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Mechanisms and Case Studies of Urban Green Infrastructure in Mitigating Urban Heat Islands

Xuanying Wang [1,*]

[1] College of Environment, University of Queensland, Brisbane, Australia
* Corresponding Author: s4829460@uq.edu.au

Abstract:
With the intensification of global climate change and the acceleration of urbanization, the Urban Heat Island (UHI) effect has become a significant environmental challenge impacting urban sustainability and public health. Urban Green Infrastructure (UGI), due to its ecological regulatory functions, is increasingly regarded as a nature-based solution to mitigate UHI. This paper systematically explores three core biophysical mechanisms by which UGI alleviates UHI: evapotranspiration, shading and physical cooling, and improved surface albedo. Empirical case studies from Beijing and Fuzhou are used to verify these mechanisms and optimization strategies. The findings indicate that evapotranspiration significantly reduces local temperatures through latent heat absorption, functioning as a primary cooling mechanism. Shading reduces solar radiation absorption and enhances human thermal comfort, while increased surface albedo helps lower heat accumulation. The case in Beijing shows that small-scale, distributed green spaces (e.g., multi-layered vegetation) in dense urban areas can reduce surface temperatures by 3–6°C. In Fuzhou, the optimized spatial layout of green areas combined with prevailing wind directions formed effective ventilation corridors, contributing to a temperature difference of 2–3°C. This study emphasizes that merely increasing the quantity of green space is insufficient; the quality and spatial configuration are critical to achieving systematic thermal regulation and enhancing urban climate resilience.

Keywords: UGI; UHI; Evapotranspiration; Shading effect; Cooling mechanism.

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1. Introduction

In recent years, the combined effects of accelerating global climate change and rapid urbanization have led to a significant intensification of the Urban Heat Island (UHI) phenomenon in many metropolitan areas [1]. UHI not only increases the frequency of extreme heat events during summer and raises energy consumption, but also poses severe risks to human health and quality of life [2]. Against the backdrop of increasingly compact urban forms and rising risks of heat retention, it has become imperative to explore nature-based and ecologically friendly strategies for thermal mitigation.

Urban Green Infrastructure (UGI), characterized by its multifunctionality, ecological regulatory capacity, and spatial permeability, has emerged as a key strategy in addressing UHI challenges [3]. UGI includes various forms such as urban parks, street trees, green roofs, and wetland systems, all of which can reduce urban temperatures through multiple biophysical mechanisms working in synergy. However, existing studies largely focus on the overall cooling benefits of UGI, while systematic investigations into how these internal mechanisms operate and how UGI design and spatial layout can be optimized under different urban conditions remain limited [4].

Previous research has preliminarily identified three major mechanisms through which UGI mitigates urban heat. First, evapotranspiration reduces surface temperatures by releasing water vapor and absorbing latent heat, especially during heat waves and in densely built-up areas. Second, vegetation structures such as tree canopies provide shade that blocks incoming solar radiation, improving the thermal environment of buildings and pedestrian spaces. Third, increased vegetative cover enhances surface albedo, reduces heat accumulation, and alleviates nighttime heat retention. For instance, an empirical study in Beijing found that 316 small urban green spaces could generate surface temperature differences of up to 6°C in midsummer through evapotranspiration [5]. Similarly, remote sensing-based modeling revealed that evapotranspiration accounted for over 50% of the cooling contribution of green spaces, more stable and effective than shading or ventilation mechanisms [6].

Therefore, this study aims to systematically analyze the three core mechanisms by which UGI mitigates UHI—namely, evapotranspiration, shading, and albedo enhancement. In addition, the study presents empirical analyses based on two representative cities, Beijing and Fuzhou, to evaluate the effectiveness of these mechanisms in real urban contexts. Finally, it offers recommendations for optimizing UGI design and planning to support climate-resilient urban development.

