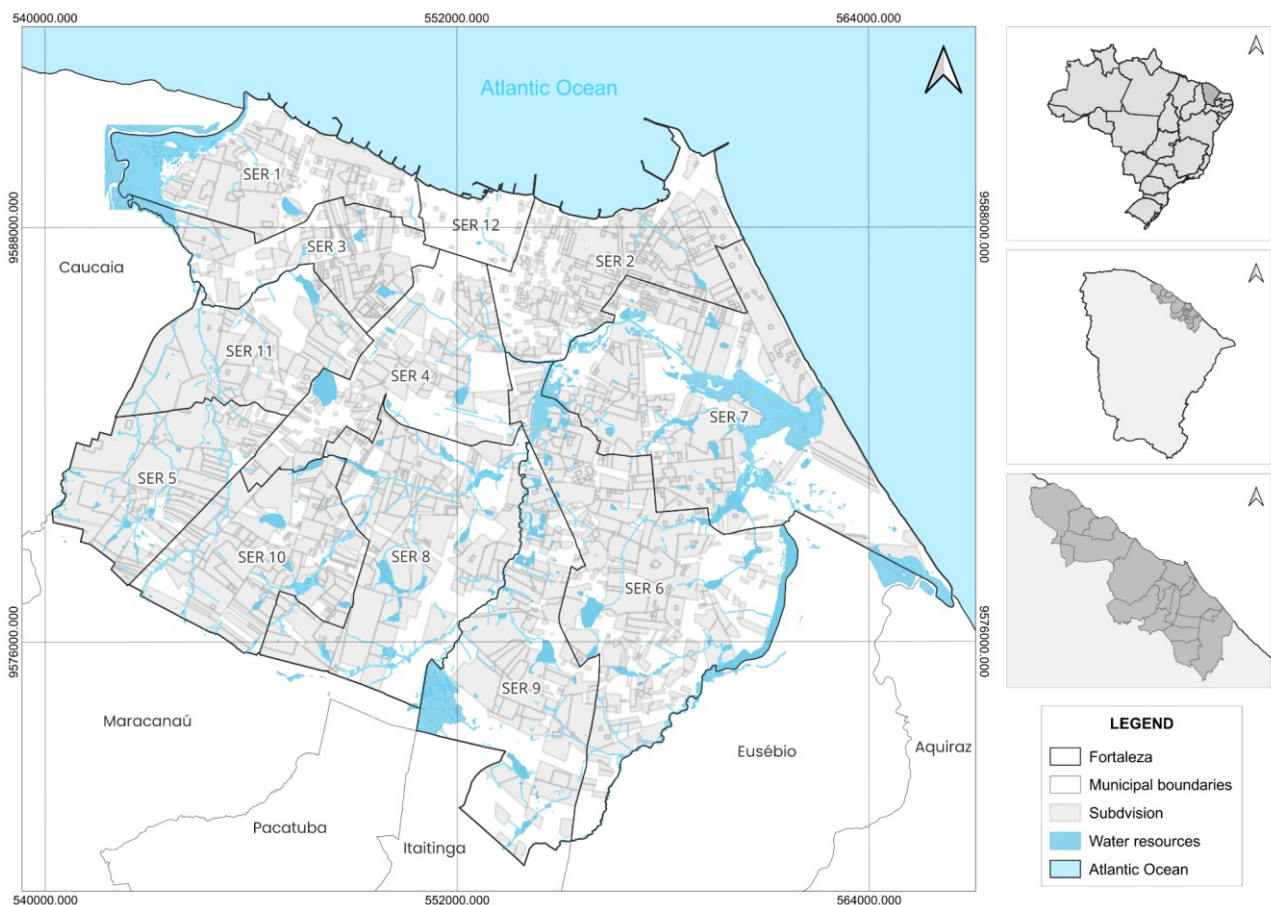


Figure 1 - Area of study.

Source: Author's compilation with data from the Municipal Government of Fortaleza (2023).

The integration of geospatial analysis with demographic and climatic data enables a comprehensive understanding of how land use, urban morphology, and social vulnerability contribute to variations in surface temperature across Fortaleza.

2.1 Data Collection and Analysis

All spatial datasets used in this study were standardized to a common cartographic reference system to ensure compatibility and accuracy in spatial analyses. Landsat 8 OLI/TIRS satellite images were acquired from the United States Geological Survey (USGS) platform in Level-1 format, which preserves the original radiometric and geometric fidelity of the data. These images were projected to the Universal Transverse Mercator (UTM) coordinate system, Zone 24 South, using the SIRGAS 2000 datum — the official geodetic reference for Brazil — to ensure alignment with national spatial datasets.

Ancillary layers, including municipal boundaries, hydrography, vegetation cover, and land use data, were obtained from the Brazilian Institute of Geography and Statistics (IBGE) and the MapBiomias Project. These vector datasets were originally provided in geographic coordinates (latitude/longitude) and were reprojected to the same UTM/SIRGAS 2000 system to avoid spatial distortions during overlay and analysis.

Georeferencing procedures were conducted in QGIS 3.x, using the “Reproject Layer” and “Align Raster” tools to ensure sub-pixel accuracy between datasets. Positional accuracy was verified by cross-referencing control points with high-resolution orthophotos provided by the Brazilian National Institute for Space Research (INPE). Discrepancies greater than one pixel (30 m) were corrected through affine transformation, prioritizing minimal resampling to preserve data quality.

This harmonized geospatial framework allowed for precise integration of thermal, land use, and socio-environmental datasets, enabling reliable correlation analyses between surface temperature patterns and urban form variables across Fortaleza’s territory.

3 RESULTS AND DISCUSSIONS

The analysis of Fortaleza’s urban climate between 2014 and 2022 demonstrates that population density, coupled with the loss of natural vegetation and water bodies, are the dominant drivers of surface temperature increases. This trend is particularly pronounced in areas undergoing rapid densification, where the replacement of permeable and vegetated land with impervious materials such as asphalt and concrete has amplified the Urban Heat Island (UHI) effect. Despite this, localized evidence shows that tree canopies, pocket green spaces, and strategic building shading can significantly mitigate thermal discomfort even in highly urbanized contexts, underscoring the potential of targeted microclimatic interventions.

