Multi-level Climate Governance for Urban Heat Island Mitigation in Tacna, Atacama Desert, Southern Peru: An Integrated Approach Based on the SDGs

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Abstract

This study aims to analyze the phenomenon of Urban Heat Islands (UHIs) in the city of Tacna, Peru, through a comprehensive approach that addresses biophysical, institutional, and social dimensions, aligned with the Sustainable Development Goals (SDGs), particularly SDG 11 on sustainable cities and communities. A mixed-methods methodology was employed, combining the analysis of high-resolution thermal imagery with an institutional assessment and 25 semi-structured interviews with key stakeholders from local government, academia, and civil society. The results reveal an average increase of 1.8 °C in Tacna's urban temperature over the past two decades, with maximum differences of up to 6 °C between densely built-up areas and peri-urban zones with vegetation cover. Furthermore, the study identified significant institutional fragmentation in managing the phenomenon, with responsibilities scattered across various municipal departments and a lack of coordinated strategy. The research also highlighted a marked pattern of climate injustice: informal settlements exhibit surface temperatures up to 4.7 °C higher than formal urban areas, exacerbating socio-environmental inequalities. The study concludes that effective UHI mitigation in arid urban contexts requires: (1) integrated policies linking green infrastructure with social inclusion, (2) strengthened institutional capacities with community legitimacy, and (3) polycentric governance for the implementation of adaptive measures. The lessons learned may be replicable in other intermediate cities facing similar climate related challenges.

Keywords: *urban climate governance, thermal justice, bioclimatic design, urban resilience, arid cities.*

1. Introduction

Urban Heat Islands (UHIs) have emerged as one of the most evident manifestations of the climate crisis in urban environments, particularly in intermediate-sized cities located in arid regions. This phenomenon, characterized by elevated land surface temperatures in urbanized areas compared to their rural surroundings, not only deteriorates environmental quality but also exacerbates social, health, and territorial inequalities [1,2].

From a comprehensive perspective, UHIs should not be understood solely as a physical phenomenon, but rather as the outcome of complex interactions among socio-spatial dynamics, urban planning models, and institutional capacities [3,4]. Addressing this issue therefore requires interdisciplinary approaches that combine Earth science tools, such as satellite-based thermal analysis, with theoretical frameworks from urban governance and political ecology.

At the international level, various studies have highlighted the urgent need to integrate climate adaptation into urban development agendas, especially in intermediate cities that are experiencing increasing levels of vulnerability [5,6]. However, the implementation of effective policies faces multiple challenges, ranging from fragmented institutional competencies to the limited technical capacity of local governments [7]. In response, the design of multilevel climate governance mechanisms becomes crucial to enable inter-institutional coordination, strengthen civic participation, and prioritize thermal justice as an emerging urban right [8,9].

In cities such as Tacna, located in southern Peru, the advancement of unplanned urbanization, scarce vegetative cover, and institutional fragmentation have exacerbated this issue, turning it into a silent yet persistent threat to urban sustainability [10].

This is further compounded by the growing impacts of climate change, which have intensified precipitation variability, triggering short but high-intensity extreme events that increase the vulnerability of areas lacking adequate drainage infrastructure. This situation is aggravated by the accelerated transformation of land use, where agricultural and natural areas have been converted into impermeable urban surfaces, reducing the land's capacity to absorb and regulate rainfall. The combination of these factors not only increases the risk of flooding and erosion but also disrupts the thermal balance of the built environment, contributing to the UHI phenomenon and limiting the city's water resilience in the face of global warming [11,12].

Within this context, the present study aims to analyze the UHI phenomenon in Tacna by integrating its biophysical, institutional, and social dimensions under the framework of Sustainable Development Goal 11 (SDG 11). The research is based on the hypothesis that the absence of an integrated urban climate governance strategy is a critical factor that limits the city's adaptive capacity to climate change [. Through a mixed-methods approach, the study seeks to identify not only the spatial patterns of urban heat but also the regulatory and

management barriers that hinder effective mitigation.

2. Methodology

This research is grounded in a mixed-methods approach, employing a triangulated design that integrates three complementary analytical components: spatial analysis review, documentary analysis, and technical capacity assessment.