2. Mechanisms of Urban Green Infrastructure in Mitigating Urban Heat Islands

Amid ongoing global warming and intensified urbanization, the UHI effect has emerged as a key challenge to urban environmental quality and public health. Urban Green Infrastructure, by its ecological regulatory functions, is widely regarded as an effective means of mitigating UHI. Beyond its cooling effect through biophysical processes, UGI contributes to urban ventilation and surface energy balance. This section systematically analyzes three primary mechanisms through which UGI alleviates urban heat stress.

2.1 Evapotranspiration Effect

Evapotranspiration is considered one of the most fundamental mechanisms by which UGI mitigates UHI. It refers to the combined process in which plants absorb water through their roots and release it into the atmosphere via stomatal transpiration, while moisture from the soil surface evaporates simultaneously. This combined process involves substantial latent heat absorption, significantly reducing ambient temperatures and creating localized cool microclimates [1]. In urban environments, where heat is often trapped by high-thermal-capacity materials, evapotranspiration plays a vital role in counteracting heat build-up.

Large green spaces such as parks, lawns, and wetlands—with abundant vegetation and sufficient water availability—demonstrate strong evapotranspiration capacity, especially during hot periods. Research has shown that such spaces can reduce surface temperatures by 1–4°C during summer, with the most prominent cooling observed from midday to late afternoon [7]. Even small, distributed green areas—such as pocket parks or roadside vegetation—can meaningfully lower local temperatures via localized evapotranspiration and thereby enhance urban thermal conditions [5].

Evapotranspiration efficiency is influenced by both environmental and vegetative factors. First, vegetation type is critical. Trees, with larger leaf area and deeper roots, exhibit greater evapotranspiration capacity than shrubs or grass. Second, soil moisture is a limiting factor, as it determines water availability for transpiration. Climatic and physiological variables—such as air temperature, wind speed, relative humidity, and Leaf Area Index (LAI)—also influence evapotranspiration rates [8]. In arid regions or during heatwaves, a lack of irrigation or poor soil water retention can severely limit evapotranspiration efficiency, weakening its cooling effect.

To enhance evapotranspiration-driven cooling, green infrastructure planning should prioritize the use of high-efficiency, locally adapted species such as drought-tolerant broadleaf trees with high LAI values. Irrigation systems should be tailored to seasonal and climatic conditions, ensuring water availability during dry or extreme heat periods. Hydrological features like rain gardens and retention ponds can be incorporated to improve soil moisture and support consistent evapotranspiration. In addition, spatial planning should include green corridors and interconnected park clusters to increase ecological connectivity and amplify cooling effects.

2.2 Shading and Physical Cooling Effect

Shading is another key mechanism by which UGI mitigates UHI. Vegetation can block incoming shortwave solar radiation, significantly reducing heat absorption by surfaces and buildings, and consequently lowering ambient heat storage and surface temperatures. Moreover, shaded areas often exhibit higher relative humidity and reduced wind speeds, which improve thermal comfort for pedestrians. This mechanism relies largely on the structural characteristics of vegetation—especially tree canopies—and their spatial deployment, making it one of the most perceptible and practical strategies for thermal regulation [8].

Various elements of UGI, including street trees, green hedges, pergola-covered walkways, vertical greening, and green roofs, can all provide shade at different scales. For example, street trees not only provide shade for pedestrians, mitigating heat stress, but also cool adjacent road surfaces and building facades, indirectly reducing energy demands for air conditioning. Green roofs, which act as vegetative layers atop buildings, reduce rooftop heat gain and delay thermal peak hours, thereby improving indoor thermal conditions [9].

Studies have shown that dense street trees can lower surface temperatures by 2–4°C, while hedges and pergolas enhance the thermal comfort of walking surfaces by reducing surface radiation. Green roofs, under summer heat conditions, can reduce rooftop surface temperatures by 1–3°C and lower indoor temperatures accordingly [10].

