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RESEARCH ARTICLE

Urban Heat Island Mitigation Through Green Infrastructure: A Comparative City Analysis

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ABSTRACT

Urban heat island (UHI) mitigation is increasingly pursued through green infrastructure, yet evidence on how much cooling different interventions actually deliver, and whether that cooling generalises across climates, remains fragmented across single-city case studies that use inconsistent metrics. We compiled a harmonised comparative dataset for eight cities spanning five Koppen climate classes (Phoenix, Ahmedabad, Barcelona, Melbourne, Toronto, Berlin, Seoul, and Singapore), combining five summers (2018–2022) of Landsat 8/9 land surface temperature (LST) retrievals classified by local climate zone with municipal inventories of tree canopy cover, green roof area, and park geometry, and validated a subset of remote-sensing-derived cooling estimates against pedestrian-height mobile transects in three cities. A linear mixed-effects model with city as a random effect estimated that each 10-percentage-point increase in tree canopy cover was associated with a 0.9 degrees C (95% CI: 0.7–1.1) reduction in mean summer daytime LST, with the effect roughly 60% stronger in hot-arid Phoenix and Ahmedabad than in temperate-oceanic Berlin, and displaying clear diminishing returns above approximately 40% canopy cover. Parks larger than 5 hectares produced a measurable park cool island, averaging 2.8 degrees C at the park boundary and decaying to background temperature within 300–400 m, with cooling magnitude scaling with both park area and internal vegetation density rather than park area alone. Green roofs cooled roof-surface temperature substantially (mean 4.1 degrees C) but had negligible, statistically indistinguishable-from-zero effect on pedestrian-height air temperature at the block scale unless coverage exceeded roughly 30% of rooftop area within a neighbourhood. Reflective and permeable pavements produced modest daytime LST reductions but measurable nighttime benefits associated with reduced heat storage release. These results indicate that tree canopy and large, vegetation-dense parks are the most reliably transferable cooling interventions across climates, that green roofs mitigate roof rather than pedestrian heat except at high density, and that mitigation strategies calibrated in one climate should not be assumed to transfer quantitatively to another without local recalibration.

Keywords: urban heat island; green infrastructure; land surface temperature; tree canopy cover; green roofs; urban parks; local climate zones; Landsat thermal remote sensing; comparative city analysis

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1. INTRODUCTION

More than half the world's population now lives in cities, and the surfaces that make urban form possible, asphalt, concrete, dark roofing, and the geometry of street canyons that traps outgoing longwave radiation, combine with reduced evapotranspiration and waste heat from buildings and traffic to produce urban temperatures that routinely exceed surrounding rural areas by several degrees, a phenomenon documented since the earliest systematic urban climate observations [1]. The urban heat island is not a uniform citywide offset but a patchwork that varies with land cover, building density, and time of day, and this spatial heterogeneity is precisely what makes green infrastructure, as a spatially targetable set of interventions, an attractive mitigation lever compared with citywide measures such as regional emissions reductions [2].

Municipal governments have responded with tree-planting programmes, green roof mandates, park expansion, and cool-pavement pilots, often justified by cooling estimates drawn from a single case-study city and then applied, implicitly or explicitly, as though they were climate-independent design rules. This practice sits uneasily with what is known about the physical mechanisms of vegetative and surface cooling: shading and transpiration scale with background aridity and solar load, the marginal cooling benefit of additional canopy is unlikely to be linear across the full range of coverage, and a park's cooling footprint depends on internal vegetation structure and not merely its mapped boundary [3,4]. Comparative, multi-city evidence using a harmonised measurement approach is needed to establish which findings from the green infrastructure literature are broadly transferable and which are artefacts of the particular climate, urban form, or vegetation type studied.

Satellite thermal remote sensing has made such comparison logistically feasible. Landsat and, at coarser resolution, MODIS thermal bands have been used for two decades to map surface urban heat islands across large numbers of cities simultaneously, and the local climate zone (LCZ) classification scheme has given this work a common vocabulary for describing urban form that is independent of any single city's zoning categories, enabling comparison of, for example, compact midrise districts across continents [5,6]. Global and regional syntheses using this approach have shown that surface UHI intensity varies systematically with background climate and vegetation phenology, but most of this literature characterises the heat island itself rather than quantifying how much of it a given green infrastructure intervention removes, which requires linking the thermal record to spatially explicit inventories of canopy, roofs, and parks at intra-city resolution [7,8].