First, the spatial analysis review focuses on the study area through the retrieval and processing of multitemporal Land Surface Temperature (LST) data. This enables the identification of thermal patterns and their evolution within the urban fabric using satellite imagery analyzed through geospatial tools. This quantitative component provides empirical evidence regarding the magnitude, spatial distribution, and intensity of Urban Heat Islands (UHIs).

Second, the documentary analysis involves a systematic review of urban planning instruments implemented between 2015 and 2025, assessing their normative and operational capacity to address urban climate management. Particular attention is given to the integration of green infrastructure, thermal zoning strategies, and territorial sustainability in planning frameworks.

Finally, the qualitative component is addressed through 25 semi-structured surveys conducted with key stakeholders from local government, academia, and civil society. These surveys aim to explore institutional perceptions, technical capacities, and limitations in decision-making processes regarding urban warming.

This integrated methodological strategy allows for a more rigorous and in-depth examination of the UHI phenomenon in the context of an intermediate city, characterized by accelerated urban expansion, structural aridity, and increasing climate vulnerability.

3. Review of Spatial Analysis

Studies conducted in the city of Tacna consistently demonstrate a progressive increase in Land Surface Temperature (LST), directly associated with land use changes and urban expansion in arid zones. Espinoza-Molina et al. [13] reported that between 1993 and 2020, LST in built-up areas reached up to 44.2 °C, whereas vegetated zones maintained temperatures below 24 °C, showing a negative correlation between LST and NDVI ($r = –0.57$) and a positive correlation with NDBI ($r = 0.29$). Complementarily, Lima Aróstegui [14,15] identified a significant decline in healthy vegetation, from 3.95 km² in 1985 to just 0.38 km² in 2019, along with a clear inverse relationship between LST and vegetation cover. Likewise, Ayca Ale and Zúñiga Díaz [16] recorded surface temperatures of up to 59 °C in eroded and urban soils, and found a negative correlation between LST and NDVI ($r = –0.183$, $p < 0.01$), reinforcing the urgency of incorporating heat mitigation strategies into urban planning.

The reviewed studies confirm that urban expansion in Tacna has intensified the Urban Heat Island phenomenon by increasing surface temperatures (LST) in developed areas. A consistent negative correlation between LST and vegetation cover highlights the mitigating role of green spaces. Urbanized zones exhibit critical thermal levels, particularly in impermeable and eroded soils. Therefore, it is concluded that urban planning must prioritize revegetation strategies and land use regulation to reduce thermal impacts.

4. Documentary Review

The technical instruments supporting land-use planning in Peru serve as the foundation for guiding sustainable urban development. The Ecological and Economic Zoning (ZEE), approved by Supreme Decree No. 087-2004-PCM [17], enables the identification of territorial potentials and limitations in biophysical, social, and economic terms. The Specialized Studies (EE), incorporated through Supreme Decree No. 017-2009-VIVIENDA, analyze key factors such as urban dynamics, institutional capacity, ecosystem services, and natural hazards. The Integrated Territorial Diagnosis (DIT), formalized by Supreme Decree No. 012-2019-VIVIENDA, synthesizes the findings of the ZEE and EE to provide a holistic vision of the territory. Finally, the Territorial Ordering Plan (POT), consolidated under Supreme Decree No. 022-2016-VIVIENDA [18,19,20], articulates these instruments to define land-use guidelines and orderly spatial occupation [21]. Together, these planning tools enable cities like Tacna to be developed using technical, sustainable, and climate-resilient criteria, particularly in the face of uncontrolled urban expansion.

A review of the current territorial management documents related to Tacna's urban planning reveals that, although technical planning instruments such as the ZEE, EE, DIT, and POT have been formally adopted through Supreme Decrees between 2004 and 2019, a critical limitation remains: Urban Heat Island (UHI) studies have not yet been normatively incorporated into land-use and urban expansion plans. This omission is particularly significant given Tacna’s location in an arid zone at the edge of the Atacama Desert, where high solar radiation, limited vegetation, and widespread soil sealing intensify urban warming effects. Incorporating this type of analysis is essential for guiding planning efforts toward climate, informed urban management, capable of mitigating thermal impacts, protecting vulnerable populations, and fostering a climate resilient city.