The city’s historical trajectory of occupation—marked by unregulated coastal expansion, encroachment on dunes, rivers, and lagoons, and the proliferation of informal settlements—has reshaped its microclimate. The original tropical savanna biome and its biodiversity once acted as buffers, moderating surface temperatures.

The degradation of these natural systems has not only intensified heat exposure but also reduced the resilience of vulnerable populations, who often reside in the hottest and least vegetated zones.

Correlating land use and occupancy data with surface temperature maps reveals critical hotspots in regions such as Praia do Futuro, Barra do Ceará, and the Maranguapinho River Basin. These areas combine high population density with diminished green-blue infrastructure, resulting in persistently elevated thermal values. The findings point to the urgent need for policies that prioritize the conservation and restoration of natural cooling elements, particularly in socially disadvantaged neighborhoods where adaptive capacity is limited.

Addressing these challenges requires embedding urban climatology into municipal legislation, urban design guidelines, and environmental licensing processes. An effective response depends on coordinated governance involving at least the Municipal Secretariats of Planning, Environment, Urbanism, Infrastructure, Housing, and Civil Defense. Beyond interdepartmental cooperation, citizen engagement in co-managing green and blue infrastructure can enhance both the reach and sustainability of interventions.

Fortaleza has experienced rapid and intense demographic expansion, particularly between 1960 and 1980, when the city's population doubled in just two decades. Since then, growth has continued at a high pace, often in the absence of comprehensive urban planning. One direct outcome of this process is the proliferation of informal settlements, which currently house approximately 42% of the city's population (Municipal Government of Fortaleza, 2020). This urban dynamic not only reflects but also reinforces deep socio-spatial inequalities, increasing the city's vulnerability to the impacts of climate change.

Beyond population density, environmental indicators such as vegetation cover and the extent of water bodies are central to understanding Fortaleza's changing microclimate. MapBiomas data (2023) reveal that between 1985 and 2022, forest cover declined from 7,695 hectares to 2,079 hectares—a loss of 73%—while surface water areas decreased from 1,195 hectares to 739 hectares, a reduction of 38.16%. The combined decline of these natural cooling elements, coupled with high building density and unregulated construction, has intensified the Urban Heat Island (UHI) effect, amplifying thermal discomfort and the formation of urban heat hotspots.

Average surface temperature analysis from 2014 to 2022 reveals an anomalous spike in 2019, followed by a brief stabilization in 2020 and a subsequent upward trend in 2021 and 2022. The 2020 stabilization may partially reflect reduced urban activity during the COVID-19 pandemic, particularly declines in vehicular traffic and industrial output.

The sharp increase in 2019 aligns with climatic anomalies associated with El Niño. According to NOAA, an El Niño event developed between 2018 and 2019, despite being classified as “neutral” by INMET. During El Niño formation, weakened trade winds disrupt ocean–atmosphere interactions, causing warm surface waters

to persist in the Pacific Ocean—up to 3°C above normal—triggering droughts in northern and northeastern Brazil and increased rainfall in the south.

To refine the identification of thermal extremes, temperatures above the 80th percentile were analyzed. These values were predominantly in the 40–45°C range, while overall averages tended to fall between 35–40°C. Maximum temperature analyses confirmed this pattern, underscoring the robustness of the percentile-based method in isolating extreme thermal conditions—a key consideration in urban climate research.

The nine-year temperature series provides a valuable perspective on both gradual warming trends and seasonal variability in Fortaleza. This dual insight enables the differentiation between long-term climate change signals and short-term fluctuations related to wet/dry seasonality or monthly thermal cycles.

From a planning perspective, these trends have direct implications for forecasting energy demand and public health needs. Anticipating seasonal peaks in temperature can help utility companies optimize electricity generation for cooling systems, while municipal authorities can better prepare for heat-related health risks, particularly among vulnerable populations.

Figures 11 to 14 present box-and-whisker plots that summarize the distribution of surface temperatures for each year between 2014 and 2022. This visualization method clearly displays medians, quartiles, outliers, and the spread of values, enabling comparative analyses over time and across the city's zones.

In addition, Figure 3 offers spatial representations of maximum, average, and minimum surface temperatures based on the 80th percentile, using a color-coded gradient where red denotes the hottest areas and blue the coolest. The 2019 maps stand out, showing the highest maximum temperatures of the study period. Consistently, cooler zones are associated with the presence of water bodies, while the hottest correspond to densely urbanized areas with minimal vegetation.

One illustrative example is the Praia do Futuro region. Historically dominated by extensive fixed and mobile dune systems, this northeastern coastal zone has undergone accelerated urbanization in the last decade. Spatial temperature maps clearly indicate that recently urbanized sections now register some of the highest surface temperatures in Fortaleza, illustrating the direct thermal consequences of land cover transformation.

These findings reveal the intricate relationship between urban expansion, topography, and land use changes, emphasizing the need to account for the spatial distribution of water resources and green infrastructure when analyzing temperature variability. Within the study period, 2018 and 2020 stand out as cooler years, with lower surface temperatures predominantly concentrated in natural environments—such as rivers, streams, lagoons, green corridors, and protected conservation units.

The creation of an open-access, georeferenced urban climate data platform would serve as a cornerstone for evidence-based policymaking. By combining historical climate series, high-resolution remote sensing

products, and prospective modeling, such a platform could inform zoning revisions, guide tree planting and water body rehabilitation, and forecast the thermal impacts of future developments. Integrating these tools into medium- and long-term planning frameworks has the potential to reduce public expenditures on reactive measures, improve thermal comfort, and strengthen Fortaleza’s resilience to the advancing impacts of climate change.