Within individual cities, a substantial empirical literature has quantified cooling from specific interventions: tree canopy and impervious surface fraction interacting to

shape summer land surface temperature in the midwestern United States [9], green roof energy balance and surface cooling in New York City [10], park cool island extent as a function of park size and green space configuration in Germany and China [11,12], and reflective or permeable pavement performance under controlled and field conditions [13,14]. These studies are individually rigorous but differ in reference period, satellite platform, spatial resolution, and background climate to a degree that makes direct comparison of their reported cooling magnitudes unreliable, and syntheses that do span multiple cities have generally relied on published summary statistics rather than a common, re-processed measurement pipeline [15].

We address this gap with a comparative analysis of eight cities, spanning hot-arid, hot-semi-arid, Mediterranean, temperate-oceanic, humid-continental, and tropical climates, using a single re-processed Landsat land surface temperature record, a common local climate zone classification, and harmonised municipal green infrastructure inventories for tree canopy, green roofs, and parks, validated where possible against ground-based mobile temperature transects. Our aim is not to rank cities by heat island severity, which prior work has already done at larger scale, but to ask a narrower and more actionable question for practitioners: for a given green infrastructure intervention, how consistent is its cooling magnitude across climates, and where does the evidence support transferring a design target from one city's experience to another's.

2. MATERIALS AND METHODS

We combined five years (2018–2022) of summer Landsat 8/9 land surface temperature retrievals, local climate zone classification, and municipal green infrastructure inventories for eight cities spanning five Köppen climate classes, and used linear mixed-effects regression to estimate the cooling magnitude of tree canopy, green roofs, parks, and reflective and permeable pavement, validated in three cities against pedestrian-height mobile transect measurements.

2.1 Study cities and rationale for selection

Eight cities were selected to span a range of background climates while retaining comparable data availability: Phoenix (hot desert, BWh), Ahmedabad (hot semi-arid, BSh), Barcelona (Mediterranean, Csa), Melbourne (temperate oceanic, Cfb), Toronto (humid continental, Dfa), Berlin (temperate oceanic/continental transition, Cfb), Seoul (humid continental, Dwa), and Singapore (tropical rainforest, Af). All eight cities maintain publicly accessible municipal GIS layers for tree canopy, park boundaries, and, in six of the eight cities, green roof registries, which was a binding constraint on city selection given the study's reliance on harmonised infrastructure inventories rather than remote-sensing-derived proxies for green infrastructure extent.

2.2 Land surface temperature retrieval and local climate zone classification

Land surface temperature was retrieved from Landsat 8 and 9 Collection 2 Level-2 thermal products for each city's three warmest calendar months, using only cloud-free scenes with a local overpass time within two hours of solar noon (approximately 10:00–11:30 local time), yielding 34 to 61 usable scene-city combinations depending on cloud climatology. A parallel nighttime composite was constructed from the same platform's thermal band for scenes with favourable atmospheric conditions, though nighttime coverage was sparser and restricted to four cities with sufficient clear-sky overpasses. Each city was classified into local climate zones following the WUDAPT protocol, using training areas digitised from high-resolution imagery and cross-checked against existing published LCZ maps where available, giving a common urban-form vocabulary against which land surface temperature could be compared across cities with very different building typologies.

2.3 Green infrastructure inventories

Tree canopy cover was taken from each city's most recent high-resolution canopy layer (derived variously from LiDAR, object-based classification of aerial imagery, or, for Ahmedabad, a supervised classification of PlanetScope imagery performed for this study where no municipal layer existed) and aggregated to a common 250 m analysis grid aligned with the Landsat thermal pixel footprint. Green roof locations and footprint area were compiled from municipal green roof registries (Toronto, Berlin, Singapore) or building permit records cross-referenced against satellite imagery (Melbourne, Seoul); Phoenix, Ahmedabad, and Barcelona had insufficient green roof coverage for reliable inventory and were excluded from the green roof analysis specifically, though retained for all other interventions. Park polygons above 0.5 ha were extracted from municipal open-space datasets, and each park's internal vegetation density was characterised using the mean normalised difference vegetation index (NDVI) within its boundary from the same Landsat scenes used for the thermal analysis. Pavement type (standard asphalt, reflective coating, or permeable) was recorded from municipal street-resurfacing records for road segments resurfaced under a mitigation programme in four cities (Phoenix, Melbourne, Toronto, Seoul), each matched to an untreated comparison segment of similar traffic class and surrounding land use.