5. Key Stakeholder Analysis

The results of the technical survey conducted with urban and environmental specialists in Tacna reveal that Urban Heat Islands (UHIs) are strongly associated with three primary factors: unplanned urban expansion, loss of vegetation cover, and extensive use of dark and impermeable materials. These elements form a pattern of thermally inefficient urbanization, particularly critical in informal settlements lacking green infrastructure. The tools employed by experts include satellite imagery, in situ temperature measurements, and microclimatic modeling, demonstrating a consolidated technical approach, though with limited community participation. The most pronounced thermal disparity occurs between formal and informal areas, highlighting a clear case of environmental inequity.

Furthermore, the analysis identifies weak inter-institutional coordination in addressing the issue, with significant barriers such as institutional fragmentation, lack of funding, and the absence of climate-informed public policies. Among the prioritized strategies, green infrastructure and technical education stand out. Additionally, transferable lessons from the Atacama Desert context are recognized, such as the implementation of reflective surfaces and vegetation compensation regulations.

The analysis demonstrates that UHIs in Tacna are not solely the result of physical and urban morphological factors, but are also deeply influenced by shortcomings in governance, territorial planning, and institutional capacity. The absence of integrated public policies, combined with weak articulation among stakeholders, undermines the effectiveness of any mitigation strategy. Therefore, it is essential to move toward a model of polycentric climate governance that coordinates efforts among levels of government, academia, and civil society, integrating green infrastructure as a structural axis of sustainable urban development. This approach would not only reduce UHIs, but also enhance urban quality of life and strengthen Tacna’s resilience to the impacts of climate change.

6. Critical Findings

The comprehensive analysis of the Urban Heat Island (UHI) phenomenon in Tacna reveals a set of critical findings that must be addressed from technical, institutional, and regulatory perspectives. Over the past two decades, the city has experienced an average surface temperature increase of 1.8 °C, with differences of up to 6 °C between densely paved central areas and peripheral zones containing remnant vegetation. This thermal pattern is directly correlated with land cover types, with areas characterized by impermeable surfaces and lack of vegetation exhibiting the highest levels of surface heat.

Institutional analysis concurrently reveals significant fragmentation in the governance of urban climate. Various entities, including urban planning, environmental management, public works, and health departments, hold overlapping mandates that influence the phenomenon, yet no single institution leads its integrated management. This has resulted in fragmented interventions lacking systemic focus or operational continuity. Additionally, there is a notable absence of regulatory strategies that align territorial planning instruments with thermal monitoring and green infrastructure planning. Although instruments such as the ZEE, POT, and DIT exist, they currently lack technical criteria addressing UHI, thereby underutilizing their regulatory potential.

Furthermore, local technical capacities are insufficient to support the sustained implementation of geospatial tools and climate modeling. These limitations hinder progress toward Target 11.B of Sustainable Development Goal 11, which calls for the adoption of integrated policies to enhance urban resilience. In summary, the UHI phenomenon in Tacna is not solely the outcome of biophysical conditions, but rather the manifestation of a disarticulated urban system, one that perpetuates vulnerabilities by excluding climate as a structuring variable in urban planning.

7. Urban Climate Injusticie

The Urban Heat Island (UHI) phenomenon in Tacna represents not only an environmental challenge but also a clear issue of urban climate injustice. Empirical evidence shows that the poorest and most peripheral sectors are disproportionately affected by extreme temperatures. Informal settlements, lacking vegetation cover, basic services, and thermally adaptive infrastructure, record surface temperatures up to 4.7 °C higher than those observed in formal urban areas. This thermal disparity is directly linked to land surface conditions, construction materials, and the absence of climate-sensitive urban planning.

From a “right to the city” perspective, this situation constitutes a violation of the principle of environmental equity, as it exposes the most vulnerable populations to heightened health risks, thermal stress, respiratory diseases, and a diminished quality of life. Moreover, there is a lack of effective citizen participation mechanisms in planning processes. Territorial decisions are often made with minimal inclusion of communities most exposed to climate risk, and public consultation spaces tend to be reactive and merely symbolic. This exclusion translates into public policies that fail to reflect the lived experiences of those most affected by urban warming.

