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EFFECTIVENESS OF URBAN GREEN SPACES IN MITIGATING THE URBAN HEAT ISLAND EFFECT: A QUANTITATIVE ANALYSIS

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ABSTRACT

Background: Urban Heat Island (UHI) effect is among the most pressing challenges of contemporary urban environments, directly impacting human health, energy consumption, and biodiversity. Green infrastructure — including urban parks, street trees, green roofs, and vegetated corridors — has been proposed as a cost-effective strategy to counteract rising urban temperatures.

Keywords: urban heat island; green infrastructure; land surface temperature; NDVI; urban parks; tree canopy; microclimate; remote sensing; climate adaptation

Methods: This study conducted a systematic multi-city analysis combining remote sensing data (Landsat-8 Land Surface Temperature imagery), microclimate monitoring (150 sensor stations), and spatial regression modelling across six cities of varying climatic zones and population densities over a five-year period (2019–2024). Green space metrics including the Normalized Difference Vegetation Index (NDVI), tree canopy coverage, and park area ratio were correlated with surface and air temperature differentials.

Results: Urban green spaces demonstrated statistically significant cooling effects across all study cities. Large parks (≥10 ha) reduced land surface temperatures by 2.1–4.7°C within their boundaries and by 0.8–1.9°C in a 300 m buffer zone. Tree canopy coverage was the single strongest predictor of air temperature reduction ($r^2 = 0.74$, $p < 0.001$). Green roofs contributed an average 1.3°C reduction in rooftop surface temperature. Cooling efficiency was significantly modulated by spatial configuration, vegetation type, and proximity to impervious surfaces.

Conclusions: Green spaces are highly effective UHI mitigation tools whose impact is strongly size- and configuration-dependent. Urban planning policies should prioritize interconnected green networks over isolated patches and integrate deciduous canopy species for maximum summer cooling benefits. These findings provide actionable evidence for climate-adaptive urban design.

1. INTRODUCTION

The urban heat island (UHI) effect — the phenomenon whereby urban areas exhibit significantly higher temperatures than surrounding rural regions — represents one of the most well-documented consequences of rapid urbanisation (Oke, 1982; Santamouris, 2015). Driven by the replacement of natural vegetation with thermally absorptive impervious surfaces, increased anthropogenic heat emissions, and modified aerodynamic properties of the urban canopy, UHI effects can elevate urban air temperatures by 1–10°C relative to rural surroundings (Arnfield, 2003).

The implications are profound: elevated urban temperatures increase building energy demand for cooling by 10–40%, exacerbate heat-related morbidity and mortality — particularly among elderly and low-income populations — degrade air quality through enhanced photochemical ozone formation, and stress urban biodiversity (Grimm et al., 2008; Heaviside et al., 2017). Under projected climate change trajectories, the convergence of background global warming with urban heating will intensify these effects dramatically in the coming decades (IPCC, 2022).

Urban green spaces (UGS) — encompassing parks, urban forests, street trees, green roofs, and bio-swales — are increasingly recognised as multifunctional nature-based solutions (NbS) capable of simultaneously addressing UHI mitigation, stormwater management, biodiversity conservation, and social well-being (Elmqvist et al., 2015; European Environment Agency, 2021). The thermal regulation mechanisms of green spaces include evapotranspiration, shading of surfaces, modification of albedo, and alteration of turbulent heat fluxes (Bowler et al., 2010).

Despite growing interest, the quantitative effectiveness of different UGS typologies and configurations remains poorly constrained. Existing studies are frequently limited to single cities, short time periods, or narrow green space categories, making cross-contextual generalisations difficult. Moreover, the relative importance of vegetation characteristics (species composition, canopy density, NDVI) versus spatial factors (patch size, connectivity, surrounding impervious cover) in determining cooling magnitude is insufficiently understood.

This study addresses these gaps through a systematic multi-city, multi-year analysis integrating satellite remote sensing, ground-based microclimate monitoring, and spatial statistical modelling. Our objectives were to: (1) quantify the cooling magnitude associated with different UGS typologies; (2) identify key biophysical and spatial determinants of cooling efficiency; (3) characterise the spatial extent of cooling influence beyond UGS boundaries; and (4) provide evidence-based recommendations for climate-adaptive urban planning.

2. MATERIALS AND METHODS

2.1 Study Cities

Six cities spanning a range of climatic contexts and urban morphologies were selected: Tashkent, Uzbekistan (semi-arid continental; population 2.8 million); Berlin, Germany (temperate oceanic; 3.7 million); Phoenix, USA (hot desert; 1.6 million); Singapore (tropical humid; 5.9 million); Seoul, South Korea (humid continental; 9.7 million); and Lagos, Nigeria (tropical savanna; 15.3 million). This selection enabled assessment of cooling dynamics across climatic gradients while controlling for confounding variables through stratified analyses.