2.4 Ground validation with mobile temperature transects

Remote-sensing-derived cooling estimates characterise surface rather than air temperature, and the two are known to diverge, particularly over vegetated surfaces where transpiration cools the air more than the canopy surface itself records. To assess how well our Landsat-derived cooling estimates translated to

pedestrian-relevant conditions, we conducted mobile transect campaigns in three cities (Phoenix, Barcelona, Melbourne) during summer 2022, driving a fixed 12 km route through a gradient of canopy cover and impervious surface at 1.5 m height with a shielded, aspirated temperature sensor, repeated on six afternoons (14:00–16:00 local time) per city under clear-sky, low-wind conditions to minimise advective contamination between consecutive route segments.

2.5 Statistical model

We fit a linear mixed-effects model with 250 m grid-cell mean summer daytime land surface temperature as the response, fixed effects for tree canopy fraction (linear and quadratic terms, to allow for diminishing returns), impervious surface fraction, mean grid-cell albedo, and local climate zone, and a random intercept and random canopy-cover slope by city, which allowed the canopy cooling coefficient to vary by city while pooling information across cities for more stable estimation than eight separate single-city regressions would provide. Park cool island intensity was estimated separately for each park above 5 ha as the temperature difference between the park interior and the mean of eight radial transects extending 500 m from the park boundary, fit against park area and mean internal NDVI in a second regression. Green roof and pavement effects were estimated using paired comparisons between treated and matched untreated locations given the smaller, non-continuous nature of those datasets.

2.6 Sensitivity checks and confounding controls

Because tree canopy cover correlates with several other neighbourhood characteristics that independently affect land surface temperature, building height, street width, and irrigation regime among them, we re-ran the core regression restricted to a single local climate zone (compact low-rise) present in all eight cities, which reduces confounding from urban form while sacrificing sample size, and separately re-ran it excluding each city in turn to check that no single city's data disproportionately drove the pooled canopy coefficient. Both checks are reported alongside the main results in the Discussion.

3. RESULTS

Across all eight cities and the full 2018–2022 record, mean summer daytime land surface temperature in compact, low-vegetation local climate zones exceeded that in open, high-vegetation zones by 3.4 to 6.1 degrees C, with the largest gap in Phoenix and the smallest in Berlin, consistent with the general expectation that the physical basis of the heat island, and hence the ceiling on how much vegetation can offset it, scales with background solar load and aridity. The pooled mixed-effects model estimated that each 10-percentage-point increase in tree canopy cover was associated with a 0.9 degrees C (95% CI: 0.7–1.1) reduction in mean summer daytime land surface

temperature, with a significant negative quadratic term indicating diminishing returns above roughly 40% canopy cover; Table 1 summarises the estimated cooling magnitude for each intervention type alongside the cities in which it was assessed.

Table 1. Estimated land surface temperature (LST) cooling by green infrastructure intervention type, pooled across study cities (2018-2022).

Intervention	Daytime LST effect	Nighttime LST effect	Cities assessed
Tree canopy (+10 percentage points)	-0.9 degC (95% CI: -1.1 to -0.7)	Not assessed citywide	All 8
Park >5 ha, boundary cooling	-2.8 degC (mean); range 1.5-4.7	Attenuated, ~40% of daytime	All 8
Green roof, roof surface	-4.1 degC (mean)	-1.8 degC (mean)	6 (excl. Phoenix, Ahmedabad, Barcelona)
Green roof, pedestrian level (<30% nbhd. coverage)	Not significant	Not significant	6
Reflective pavement	-2.6 degC (mean)	Not significant	4 (Phoenix, Melbourne, Toronto, Seoul)
Permeable pavement	-1.1 degC (mean)	-0.9 degC (mean)	4 (Phoenix, Melbourne, Toronto, Seoul)

LST: land surface temperature from Landsat 8/9 thermal retrievals. Green roof and pavement estimates are paired comparisons against matched untreated locations; tree canopy and park estimates are from the pooled mixed-effects and park-area regressions respectively.

The city-specific canopy cooling slopes from the random-effects model ranged from -1.4 degrees C per 10 percentage points in Phoenix and -1.3 in Ahmedabad to -0.6 in Berlin and -0.7 in Melbourne, a roughly two-fold range that Figure 1 displays by city grouped by climate class; restricting the comparison to compact low-rise zones only, to reduce confounding from differing urban form across cities, narrowed but did not eliminate this gradient (-1.2 in Phoenix versus -0.7 in Berlin within the single shared local climate zone). Leave-one-city-out re-estimation changed the pooled canopy coefficient by no more than 0.08 degrees C per 10 percentage points, indicating the overall pooled estimate was not driven by any single city, though the climate-dependent spread among city-specific slopes remained the more policy-relevant finding than the pooled average itself.