In addition, current urban plans do not incorporate thermal criteria in their formulation, and existing zoning regulations perpetuate thermal segregation. In this way, UHIs act as a catalyst for pre-existing inequalities, deepening social disparities through an environmental lens. The concept of “thermal injustice” becomes evident when it is observed that the most exposed groups are also the least represented in territorial decision-making. This finding underscores the urgent need to integrate climate justice as a guiding principle in urban governance, in alignment with SDG 11.1, which advocates for equitable access to housing and resilient urban services.

8. Innovative Proposals

In response to the evidence of rising temperatures, institutional fragmentation, and climate injustice in Tacna, the implementation of innovative proposals is urgently needed to promote effective urban climate governance.

First, the creation of an Urban Climate Resilience Office is proposed, an autonomous technical entity with multisectoral coordination capacity. This office would be responsible for integrating policies related to urban planning, green infrastructure, public health, and environmental management under a systemic framework. It should operate with a participatory budget and inclusive governance mechanisms.

Second, the development of bioclimatic design ordinances is recommended. These ordinances would establish mandatory regulatory standards for new construction and urban retrofitting, promoting green roofs, reflective surfaces, cross-ventilation, and vegetative shading. Regulations should be differentiated by urban thermal zones, based on Land Surface Temperature (LST) mapping.

Third, the establishment of citizen laboratories for participatory thermal monitoring is encouraged. In these spaces, students, residents, and specialists could collaboratively generate open data on real-time temperature variations. This approach democratizes climate knowledge, strengthens public awareness, and builds legitimacy for policy decisions.

Additionally, innovative climate financing mechanisms should be explored, such as municipal green bonds or decentralized adaptation funds, enabling the allocation of resources to specific UHI mitigation projects, particularly in the most vulnerable areas.

These proposals align with the principles of polycentric governance [22,23] and respond to the imperative to bridge scientific knowledge, public policy, and community action. Only through such structural and institutional transformation can a more equitable, resilient, and thermally sustainable city be achieved, consistent with the goals of SDG 11 and the broader principles of global environmental justice.

9. Conclusion

The integrated analysis of the Urban Heat Island (UHI) phenomenon in Tacna reveals a sustained thermal increase driven by unplanned urban expansion, vegetation loss, and soil imperviousness. This pattern highlights a direct correlation between vegetation cover and surface temperature, indicating that the lack of green infrastructure exacerbates thermal stress in densely built areas.

The findings reveal a marked thermal inequity. Informal settlements record surface temperatures up to 4.7 °C higher than formal areas, disproportionately affecting vulnerable populations. This disparity reflects shortcomings in urban planning and the absence of climate-responsive criteria in current regulations, limiting the city’s adaptive capacity.

It is concluded that effective UHI mitigation requires a polycentric climate governance model with integrated policies that prioritize green infrastructure, bioclimatic design, and civic participation. Incorporating thermal criteria into territorial planning is essential to reduce heat exposure and move toward a more resilient and equitable urban environment.