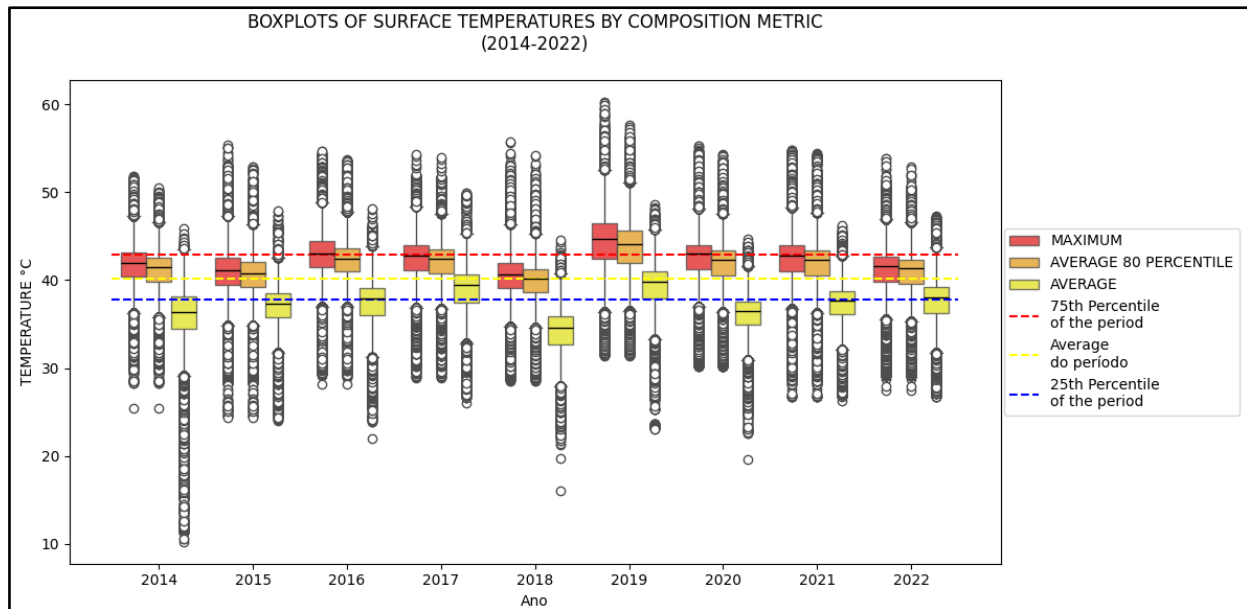


Figure 2 - Surface Temperature Metric Composition Chart (2014-2022).
Source: Author elaboration (2023).

Over nine years, the data reveal notable transformations in temperature patterns within areas experiencing densification and verticalization—particularly along the coastal strip. One of the most striking trends is the intensification of surface temperatures in these zones, driven by high-density construction and the proliferation of impermeable surfaces such as asphalt and concrete. These materials store heat during the day and release it gradually at night, sustaining elevated nocturnal temperatures and amplifying the Urban Heat Island (UHI) effect (Costa *et al.*, 2024; Coelho, 2022; Fernandes *et al.*, 2024). In coastal sectors, this warming may be further exacerbated by the reflection of solar radiation from water surfaces, which can intensify localized heating (Santos *et al.*, 2024).

The encroachment of rivers and lagoons for urban expansion has further eroded natural cooling mechanisms. Historically, these water bodies functioned as thermal buffers, moderating surrounding temperatures through evaporative cooling; their replacement by built structures disrupts this balance, transforming once-temperate zones into thermal hotspots—especially during the hottest months when cooling functions are most needed (Paschalis *et al.*, 2021). In parallel, the loss of vegetated areas has magnified heat retention. Vegetation not only shades surfaces but also promotes evapotranspiration, contributing to cooler microclimates (Yu; Zahidi; Fai., 2025). Its removal diminishes this capacity, accelerating local warming and expanding the spatial footprint of UHIs (Alves; Lopes, 2017; Roba; Tabor, 2025).