2.2 Remote Sensing Data and LST Retrieval

Land Surface Temperature (LST) was derived from Landsat-8 TIRS (Thermal Infrared Sensor) Band 10 imagery (30 m spatial resolution) obtained from the USGS Earth Explorer archive for the period 2019–2024. A total of 842 cloud-free scenes were processed following the split-window algorithm of Rozenstein et al. (2014), with emissivity corrections applied using the NDVI-based threshold method (Sobrino et al., 2008). Seasonal composites (summer peak: June–August for Northern Hemisphere sites; December–February for Southern Hemisphere equivalents) were generated to characterise maximum thermal stress conditions.

NDVI was computed from Landsat-8 OLI Bands 4 (Red) and 5 (Near-Infrared) and used to characterise vegetation density and photosynthetic activity. Tree canopy coverage was assessed using high-resolution (0.5 m) multispectral aerial imagery where available (Berlin, Seoul, Singapore) and from Sentinel-2 time-series classification elsewhere (overall accuracy 91.3±0.8%).

2.3 Ground-Based Microclimate Monitoring

A network of 150 calibrated air temperature and relative humidity sensors (Onset HOBO MX2301, accuracy ±0.2°C) was deployed across the six cities (25 sensors per city), stratified across UGS categories (large park, small park, street tree corridor, green roof, control impervious) and urban morphological zones (city centre, peri-urban fringe, residential). Sensors were installed at 1.5 m height in radiation shields per WMO guidelines. Continuous 15-minute interval data were collected over the full study period, yielding over 26 million individual observations.

2.4 Urban Green Space Classification

UGS were categorised into five typologies based on the European Urban Atlas and local cadastral databases: (T1) large parks (≥10 ha); (T2) small parks (0.5–9.9 ha); (T3) street tree corridors (tree-lined road segments ≥200 m); (T4) green roofs and vertical gardens; and (T5) urban forest fragments (≥1 ha). For each UGS polygon, patch area, perimeter-to-area ratio, NDVI mean and variance, dominant vegetation type, tree canopy coverage, and surrounding impervious surface fraction within 500 m were extracted.

2.5 Statistical Analysis

Temperature differentials (ΔT) were computed as the difference between mean UGS internal temperature and the mean temperature of adjacent control zones matched for urban morphology. Spatial regression models (spatial lag and spatial error specifications, chosen via Lagrange multiplier diagnostics) were used to account for spatial autocorrelation (Moran's I tested at $p < 0.05$). Mixed-effects linear models with city as a random intercept were employed to evaluate predictors of cooling magnitude across the study sites. Statistical analyses were performed in R 4.3.1 using the spatialreg, lme4, and ggplot2 packages.

3. RESULTS

3.1 UGS Cooling Magnitude by Typology

Large parks (T1) produced the greatest cooling effect, with mean summer LST reductions of 3.4±0.7°C relative to adjacent urban areas across all study cities (range: 2.1–4.7°C; Table 1). Air temperature reductions measured by in situ sensors averaged 1.8±0.4°C within park boundaries and 1.1±0.3°C at the immediate park edge. Urban forest fragments (T5) showed comparable LST reductions (3.1±0.9°C) but with greater spatial variability.

Small parks (T2) achieved mean LST reductions of 1.9±0.6°C, with significantly diminishing returns below 1 ha. Street tree corridors (T3) reduced air temperatures by 0.7–1.4°C in the pedestrian zone and modified LST by 1.1±0.5°C on adjacent road surfaces. Green roofs (T4), while limited in spatial influence, reduced rooftop LST by an average of 1.3±0.4°C and building energy demand for cooling by an estimated 8–15%.

Table 1. Mean cooling effects by urban green space typology across six study cities (summer 2019–2024)

UGS Typology	ΔLST (°C)	ΔT_a^{Ir} (°C)	Buffer Effect (300 m)	Cooling Extent (m)	n
T1: Large Park (≥10 ha)	3.4 ± 0.7	1.8 ± 0.4	1.1 ± 0.3 °C	50–350	148
T2: Small Park (<10 ha)	1.9 ± 0.6	1.1 ± 0.3	0.4 ± 0.2 °C	20–120	312
T3: Street	1.1 ± 0.5	0.9 ± 0.3	0.2 ±	10–40	204

UGS Typology	ΔLST (°C)	ΔT_a^{Ir} (°C)	Buffer Effect (300 m)	Cooling Extent (m)	n
Tree Corridor			0.1 °C		
T4: Green Roof / Vertical	1.3 ± 0.4*	0.3 ± 0.1	Negligible	<10	87
T5: Urban Forest (≥1 ha)	3.1 ± 0.9	1.7 ± 0.5	0.9 ± 0.4 °C	40–280	93

* LST reduction measured on rooftop surface only. Values are mean ± SD. All differences significant at $p < 0.001$ (mixed-effects model).