Several factors influence the effectiveness of shading. Tree species and morphology are crucial—broad-canopied trees offer larger shaded areas and are generally more effective than shrubs or ground cover. Planting density and layout patterns also play a role; while dense planting increases the continuity of shaded areas, excessive density may obstruct airflow. Additionally, the cooling benefit of shading is more pronounced on low-albedo surfaces such as asphalt and concrete. Lastly, solar angles and building orientation determine the extent and duration of shading throughout the day.

Empirical studies have validated the shading effect across various climates. Sánchez-Cordero et al. observed that green roofs in Granada reduced rooftop temperatures by 1–3°C, particularly in densely built neighborhoods [9]. The U.S. Environmental Protection Agency reported that shading from street trees could lower surrounding ground temperatures by up to 5°C, significantly improving pedestrian thermal comfort [10]. Moreover, modeling by Gill et al. indicated that increasing city-wide shade coverage by 10% could offset projected urban warming over the coming decades [11].

Urban greening initiatives should thus prioritize the selection and deployment of tree species with wide canopies, strong shading capacity, and resilience to local stressors. Street tree planting should align with road widths and solar exposure, avoiding overplanting that might hinder airflow. Green roofs should be promoted through policy incentives and standardized regulations to increase urban green coverage. In high-density areas, vertical greening and wall-mounted vegetation can help create multi-layered green shading networks with extended temporal and spatial coverage.

2.3 Albedo Enhancement Effect

Another contributing factor to the UHI effect is the widespread use of low-albedo materials in urban environments. Compared to natural surfaces, built surfaces such as asphalt and concrete absorb more solar radiation due to their low reflectivity, leading to increased heat storage and elevated surface temperatures. UGI helps mitigate this by introducing vegetation, which typically has higher shortwave albedo and thus reflects more solar energy, reducing net radiation absorption and heat accumulation.

Grasses, shrubs, and wetland vegetation, due to their lighter surface color and complex leaf structures, reflect a considerable portion of visible and near-infrared radiation. These green surfaces can reduce surface temperatures by 1–4°C during high-temperature periods, particularly from midday to early evening.

Green roofs not only provide evapotranspiration and shading benefits but also contribute to albedo enhancement. Field observations in semi-arid cities like Granada have shown that green roofs perform well in reflecting solar radiation in high insolation areas, effectively suppressing rooftop temperature peaks.

The albedo effect of UGI depends on several factors. First, plant species matter: light-colored broadleaf plants typically exhibit higher reflectivity due to their spectral properties. Second, vegetation density and LAI significantly affect surface reflectivity—higher coverage and layered vegetation structures enhance the overall albedo. Soil and substrate conditions beneath the vegetation also influence the system's reflective performance, with factors such as

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soil moisture, color, and material affecting the composite albedo. Finally, seasonal and climatic variations impact albedo dynamics; for instance, plant senescence during dry seasons can reduce reflectivity, underscoring the need for temporal maintenance strategies.

Numerous studies have affirmed the role of UGI in enhancing urban surface reflectivity. The introduction of light-colored plantings, vegetated paving, and green hedges can significantly increase surface albedo and reduce nighttime heat retention. In building applications, green roofs and high-albedo roof coatings may function complementarily—green roofs offering the combined benefits of evapotranspiration, shading, and reflectivity.

Urban planning should thus emphasize increasing surface reflectivity, particularly in heat-sensitive zones such as dense neighborhoods and transportation hubs. Vegetation selection should favor locally adapted species with high spectral reflectivity and stable performance across seasons. The co-implementation of green roofs and reflective coatings on buildings can maximize energy performance. Incorporating albedo parameters into surface material evaluation frameworks will facilitate the dual optimization of green space and energy efficiency.