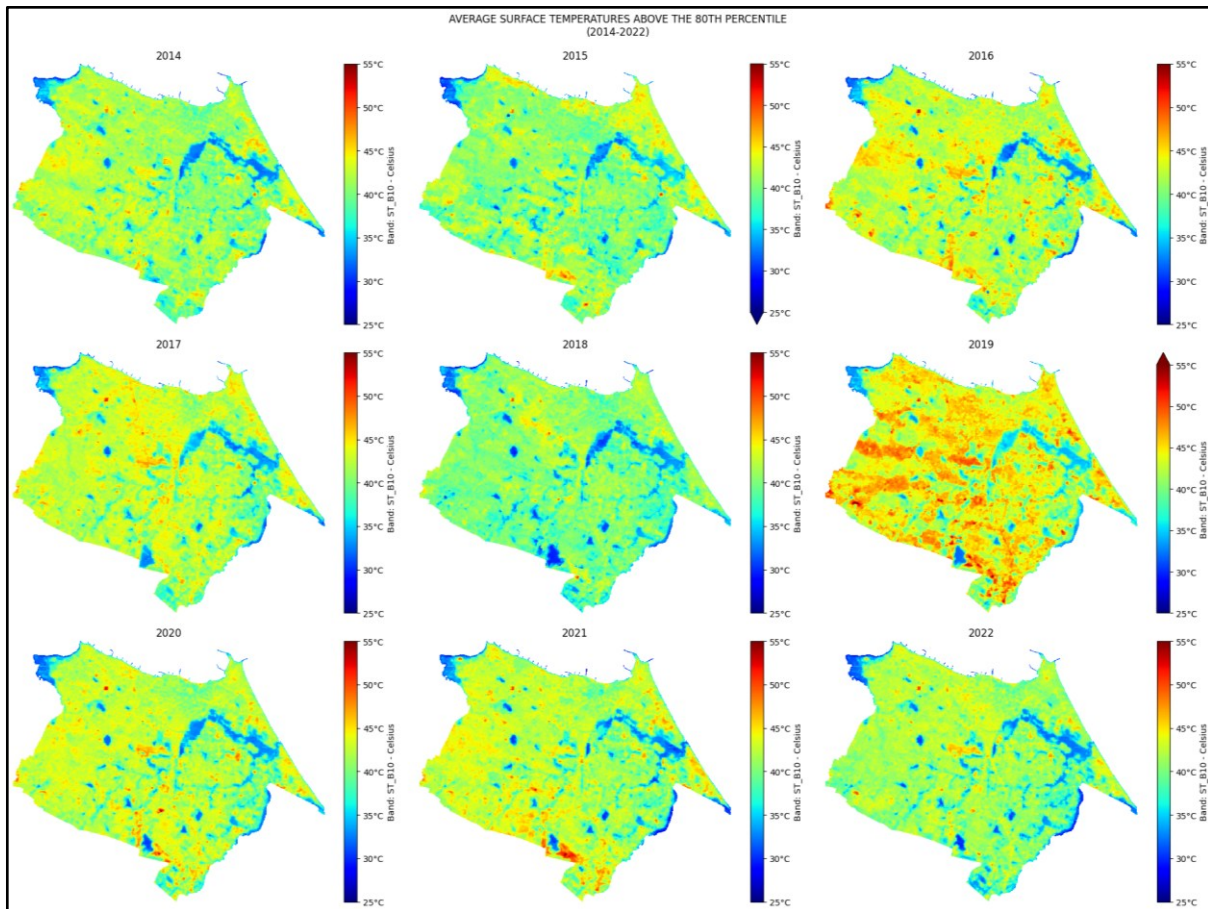


Figure 3 - Surface Temperatures Above the 80th Percentile (2014-2022).

Source: Author elaboration (2023).

In summary, the rapid and often unregulated transformation of Fortaleza—particularly in its coastal and lowland areas—has set in motion a cascade of temperature-related impacts. The urbanization of natural landscapes, the reduction of vegetated and aquatic environments, and the expansion of impermeable surfaces collectively drive the emergence and intensification of UHIs. Understanding these interactions is crucial for guiding sustainable urban development and informing climate adaptation strategies aimed at mitigating heat stress in cities.

Given the spatial variability and complexity of these patterns, there is a clear need for micro-scale, diachronic analyses that integrate high-resolution temperature data with parameters related to land use, occupation density, and the temporal evolution of urban form. Such a fine-grained approach is essential for pinpointing critical vulnerability zones and designing targeted interventions that enhance urban resilience in the face of accelerating climate change.

5 ANALYSIS OF SURFACE TEMPERATURE MAPS WITH LAND USE AND OCCUPANCY PARAMETERS

This section examines the relationship between surface temperature patterns and land use and occupancy parameters in Fortaleza. The analysis focuses on six key variables:

(i) Population Density and Surface Temperatures

Comparison of population density maps with average and maximum surface temperature data for the same period reveals a clear spatial correlation: the highest population densities coincide with the hottest zones. This is especially evident in the Maranguapinho River Basin—covering Regions 3, 5, and 11 as shown in Figure 1—where, despite the presence of water resources, many streams have been channeled, filled, or had their banks occupied. The combination of dense settlement and degraded aquatic environments significantly contributes to localized heat increases (Figure 4).

Along the coastline, Regions 1, 2, and 7 also display persistent high thermal values. Region 1 includes the neighborhoods of Barra do Ceará, Cristo Redentor, and Pirambu—among the most densely populated in the city—forming a metropolitan conurbation with Caucaia, which complicates coordinated urban management.

In Region 2, Vicente Pizón, and in Region 7, Praia do Futuro I and II, emerge as notable hotspots despite lower population densities. In these areas, heat intensification is linked to the loss of dune systems and rapid coastal urbanization, reducing natural cooling mechanisms.

(ii) Land Use and Occupancy Transformations

Urban densification and land cover changes have markedly altered Fortaleza's thermal profile. The Praia do Futuro sector is a clear example: former fixed and mobile dune fields have been replaced by residential, commercial, and industrial developments (Figure 5). These changes have substituted natural cooling elements with heat-absorbing surfaces, accelerating the Urban Heat Island (UHI) effect. Other areas in transformation show similar dynamics, with land conversion preceding even full population densification, suggesting that temperature rises can occur early in the urbanization process.

(iii) Reduction of Vegetative Cover

Vegetation loss is one of the most significant contributors to rising surface temperatures. MapBiomass data (2023) indicate that between 1985 and 2022, forest cover in Fortaleza declined from 7,695

hectares to 2,079 hectares—a 73% reduction. The spatial analysis shows a direct overlap between zones of vegetation loss and areas with higher surface temperatures.

Neighborhoods such as Vila Velha (Region 1), Palmeiras (Region 5), and Siqueira (Region 9) present high thermal values associated with vegetation removal, growing population density, and urban occupation along riverbanks. Even small-scale vegetation losses have cumulative effects, reducing evapotranspiration and shading, and thus increasing local heat retention.

(iv) Reduction of Surface Water Resources

Surface water bodies—including rivers, streams, and lagoons—have also diminished. Between 1985 and 2022, their area decreased from 1,195 hectares to 739 hectares, a 38.16% reduction in surface water weakened evaporative cooling and altered watershed dynamics (Projeto Mapbiomas, 2025). This reduction has weakened natural cooling processes, such as evaporative cooling, and disrupted watershed hydrodynamics.

Former lagoons replaced by built-up areas removed thermal buffers and, together with vegetation loss, expanded UHI footprints.

In some sectors, former water bodies have been replaced by built-up areas, eliminating critical thermal buffers (Hallefom *et al.* 2024; Vasconcelos *et al.*, 2011). These changes have turned previously temperate zones into heat accumulation areas, especially during warmer months (Santos *et al.*, 2024).

(v) Occupancy in Precarious Settlements and Risk Zones

The overlay of surface temperature maps with precarious settlements (Figure 7) reveals that many of the hottest areas coincide with zones of informal occupation. These communities often lack green spaces, adequate urban infrastructure, and building designs adapted to local climatic conditions, making residents more vulnerable to extreme heat.

Conversely, urban voids and preserved natural zones tend to be cooler, correlating with the presence of vegetation and water bodies (Figure 8). This highlights the role of environmental assets in regulating microclimates, particularly in socially vulnerable areas.