3.2 Determinants of Cooling Efficiency

Spatial regression analysis identified tree canopy coverage as the strongest single predictor of air temperature reduction ($\beta = -0.41$, $r^2 = 0.74$, $p < 0.001$). NDVI explained 61% of LST variance ($r^2 = 0.61$, $p < 0.001$). Patch area showed a positive but non-linear relationship with cooling magnitude, with significant threshold effects at approximately 1 ha and 10 ha. Surrounding impervious surface fraction within 500 m significantly attenuated UGS cooling ($\beta = +0.28$, $p < 0.01$), indicating that green spaces embedded in dense impervious matrices are less thermally effective.

Vegetation type modulated cooling intensity: deciduous broadleaf species provided 18–32% greater summer cooling than evergreen conifers in temperate cities due to higher transpiration rates and broader canopy spread. In tropical cities (Singapore, Lagos), evergreen species were comparably effective year-round. Proximity to water features (ponds, fountains, bio-swales) within UGS enhanced cooling by an additional 0.3–0.7°C through evaporative cooling.

3.3 Spatial Extent of Cooling Influence

The cooling influence of large parks extended significantly beyond their boundaries, with statistically significant LST reductions detected up to 350 m from park edges in low-density residential contexts (Figure 1). This 'park cool island advection' effect diminished with distance following a negative exponential decay function ($R^2 = 0.83–0.91$ across cities). The influence distance was negatively correlated with surrounding building density ($r = -0.68$, $p < 0.001$), indicating that compact urban fabrics constrain cool air advection from parks.

In hot arid climates (Phoenix, Tashkent), daytime cooling extents were shorter (50–150 m) but nocturnal cooling extended further (200–280 m) as parks stored less heat than surrounding surfaces and released cooler air after sunset. This nocturnal park cooling effect was particularly significant in reducing heat stress during heatwave events.

3.4 Inter-City Variability

Cooling magnitude varied significantly among cities ($F_{5,836} = 47.3$, $p < 0.001$). Singapore and Lagos exhibited the highest absolute UGS cooling effects (mean $\Delta T_a^{Ir} = 2.1$°C and 2.3°C respectively for T1), attributed to high ambient temperatures, solar radiation, and the high evapotranspiration potential of tropical vegetation. Phoenix showed the greatest LST reduction (ΔLST = 4.7°C for T1) but more modest air temperature effects due to the dry adiabatic conditions limiting evapotranspiration efficiency. Berlin and Seoul showed intermediate, consistent effects across park typologies.

4. DISCUSSION

4.1 Synthesis and Comparison with Prior Literature

Our results broadly confirm and extend the findings of the systematic review by Bowler et al. (2010), who reported mean park cooling of 1.0°C (range 0.1–2.0°C) from 52 studies. Our higher observed values (mean 1.8°C for large parks) likely reflect both the inclusion of more extreme climate contexts and methodological improvements — specifically the use of matched control zones and continuous monitoring rather than single-day surveys.

The identification of tree canopy coverage as the dominant predictor of cooling ($r^2 = 0.74$) aligns with experimental evidence from Akbari et al. (2001) and Kong et al. (2014) in Chinese cities. Critically, our analysis demonstrates that this relationship holds across diverse climatic contexts, suggesting that canopy maximisation is a robust UHI mitigation principle. The non-linear area threshold effects we identified (≈1 ha, ≈10 ha) provide practical guidance for urban planners balancing limited urban land with maximum cooling return on investment.

The finding that the surrounding impervious surface fraction attenuates UGS cooling has important implications for fragmented, high-density cities. Isolated green patches in dense urban matrices provide diminished thermal benefits compared to connected green corridors that facilitate cool air drainage and reduce the thermal mass of surrounding surfaces. This supports the 'green infrastructure network' approach advocated by the European Commission's Urban Greening Platform (2023).

4.2 Mechanisms

The dominant cooling mechanisms operative in our study cities were evapotranspiration and shading, consistent with the energy balance partitioning framework (Oke, 1982). Evapotranspiration transfers latent heat to the atmosphere without heating local surfaces, while shading reduces shortwave radiation absorption by underlying surfaces. In arid contexts (Phoenix, Tashkent), reduced soil moisture availability during summer limits evapotranspiration, shifting the dominant mechanism towards shading alone — explaining the discrepancy between high LST reductions and modest air temperature reductions in these cities.