3. Case Studies

3.1 Evapotranspiration Effects in Beijing's Urban Green Spaces

As one of China's most populous megacities, Beijing has witnessed a pronounced intensification of the urban heat island effect in recent years. Rapid expansion of built-up areas, combined with high population density, has exacerbated urban heat storage and surface temperature rise. Against this backdrop, public and diverse green spaces have become essential regulators for urban thermal mitigation[5].

Yan et al. using multi-source remote sensing data from Landsat 8 and SPOT 6, systematically evaluated the thermal regulation effects of 316 urban green spaces within Beijing's Fourth Ring Road[5]. They developed a comprehensive index system—including Land Surface Temperature (LST), Cooling Intensity (CI), Effective Range (ER), and Cooling Gradient (CG)—to quantify the cooling performance of green spaces. Their findings revealed that approximately 95% of the studied green spaces exhibited significant cooling effects during peak summer, with small-sized green patches (area < 9 hectares) in high-density urban areas achieving temperature reductions of 3–6°C. Evapotranspiration was identified as the primary driver of this effect. Multi-layered green spaces composed of trees, shrubs, and grasses showed greater cooling efficiency than monoculture lawn-type green spaces due to their higher leaf area index and diverse evapotranspiration layers.

The study also demonstrated that the cooling effect of green spaces is not solely determined by size but is influenced by vegetation structure, soil moisture, spatial configuration, and surrounding land-use features. Linear green spaces, such as strips along roads or elongated parks, performed better in sustaining cooling effects by combining evapotranspiration with enhanced ventilation functions.

This case provides empirical evidence that spatially diverse and finely distributed green spaces play a critical role in regulating urban microclimates. It further highlights the practical value of adopting spatial strategies such as "small but dense" and "scattered yet connected" in high-density urban contexts. Future urban planning should prioritize increasing the penetration and ecological connectivity of small-scale green spaces to sustain widespread and long-lasting evapotranspiration-driven cooling.

3.2 Ventilation-Driven Cooling via Green Space Layouts in Fuzhou

Fuzhou, located on the southeastern coast of China, is characterized by a typical subtropical humid climate. The city frequently experiences prolonged periods of high heat and humidity during summer. Coupled with its mountainous and riverine terrain, heat tends to be trapped in the urban core. Given the increasing intensity of UHI in Fuzhou, enhancing the spatial configuration of green infrastructure to improve ventilation and thermal dispersion has become a key strategy for local climate regulation [12].

Hong et al. conducted a comprehensive analysis in Fuzhou's central urban area using multi-source remote sensing data, including Landsat 8 OLI and Sentinel-2 MSI, along with in situ land surface temperature (LST) measurements [12]. They employed Geographically Weighted Regression (GWR) models to evaluate seasonal correlations between urban green space patterns and LST, with a particular focus on the spatial coupling between green infrastructure and dominant wind directions.

Results showed a stable negative correlation between Green Infrastructure Ratio (GIR) and surface temperatures, with the strongest effect observed in spring, when climatic conditions and vegetation vigor were most favorable. In contrast, cooling performance declined in autumn due to factors such as plant senescence, reduced moisture availability, and lower wind speeds. From a spatial perspective, connectivity and linearity of green spaces played pivotal roles in thermal regulation. Compared with isolated green patches, linear configurations such as riverside greenways and street green corridors significantly enhanced local airflow and cooling. These linear features helped establish ventilation corridors aligned with prevailing winds, effectively channeling cooler air into the urban core and facilitating heat dissipation.

Hong et al. further concluded that aligning green space distribution with urban wind patterns resulted in a stronger cooling synergy than simply expanding green coverage. Even in areas with similar green coverage, variations in green space shape and layout led to surface temperature differences of 2–3°C. This underscores that the cooling effectiveness of green infrastructure depends not just on its quantity, but also on how it is spatially distributed.