(vi) Urban Occupation in Risk Zones

A significant portion of new urban development in Fortaleza has occurred in environmentally sensitive areas—such as floodplains, riverbanks, and coastal dune fields—which are not only

physically vulnerable but also prone to thermal stress as shown in Figure 8. The occupation of these zones often involves removing protective vegetation and altering hydrological systems, exacerbating both flood risk and heat island intensity (Chapman; Foster; Kovács, 2018; Saiz-Rodríguez *et al.*, 2021; Chen; Bruhn; Seto, 2024; Yu; Zahidi; Fai, 2025).

The combination of hazard exposure (flooding, erosion) and climatic stress (heat) creates a double vulnerability, which demands integrated risk management approaches.

Implications for Urban Planning

Areas showing the greatest increases in temperature are those that have undergone the most intensive transformations—vegetation removal, surface sealing, and growth in traffic and industrial activities. The evidence demonstrates a direct and cumulative relationship between land use change and thermal dynamics.

In light of these findings, incorporating urban climatology into public policy and territorial planning is urgent. Urban form, vegetation, and water resources must be treated as strategic assets in climate adaptation. Sustainable urban planning should prioritize preserving natural cooling elements, restoring degraded ecosystems, and applying design principles that minimize heat accumulation while improving resilience to climate change.

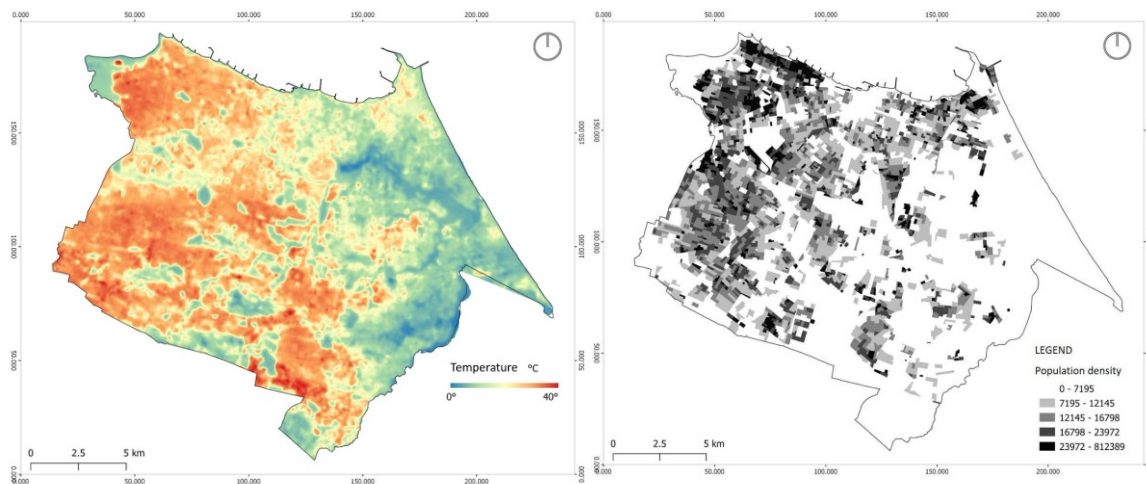


Figure 4 - Population density and surface temperature in Fortaleza.

Source: Own elaboration with data from the Municipality of Fortaleza (2023).

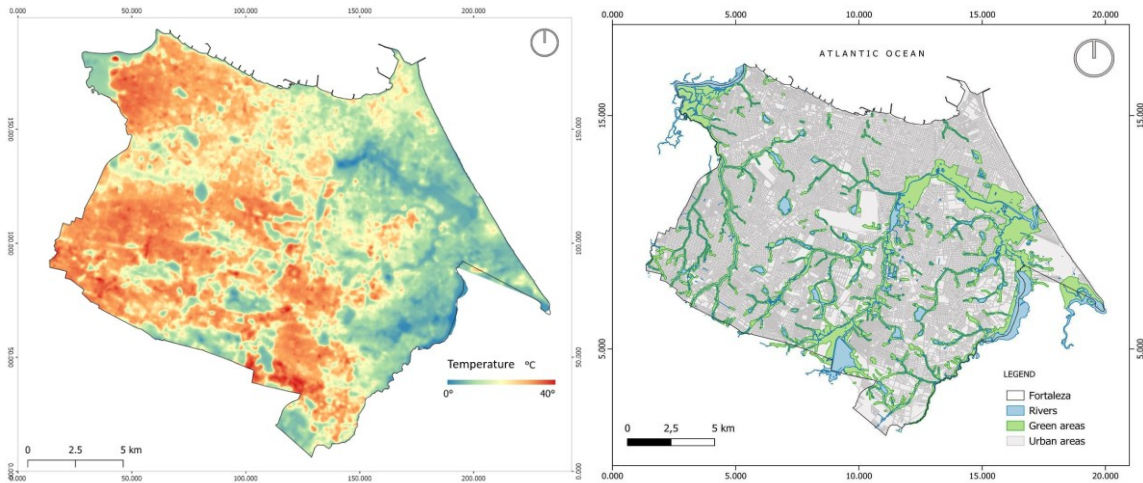


Figure 5 - Land use and occupancy and surface temperature in Fortaleza.
 Source: Own elaboration with data from the Municipality of Fortaleza (2023).