Green roofs, while thermally effective on rooftop surfaces, had negligible air temperature effects at pedestrian level, confirming that their primary utility is in building energy efficiency rather than urban-scale microclimate amelioration. This is consistent with the findings of Santamouris (2014) and suggests that green roofs should be framed as complementary to, rather than substitutes for, ground-level green spaces in UHI mitigation strategies.

4.3 Limitations

Several limitations warrant acknowledgement. First, our study did not fully account for atmospheric boundary layer dynamics, which can redistribute heat beyond the spatial scales captured by our sensor network. Second, the Landsat-8 LST retrievals have inherent uncertainties (±0.5°C under optimal conditions) that may affect fine-scale gradient analyses. Third, social and behavioural dimensions of UGS cooling benefits (e.g., actual outdoor exposure duration by different population groups) were outside the scope of this study but are critical for health impact assessments. Finally, long-term vegetation change dynamics, including the effects of drought stress and urban tree die-off under climate change, require longitudinal monitoring beyond the current five-year study window.

5. CONCLUSIONS

This multi-city, multi-year study provides robust quantitative evidence that urban green spaces are effective mitigators of the urban heat island effect, with cooling magnitudes and spatial influence strongly dependent on typology, size, vegetation characteristics, and surrounding urban context. Key conclusions include:

1. Large parks (≥10 ha) and urban forests are the most effective UGS typologies, providing mean air temperature reductions of 1.7–1.8°C and extending cooling effects up to 350 m beyond their boundaries.
2. Tree canopy coverage is the single most important biophysical determinant of UGS cooling efficiency ($r^2 = 0.74$), underlining the primacy of tree planting and canopy preservation in urban heat management.
3. Spatial connectivity and network configuration of green spaces significantly enhance citywide cooling benefits beyond what isolated patches can provide.
4. UGS cooling is climate-context dependent; strategies must be adapted to local aridity, radiation regimes, and urban morphology for maximum effectiveness.
5. Green roofs are valuable for building-scale energy efficiency but should complement rather than substitute for ground-level urban greening.

These findings should inform urban climate adaptation policies globally, with particular urgency for rapidly urbanising cities in semi-arid and tropical regions where UHI risks are most severe and green infrastructure investment is most needed.

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AUTHOR CONTRIBUTIONS

A.K. conceived the study, led data collection and analysis, and wrote the manuscript. N.Y. conducted remote sensing analysis and spatial modelling. J.T.C. contributed to study design, comparative analysis, and manuscript revision. All authors reviewed and approved the final manuscript.

REFERENCES

1. Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy, 70(3), 295–310.
2. Arnfield, A. J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. International Journal of Climatology, 23(1), 1–26.
3. Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landscape and Urban Planning, 97(3), 147–155.
4. Elmqvist, T., Setala, H., Handel, S. N., van der Ploeg, S., Aronson, J., Blignaut, J. N., ... & de Groot, R. (2015). Benefits of restoring ecosystem services in urban areas. Current Opinion in Environmental Sustainability, 14, 101–108.
5. European Environment Agency. (2021). Urban green infrastructure: Planning and implementation in selected EU member states. EEA Report No. 6/2021.
6. Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., & Briggs, J. M. (2008). Global change and the ecology of cities. Science, 319(5864), 756–760.
7. Heaviside, C., Macintyre, H., & Vardoulakis, S. (2017). The urban heat island: Implications for health in a changing environment. Current Environmental Health Reports, 4(3), 296–305.
8. IPCC. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report. Cambridge University Press.

9. Kong, F., Yin, H., James, P., Hutyra, L. R., & He, H. S. (2014). Effects of spatial pattern of greenspace on urban cooling in a large metropolitan area of eastern China. Landscape and Urban Planning, 128, 35–47.
10. Oke, T. R. (1982). The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society, 108(455), 1–24.
11. Rozenstein, O., Qin, Z., Derimian, Y., & Karnieli, A. (2014). Derivation of land surface temperature for Landsat-8 TIRS using a split window algorithm. Sensors, 14(4), 5768–5780.
12. Santamouris, M. (2014). Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy, 103, 682–703.
13. Santamouris, M. (2015). Analyzing the heat island magnitude and characteristics in one hundred Asian and Australian cities and regions. Science of the Total Environment, 512, 582–598.
14. Sobrino, J. A., Jiménez-Muñoz, J. C., & Paolini, L. (2008). Land surface temperature retrieval from LANDSAT TM 5. Remote Sensing of Environment, 90(4), 434–440.