Based on these findings, the study proposed strategies to optimize urban green infrastructure layouts—for example, enhancing spatial connectivity by integrating linear greenbelts with core green nodes. Planners are encouraged to preserve and restore green zones within natural ventilation pathways and to coordinate riverside green spaces with major road-based green corridors to deliver dual ecological functions of cooling and ventilation. This study provides quantitative evidence for coupling green space morphology, ventilation, and temperature regulation in hot and humid cities, offering regionally adaptable guidance for urban climate-sensitive planning.

4. Conclusion

This study systematically examined three core mechanisms through which UGI mitigates the UHI effect: evapotranspiration, shading, and albedo enhancement. Findings show that these mechanisms work synergistically in urban environments, forming a composite regulatory system involving energy balance, radiation blocking, and cool air guidance. Evapotranspiration serves as the primary driver of cooling, shading significantly improves thermal comfort, and increased surface albedo effectively reduces net heat accumulation, particularly on rooftops and impervious surfaces.

The case studies further validated the theoretical mechanisms. In Beijing, small and distributed multi-layered green spaces within high-density built-up areas achieved substantial evapotranspiration-based cooling (3–6°C), with spatial connectivity influencing the extent and persistence of temperature reduction. In Fuzhou, green space layouts coordinated with prevailing wind directions outperformed mere green area expansion, producing temperature differences of 2–3°C due to improved air flow and heat dissipation.

The study emphasizes that the effectiveness of UGI in alleviating UHI depends not only on the quantity but also on the quality and spatial distribution patterns. Urban planning should adopt an integrated "function–structure–environment" perspective to optimize UGI configuration and enhance overall thermal regulation capacity.

In conclusion, UGI represents a nature-based solution with great potential for improving urban microclimates, enhancing resilience, and fostering livable cities. Future efforts should deepen the understanding and application of these mechanisms through policy, technical, and institutional pathways, facilitating the fine-scale deployment of UGI in dense urban areas and supporting multi-objective sustainable urban development.

References

[1] M. Santamouris, Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments, Sol. Energy 103 (2014) 682–703.

[2] D. Li, W. Liao, A.J. Rigden, X. Liu, D. Wang, S. Malyshev, E. Shevliakova, Urban heat island: Aerodynamics or imperviousness?, Sci. Adv. 6 (2020) eaaz3471.

[3] European Environment Agency, Urban green infrastructure: Connecting people and nature for sustainable cities, EEA Report, (2021).

[4] K.R. Gunawardena, M.J. Wells, T. Kershaw, Utilising green and blue space to mitigate urban heat island intensity, Sci. Total Environ. 584–585 (2017) 1040–1055.

[5] H. Yan, L. Dong, X. Zhang, L. Li, L. Yang, Characterizing the cooling effect of urban green spaces using remote sensing data in Beijing, Remote Sens. 13 (2021) 745.

[6] Z. Yuan, Modeling evapotranspiration-based cooling contribution in urban green spaces: A case from high-density districts, Urban Clim. 50 (2024) 101596.

[7] Forest Research, The cooling effects of urban green spaces, Forest Research UK, (2022).

[8] E. Jamei, P. Rajagopalan, M. Seyedmahmoudian, Y. Jamei, Review on the impact of urban geometry and pedestrian level greening on outdoor thermal comfort, Renew. Sustain. Energy Rev. 54 (2016) 1002–1017.

[9] S. Sánchez-Cordero, E. Gómez-Baggethun, D. Haase, Multifunctionality of urban green roofs: Impacts on microclimate and ecosystem services, Urban For. Urban Green. 81 (2025) 127939.

[10] U.S. Environmental Protection Agency (EPA), Using trees and vegetation to reduce heat islands, (2021).

[11] S.E. Gill, J.F. Handley, A.R. Ennos, S. Pauleit, Adapting cities for climate change: The role of the green infrastructure, Built Environ. 33 (2007) 115–133.

[12] Y. Hong, X. Li, J. Liu, Spatial coupling between green infrastructure and urban ventilation corridors: A case study of Fuzhou, China, Urban Clim. 46 (2023) 101338.