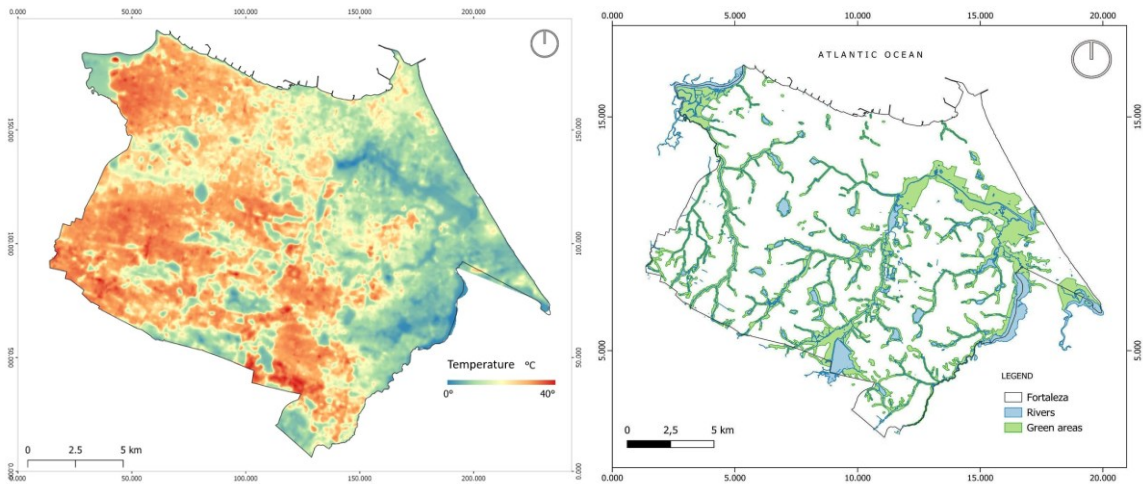


Figure 6 - Vegetative cover and surface temperature in Fortaleza.
 Source: Own elaboration with data from the Municipality of Fortaleza (2023).

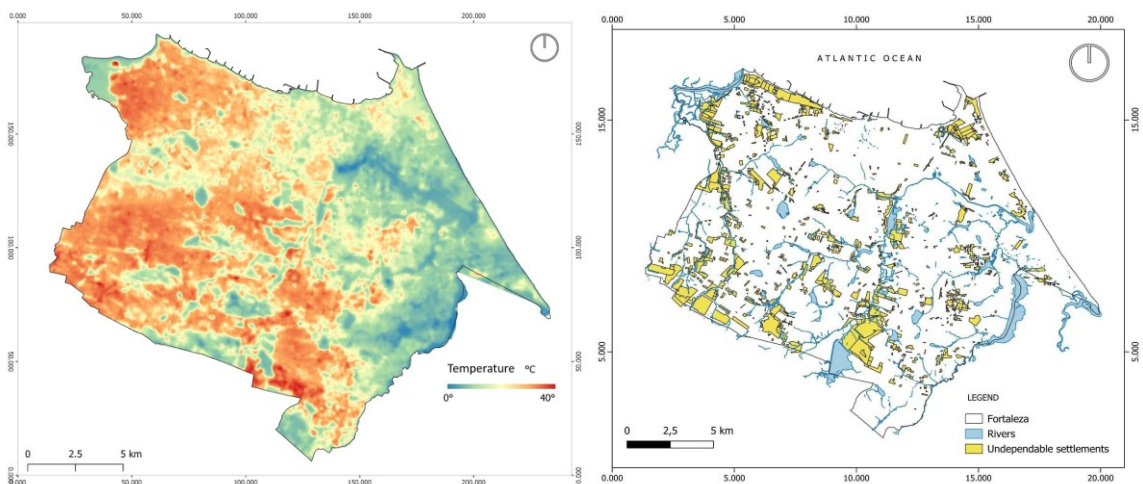


Figure 7 - Precarious settlements and risk areas in Fortaleza.
 Source: Own elaboration with data from the Municipality of Fortaleza (2023).

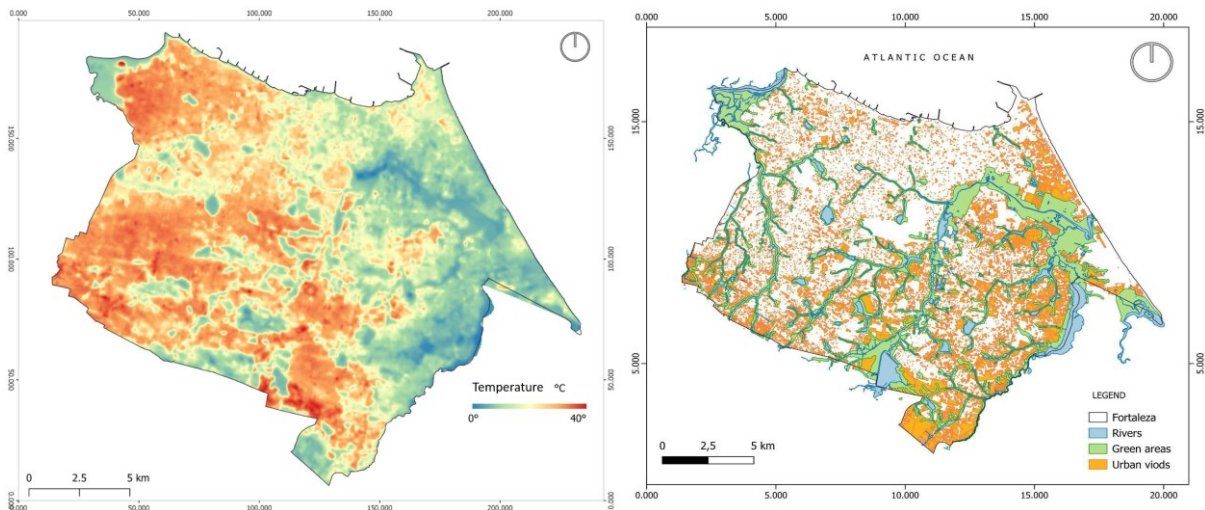


Figure 8 - Urban voids and lot grid in Fortaleza.
Source: Own elaboration with data from the Municipality of Fortaleza (2023).

Interestingly, certain conurbation zones along the boundary between Fortaleza and Aquiraz—despite undergoing recent urban growth (Orange legend in Figure 8)—have maintained relatively lower surface temperatures when compared to the other zones of the city. This cooling effect is largely attributed to their proximity to significant water bodies, most notably Lagoa da Precabura, which exerts a strong moderating influence on local thermal conditions, as shown in Figure 8. Such evidence underscores the importance of balancing urban development with the preservation of natural resources, as vegetation and water bodies are key regulators of urban microclimates, capable of reducing thermal extremes and mitigating the formation of heat islands.