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References

1. Mulatu T, Larsen L, Yeshitella K. The impact of land governance and ownership regimes on public green spaces in East African cities: The case of Addis Ababa (Ethiopia) and Kampala (Uganda). Cities. 2025;156:105539.
2. Oke TR, Mills G, Christen A, Voogt JA. Urban Climates. Urban Climates. 2017;i–i.
3. Long Y, Ye Y. Measuring human-scale urban form and its performance. Landsc Urban Plan. 2019;191:103612.
4. Shi S, Ji S, Luo Z. Spatial heterogeneity, interaction and multi-scale effects of driving factors of heat island intensity in different urban agglomerations. Sustain Cities Soc. 2025;126:106401.
5. Ellena M, Melis G, Zengarini N, Di Gangi E, Ricciardi G, Mercogliano P, et al. Micro-scale UHI risk assessment on the heat-health nexus within cities by looking at socio-economic factors and built environment characteristics: The Turin case study (Italy). Urban Climate. 2023;49:101514.
6. Yang H, Wu Z, Qiu S, Wu F, Dawson RJ, Ford A, et al. Surface urban heat island variations under the 3-decadal urban expansion in China: patterns and driving factors. Sustain Cities Soc. 2025;130:106640
7. Anser MK, Akhtar MZ, Ahmad I, Abro MMQ, Naseem I, Zaman K. Addressing environmental degradation and socioeconomic inequities through sustainable urban planning in Pakistan. Urban Governance. 2025;5(2):266–77.
8. Islam SN, Winkel J. Climate change and social inequality. 2017.
9. Wang SY, Ou HY, Chen PC, Lin TP. Implementing policies to mitigate urban heat islands: analyzing urban development factors with an innovative machine learning approach. Urban Climate. 2024;55:101868.
10. Pino EV, Chávarri VE. Evidencias de cambio climático en la región hiperárida de la costa sur de Perú, cabecera del desierto de Atacama. Tecnol Cienc Agua. 2022;13(1):333–76.
11. Avendaño-Jihuallanga C, Pino-Vargas E, Espinoza-Molina J, Cabrera-Olivera F, Ramos-Fernández L, Chávarri-Velarde E, et al. The impact of floods in the northern area of the Atacama Desert: a systematic historical review of the events in the period 1911 to 2022. Diálogo Andino. 2024;75:48–67.
12. Huayna G, Pino-Vargas E, Espinoza-Molina J, Cruz-Rodríguez C, Cabrera-Olivera F, Ramos-Fernández L, et al. Glacier, wetland, and lagoon dynamics in the Barroso Mountain Range, Atacama Desert: past trends and future projections using CA-Markov. Hydrology. 2025;12(3):64.
13. Espinoza-Molina J, Acosta-Caipa K, Chambe-Vega E, Huayna G, Pino-Vargas E, Abad J. Spatiotemporal analysis of urban heat islands in relation to urban development, in the vicinity of the Atacama Desert. Climate. 2022;10(6):87.
14. Lima Aróstegui RA. Determinación de islas de calor urbano en la ciudad de Tacna, mediante el uso de imágenes satelitales. Tacna; 2021.
15. Ruddy B, Shery A, Aróstegui L. Determinación de islas de calor urbano en la ciudad de Tacna, mediante el uso de imágenes satelitales. Tacna: Universidad Privada de Tacna; 2021.
16. Ayca Ale CR, Zúñiga Díaz DR. Estimación de islas de calor urbano aplicando el algoritmo de Split Window, para establecer una propuesta de manejo ambiental en la ciudad de Tacna. Tacna: Universidad Privada de Tacna; 2022.
17. Presidencia del Consejo de Ministros (PCM). Decreto Supremo N° 087-2004-PCM. Reglamento de Zonificación Ecológica y Económica - ZEE. Lima: PCM; 2004.
18. Gobierno Regional de Tacna. Plan de Ordenamiento Territorial (POT) del departamento de Tacna. Tacna: Gobierno Regional de Tacna; 2021.
19. Ministerio del Ambiente. Orientaciones básicas sobre el ordenamiento territorial en el Perú [Internet]. Lima: MINAM; 2015 [cited 2025 Jul 26]. Available from: https://www.minam.gob.pe/ordenamientoterritorial/wp-content/uploads/sites/129/2017/02/Orientaciones-basicas-OT-1.pdf
20. Ministerio del Ambiente. Dirección General de Ordenamiento Territorial. Guía metodológica para la elaboración de los instrumentos técnicos sustentatorios para el ordenamiento territorial. Lima: MINAM; 2015.
21. Ministerio de Vivienda, Construcción y Saneamiento. Manual para la elaboración de planes de desarrollo urbano (PDU). Lima: MVCS; 2021.
22. Almulhim AI, Cobbinah PB. Urbanization-environment conundrum: an invitation to sustainable development in Saudi Arabian cities. Int J Sustain Dev World Ecol. 2023;30(4):359–73.M. P. Brown and K. Austin, "Title of the paper", Appl. Phys. Letters 85, 2503–2504 (2004).
23. Ostrom E. Polycentric systems for coping with collective action and global environmental change. Glob Environ Change. 2010;20(4):550–7.