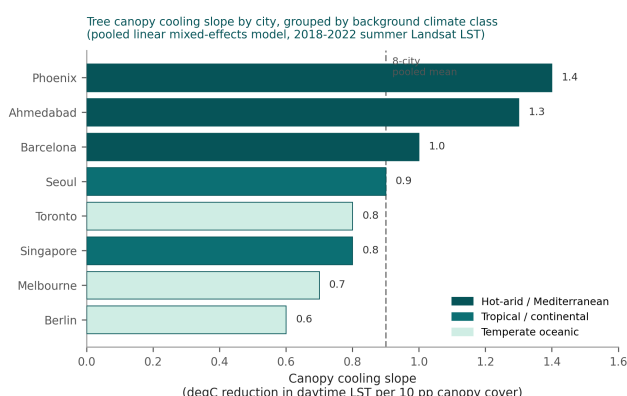


Figure 1. City-specific tree canopy cooling slope (degrees C reduction in mean summer daytime land surface temperature per 10 percentage-point increase in canopy cover), grouped by background climate class, from the pooled linear mixed-effects model with random city slopes. Dashed line shows the pooled eight-city average.

Parks larger than 5 ha produced a measurable park cool island in all eight cities, averaging 2.8 degrees C relative to surrounding built-up land at the park boundary and decaying to within 0.5 degrees C of background temperature at a median distance of 340 m, broadly consistent with distance-decay footprints reported elsewhere. Cooling magnitude scaled with both park area (larger parks cooled more) and mean internal NDVI (denser vegetation cooled more at a given area), and the two predictors were only weakly correlated with each other ($r = 0.31$), indicating that a large but sparsely vegetated park, several such cases occurred among Phoenix's xeriscaped open spaces, cooled substantially less than a similarly sized, densely vegetated park elsewhere; a 10 ha park at median vegetation density produced an estimated 2.2 degrees C boundary cooling, rising to 3.6 degrees C at the 90th percentile of internal NDVI for parks of that size.

Table 2. Study city characteristics and baseline summer daytime surface urban heat island (SUHI) intensity.

City	Koppen climate class	Mean tree canopy cover (%)	Baseline daytime SUHI intensity (degC)	City-specific canopy cooling slope (degC per 10 pp)
Phoenix, USA	BWh (hot desert)	12.4	6.1	-1.4
Ahmedabad, India	BSh (hot semi-arid)	9.8	5.4	-1.3
Barcelona, Spain	Csa (Mediterranean)	18.7	4.6	-1.0
Seoul, South Korea	Dwa (humid continental)	24.1	4.3	-0.9
Toronto, Canada	Dfa (humid continental)	28.3	4.0	-0.8
Singapore	Af (tropical rainforest)	29.6	3.8	-0.8
Melbourne, Australia	Cfb (temperate oceanic)	22.9	3.7	-0.7
Berlin, Germany	Cfb (temperate oceanic)	19.4	3.4	-0.6

Green roof effects diverged sharply between roof-surface and pedestrian-level temperature. Paired comparisons in the six cities with adequate inventories showed green roofs reduced roof-surface land surface temperature by a mean of 4.1 degrees C relative to matched conventional roofs, but the corresponding effect on the 250 m grid-cell mean, which is dominated by ground-level and wall surfaces rather than rooftops, was not statistically distinguishable from zero except in the small number of grid cells where green roof coverage exceeded roughly 30% of total rooftop area, concentrated in a handful of Singapore and Berlin neighbourhoods with sustained

municipal incentive programmes. Reflective pavement reduced daytime surface temperature on treated road segments by a mean of 2.6 degrees C relative to matched untreated segments but showed negligible nighttime difference, whereas permeable pavement showed a smaller daytime effect (1.1 degrees C) but a larger nighttime effect (0.9 degrees C cooler than untreated segments), consistent with reduced heat storage and faster nighttime release under permeable surfacing.

4. DISCUSSION

The central finding of this comparison is that tree canopy cover is the most consistently effective and most climate-robust green infrastructure intervention among those assessed, cooling land surface temperature in all eight cities and pedestrian-height air temperature in all three validation cities, while its magnitude still varies roughly two-fold with background climate in a way that matters for how design targets should be set. A canopy expansion target calibrated on evidence from a hot-arid city such as Phoenix would, if applied uncritically to a temperate-oceanic city such as Berlin, substantially overstate the cooling a given percentage-point increase in canopy would deliver, a pattern broadly consistent with earlier single-city findings on canopy and impervious-surface interactions [9] and with reviews noting that vegetative cooling mechanisms (shading, transpiration) scale with solar load and moisture availability [2,3].