8 FINAL CONSIDERATIONS

The analysis of Fortaleza’s urban climate between 2014 and 2022 demonstrates that population density, coupled with the loss of natural vegetation and water bodies, are the dominant drivers of surface temperature increases. This trend is particularly pronounced in areas undergoing rapid densification, where the replacement of permeable and vegetated land with impervious materials such as asphalt and concrete has amplified the Urban Heat Island (UHI) effect. Despite this, localized evidence shows that tree canopies, pocket green spaces, and strategic building shading can significantly mitigate thermal discomfort even in highly urbanized contexts, underscoring the potential of targeted microclimatic interventions.

The city’s historical trajectory of occupation—marked by unregulated coastal expansion, encroachment on dunes, rivers, and lagoons, and the proliferation of informal settlements—has reshaped its microclimate. The original tropical savanna biome and its biodiversity once acted as buffers, moderating surface temperatures. The degradation of these natural systems has not only intensified heat exposure but also reduced the resilience of vulnerable populations, who often reside in the hottest and least vegetated zones.

Correlating land use and occupancy data with surface temperature maps reveals critical hotspots in regions such as Praia do Futuro, Barra do Ceará, and the Maranguapinho River Basin. These areas combine high population density with diminished green-blue infrastructure (an integrated urban planning strategy that combines vegetation and water as essential infrastructure for more resilient, sustainable, and comfortable cities), resulting in persistently elevated thermal values. The findings point to the urgent need for policies that prioritize the conservation and restoration of natural cooling elements, particularly in socially disadvantaged neighborhoods where adaptive capacity is limited.

Addressing these challenges requires embedding urban climatology into municipal legislation, urban design guidelines, and environmental licensing processes. An effective response depends on coordinated governance involving at least the Municipal Secretariats of Planning, Environment, Urbanism, Infrastructure, Housing, and Civil Defense. Beyond interdepartmental cooperation, citizen engagement in co-managing green and blue infrastructure can enhance both the reach and sustainability of interventions.

The creation of an open-access, georeferenced urban climate data platform would serve as a cornerstone for evidence-based policymaking. By combining historical climate series, high-resolution remote sensing products, and prospective modeling, such a platform could inform zoning revisions, guide tree planting and water body rehabilitation, and forecast the thermal impacts of future developments. Integrating these tools into medium- and long-term planning frameworks has the potential to reduce public expenditures on reactive measures, improve thermal comfort, and strengthen Fortaleza's resilience to the advancing impacts of climate change.

REFERENCES

- ALVES, E. D. L.; LOPES, A. The Urban Heat Island Effect and the Role of Vegetation. *Atmosphere*, Basel, v. 8, n. 2, p. 18, 2017. DOI: <https://doi.org/10.3390/atmos8020018>
- BRASIL. Lei nº 10.257, de 10 de julho de 2001. Regulamenta os arts. 182 e 183 da Constituição Federal, estabelece diretrizes gerais da política urbana e dá outras providências. **Diário Oficial da União**: seção 1, Brasília, DF, ano 138, n. 132, p. 1, 11 jul. 2001. Disponível em: http://www.planalto.gov.br/ccivil_03/leis/leis_2001/110257.htm. Acesso em: 10 set. 2025.
- CHAPMAN, S.; FOSTER, A.; KOVÁCS, V. The Effect of Urban Density and Vegetation Cover on the Heat Island in a Subtropical City. *Journal of Applied Meteorology and Climatology*, [s. l.], v. 57, n. 11, p. 2555-2568, 2018.
- CHEN, S.; BRUHN, S.; SETO, K. C. Trends in socioeconomic disparities in urban heat exposure and adaptation options in mid-sized U.S. cities. *Remote Sensing Applications: Society and Environment*, v. 36, p. 101313, nov. 2024. Elsevier. DOI: 10.1016/j.rsase.2024.101313.
- COELHO, A. de A. The UHI in Fortaleza and Trends on Screen-Level Air Temperature and Precipitation. *In*: ARXIV PREPRINT, 2022. Disponível em: <https://arxiv.org/abs/2205.00319>. Acesso em: 27 set. 2025.

COSTA, G. A.; SOUSA, M. J.; SILVA, R. R.; ANDRADE, L. M. Geotecnologias aplicadas ao estudo do comportamento urbano e da temperatura de superfície. **Mercator**, Fortaleza, v. 23, e23001, 2024. DOI: <https://doi.org/10.1590/1984-2201e23001>

DIEM, P. K.; NGUYEN, C. T.; DIEM, N. K.; DIEP, N. T. H.; THAO, P. T. B.; HONG, T. G.; PHAN, T. N. Remote sensing for urban heat island research: Progress, current issues, and perspectives. **Remote Sensing Applications: Society and Environment**, [s. l.], v. 33, p. 101081, jan. 2024. DOI: [10.1016/j.rsase.2023.101081](https://doi.org/10.1016/j.rsase.2023.101081).

FERNANDES, R.; SANTOS, C. A. C.; MOURA, M. S. B.; SILVA, L. C. C. Urban Heat Island Assessment in the Northeastern State Capitals of Brazil Using Sentinel-3 Land Surface Temperature Data. **Sustainability**, Basel, v. 16, n. 11, p. 4764, 2024. DOI: <https://doi.org/10.3390/su16114764>

FORTALEZA. Lei Complementar nº 062, de 02 de fevereiro de 2009. Plano Diretor Participativo de Fortaleza. Diário Oficial do Município de Fortaleza, Fortaleza, ano 56, 13 mar. 2009.

HALLEFOM, H. B.; WU, C.; ZHANG, Y.; LI, J. The impact of urbanization-induced land use change on land surface temperature: A case study using Landsat data. **Remote Sensing**, Basel, v. 16, n. 23, p. 4502, 2024. DOI: <https://doi.org/10.3390/rs16234502>

IBGE. Censo Demográfico 2022. Rio de Janeiro, 2022. Disponível em: <https://www.ibge.gov.br/estatisticas/sociais/trabalho/22827-censo-demografico-2022.html>. Acesso em: 19 jul. 2023.

JUNG, M. W., HADDAD, M. A.; GELDER, B. K. Examining heat inequity in a Brazilian metropolitan region. **Environment and Planning B: Urban Analytics and City Science**, [s. l.], v.51, n. 1, 2024. DOI: <https://doi.org/10.1177/23998083231170634>

KLOTH, C. G.; STALOCH, R.; GOETTENR, W. J. Territorial planning and Sustainable Development Goals: implementation of metrics for analyzing the Land-use planning of the municipalities of Rio do Sul, Lontras and Presidente Nereu, Santa Catarina, Brazil. **Revista Gestão Ambiental e Sustentabilidade**, São Paulo, v. 13, n. 1, e21539, 2024. DOI: <https://doi.org/10.5585/2024.21539>

KÖPPEN, W.; GEIGER, R. **Klimate der Erde**. Gotha: Verlag Justus Perthes, 1928.

LI, G.; CAO, Y.; FANG, C.; SUN, S.; QI, W.; WANG, Z.; HE, S.; YANG, Z. Global urban greening and its implication for urban heat mitigation. **Proceedings of the National Academy of Sciences of the United States of America (PNAS)**, [s. l.], v. 122, n. 4, jan. 2025. DOI: [10.1073/pnas.2417179122](https://doi.org/10.1073/pnas.2417179122).

MAHENG, D.; PATHIRANA, A.; BHATTACHARYA, B.; ZEVENBERGEN, C.; LAUWAET, D.; SISWANTO, S.; SUWONDO, A. Impact of land use land cover changes on urban temperature in Jakarta: insights from an urban boundary layer climate model. **Frontiers in Environmental Science**, [s. l.], v. 12, 2024. DOI: [10.3389/fenvs.2024.1399041](https://doi.org/10.3389/fenvs.2024.1399041).

MAPBIOMAS. **Coleção 8**. 2023. Disponível em: <https://brasil.mapbiomas.org/>. Acesso em: 10 nov. 2023.

MOREIRA, A. B.; NÓBREGA, R. S.; WANDERLEY, L. S. de A.; MATZARAKIS, A. A. Urban Heat Island Vulnerability in the City of Recife, Pernambuco, Brazil. **Weather, Climate, and**

Society, Washington, v. 16, n. 1, p. 105-116, jan. 2024. American Meteorological Society. DOI: <https://doi.org/10.1175/WCAS-D-23-0082.1>

PASCHALIS, A.; CHAKRABORTY, T.; FATICHI, S.; MEILI, N.; MANOLI, G. Urban Forests as Main Regulator of the Evaporative Cooling Effect in Cities. **AGU Advances**, [s. l.], v. 2, n. 2, p. e2020AV000323, 2021. DOI: <https://doi.org/10.1029/2020AV000323>

PROJETO MAPBIOMAS. **MapBiomias água**: Série histórica (1985–2023), município de Fortaleza-CE (Coleção 3). São Paulo: MapBiomias. Disponível em: <https://brasil.mapbiomas.org/> Acesso em: 15 set. 2025.

RECIFE. **Lei Complementar nº 18.770, de 30 de dezembro de 2002**. Plano Diretor de Recife. Recife: Poder Executivo, 2002.

ROBA, Z. R.; TABOR, K. W. Geospatial analysis of vegetation and land surface temperature for urban heat island mitigation in Hawassa City, Ethiopia. **Scientific Reports**, [s. l.], v. 15, n. 1, p. 1-21, ago. 2025. Nature Publishing Group. DOI: [10.1038/s41598-025-17014-0](https://doi.org/10.1038/s41598-025-17014-0).

SAIZ-RODRÍGUEZ, J. A.; SALAZAR-BRIONES, C.; RUIZ-GIBERT, J. M.; MUNGARAY MOCTEZUMA, A.; LOMELI-BANDA, M. A. Analysis of urban heat island and flood-prone areas for green space planning. **Proceedings of the Institution of Civil Engineers: Urban Design and Planning**, [s. l.], v. 174, n. 2, p. 47-62, May 2021. DOI: [10.1680/jurdp.21.00006](https://doi.org/10.1680/jurdp.21.00006).

SANTOS, A. T. B. dos; LEAL JUNIOR, J. B. V.; GOMES, H. B.; COELHO, L. A. F.; GONÇALVES, W. A.; HOELZEMANN, J. J. Urban Heat Islands in Coastal Metropolitan Areas of Fortaleza and Natal, Northeastern Brazil, and Their Interactions with Local Wind Patterns. **SSRN Electronic Journal**, [s. l.], 10 Oct. 2024. DOI: [10.2139/ssrn.4983073](https://doi.org/10.2139/ssrn.4983073).

VASCONCELOS, F. P.; SENA NETA, Maria Antônia de; SILVA, Nayara Santos da; MORAIS, João Sílvio Dantas de. Avaliação comparativa, temporal e cartográfica das principais lagoas de Fortaleza (Ceará, Brasil). **Revista Geográfica de América Central**, Costa Rica, v. 2, n. 47E, p. 1-26, 2011. Disponível em: <https://www.revistas.una.ac.cr/index.php/geografica/article/download/3142/3001/6935>. Acesso em: 27 out. 2025.

YI, S.; LIU, Y.; HU, Y. AI-powered urban planning: A multimodal deep learning model for UHCI prediction and greening strategies. *In*: ARXIV PREPRINT, 2025. Disponível em: <https://arxiv.org/abs/2507.23000>. Acesso em: 13 ago. 2025.

YU, H.; ZAHIDI, I.; FAI, C. M. Mitigating Urban Heat Islands (UHI) through vegetation restoration: insights from mining communities. **Global Challenges**, [s. l.], v. 9, n. 3, p. 2400288, mar. 2025. DOI: [10.1002/gch2.202400288](https://doi.org/10.1002/gch2.202400288).

ZHOU, Y.; GUAN, H.; HUANG, C.; FAN, L.; GHARIB, S.; BATELAAN, O.; SIMMONS, C. Sea breeze cooling capacity and its influencing factors in a coastal city. **Building and Environment**, [s. l.], v. 166, p. 106408, Dec. 2019. DOI: [10.1016/j.buildenv.2019.106408](https://doi.org/10.1016/j.buildenv.2019.106408).