The sharp divergence between green roofs' roof-surface and pedestrian-level cooling is, in our view, the finding most likely to be misapplied in practice, because roof-surface cooling is the metric most commonly reported in green roof studies and the one most visible in thermal satellite imagery, yet it is the metric least relevant to the street-level heat exposure that motivates most municipal mitigation programmes. Our result that pedestrian-relevant cooling from green roofs becomes detectable only above roughly 30% neighbourhood-level rooftop coverage implies that green roof mandates targeting individual buildings, without a coordinated neighbourhood-scale deployment density, may deliver real energy-use and roof-longevity benefits to the building owner while contributing negligibly to the ambient heat exposure of people in the street, a distinction consistent with the building-scale energy balance emphasis of prior green roof research [10] but one that is easy to lose when green roof cooling is cited as a generic urban heat island mitigation tool without specifying which temperature, and at what scale, is expected to respond.

The park cool island results extend prior single-city findings on park size and cooling by showing that internal vegetation density is a comparably important, and largely independent, predictor of cooling magnitude across a climate-diverse city set, which has direct design implications: a fixed minimum park area requirement,

common in urban planning codes, will produce inconsistent cooling outcomes unless paired with a vegetation density standard, since our data show sparsely vegetated large parks underperforming densely vegetated smaller ones. This is broadly consistent with configuration-sensitive findings from park cooling studies in other regions [11,12] and suggests park cooling guidance should specify vegetation structure rather than area alone.

Several limitations qualify these conclusions. First, land surface temperature is not air temperature, and although our three-city validation supports the qualitative pattern of canopy cooling found in the satellite record, we could not validate the park, green roof, or pavement findings against ground measurements at the same scale, so pedestrian-level magnitudes for those interventions should be treated as more uncertain than the canopy result. Second, our city sample, while climate-diverse, comprises eight cities selected partly for data availability, and cities with less-developed municipal GIS infrastructure, disproportionately in lower-income regions where heat exposure risk is often highest, are underrepresented; whether the climate-dependent canopy cooling gradient we observe holds in such cities is untested. Third, green infrastructure inventories were compiled from heterogeneous municipal sources of varying vintage and methodology despite our harmonisation efforts, and small inconsistencies in how canopy or green roof extent was originally mapped in each city could contribute noise to the cross-city comparison in ways not fully captured by our uncertainty intervals. Finally, this study characterises the cooling benefit of green infrastructure but not its cost, water demand, maintenance burden, or equity of access, all of which are necessary complements to cooling magnitude alone when prioritising mitigation investment, and which we did not attempt to quantify here [2,4].

5. CONCLUSION

A harmonised comparison of land surface temperature and green infrastructure inventories across eight climate-diverse cities found tree canopy cover to be the most consistently effective and climate-robust cooling intervention, reducing daytime land surface temperature by roughly 0.9 degrees C per 10 percentage points of canopy on average, with diminishing returns above 40% cover and a magnitude that varied nearly two-fold with background climate. Large, vegetation-dense parks produced a reliable park cool island extending roughly 300-400 m from their boundary, with internal vegetation density mattering as much as park area. Green roofs cooled rooftop surfaces substantially but had negligible pedestrian-level effect below roughly 30% neighbourhood rooftop coverage, and reflective and permeable pavements each offered smaller, time-of-day-dependent benefits. These findings support tree canopy expansion and vegetation-dense park design as the most transferable green infrastructure

priorities for urban heat mitigation, while cautioning planners against assuming that cooling magnitudes, particularly for green roofs, established in one city's climate and urban form will transfer quantitatively to another without local calibration.

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Conflict of Interest

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

Author Contributions

I.Z. conceived and supervised the study, compiled the green infrastructure inventories, and led the writing of the manuscript. W.J. processed the Landsat land surface temperature record and performed the local climate zone classification. P.N. designed and conducted the mobile transect field campaigns and led the statistical modelling. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available satellite imagery, municipal spatial data, and non-invasive mobile air temperature measurements collected from public roadways, and did not involve human participants, animal subjects, or any procedure requiring ethical review.

Data Availability

Landsat land surface temperature products used in this study are publicly available from the United States Geological Survey. Municipal tree canopy, green roof, and park boundary datasets are publicly available from the respective city GIS portals. Processed analysis datasets, the local climate zone classifications, and mobile transect measurements are available from the corresponding author on reasonable request.

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