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Dr. Zhang Wei
School of Environmental Science and Engineering, Tsinghua University, Beijing, China

Dr. Liu Fang
College of Urban and Environmental Sciences, Peking University, Beijing, China

Corresponding Author:
Dr. Zhang Wei
School of Environmental Science and Engineering, Tsinghua University, Beijing, China

The role of urban green roof systems in mitigating heat island effects: A case study approach

Zhang Wei and Liu Fang

Abstract
The increasing intensity of the Urban Heat Island (UHI) effect poses a critical environmental challenge for rapidly urbanizing regions worldwide. This study investigates the role of urban green roof systems in mitigating urban thermal stress through a comprehensive case study approach that integrates field experimentation with microclimatic modeling. Two comparable mid-rise commercial buildings one equipped with an extensive green roof and another with a conventional concrete roof were monitored over a six-month summer period to assess variations in surface and ambient air temperatures, substrate conditions, and energy flux parameters. Empirical data revealed that the green roof significantly reduced mean surface temperature by approximately 3.1 °C and ambient air temperature by 0.6 °C compared to the control roof, confirming its measurable contribution to UHI mitigation. Statistical analyses, including paired t-tests and linear regressions, validated the observed temperature differentials (p<0.001) and identified substrate depth and soil moisture as major determinants of cooling performance. The results from ENVI-met simulations further demonstrated that cooling effects extended beyond the rooftop, reducing near-surface urban canopy temperatures within a 200 m radius. These findings align with global evidence supporting vegetated roofs as a sustainable, low-energy, and climate-adaptive strategy for urban environments. The study concludes that optimized green roof design emphasizing appropriate substrate depth, moisture retention, and vegetation selection—can serve as a highly effective tool for urban climate resilience. Practical recommendations include integrating green roof systems into urban development policies, promoting incentive-based adoption, and ensuring periodic maintenance to sustain long-term performance. Overall, this research highlights the multifaceted value of green roofs in promoting thermal comfort, improving air quality, conserving energy, and fostering ecological sustainability within modern cities.

Keywords: Urban heat island, green roof systems, urban microclimate, thermal performance, evapotranspiration, substrate moisture, sustainable urban design, case study, heat mitigation, climate resilience

Introduction

Rapid urbanization has significantly intensified the Urban Heat Island (UHI) effect, where dense built environments absorb and retain more heat than surrounding rural landscapes. This phenomenon increases urban air temperatures, degrades air quality, and elevates energy consumption for cooling, thereby contributing to adverse health and environmental outcomes [1, 2]. Among various mitigation strategies, green roof systems vegetated layers installed atop buildings have emerged as an effective, nature-based solution that combines ecological, thermal, and hydrological benefits [3, 4]. Green roofs mitigate surface temperatures through shading, evapotranspiration, and enhanced thermal insulation, simultaneously improving microclimate comfort and reducing building energy loads [5, 6]. Empirical studies in Tokyo, Chicago, and Singapore revealed surface temperature reductions of 20-30 °C compared with conventional roofs under peak summer conditions [7-9]. Furthermore, large-scale simulation analyses suggest that widespread green roof implementation could decrease average urban air temperatures by up to 3 °C, depending on vegetation type, substrate depth, and irrigation frequency [10, 11].

Despite these advantages, spatial variability in green roof performance remains a critical issue. Factors such as plant species composition, substrate depth, moisture content, and local climatic conditions influence the cooling potential and long-term sustainability of such systems [12-14]. Moreover, existing research often emphasizes temperate climates, leaving tropical and subtropical urban contexts underrepresented in quantitative evaluations [15]. This case study-based investigation, therefore, aims to bridge that research gap by empirically quantifying the cooling performance of extensive and intensive green roof systems in a real urban setting.

The problem statement underpinning this work is the limited empirical evidence connecting green roof configurations with measurable UHI mitigation outcomes in diverse climates. The objectives are: (i) to evaluate the temperature differential between vegetated and non-vegetated rooftops; (ii) to assess the influence of substrate depth and vegetation type on heat flux reduction; and (iii) to model the spatial propagation of temperature moderation within the surrounding urban canopy. The hypothesis tested is that optimally designed green roofs, when maintained under adequate irrigation regimes, will reduce rooftop surface temperatures by ≥ 2 °C and ambient air temperatures by ≥ 0.5 °C relative to conventional roofs, thereby contributing measurably to UHI reduction in the case study area.

Material and Methods

Materials

The present study was conducted within a densely built urban zone characterized by high impervious surface coverage and limited vegetation canopy. The selected case study site consisted of two comparable mid-rise commercial buildings (each approximately 800 m² roof area) located within a mixed-use urban precinct. One building was retrofitted with an extensive green roof system, while the adjacent building served as a control with a conventional reinforced concrete roof. The green roof assembly comprised four functional layers: a waterproofing membrane, root barrier, lightweight drainage mat, and a 10 cm engineered substrate blend of pumice, compost, and cocopeat, consistent with recommendations from previous experimental frameworks [3, 7, 9]. Vegetation was selected from locally adapted drought-tolerant species—Sedum spurium, Portulaca grandiflora, and Cynodon dactylon—known for high evapotranspiration rates and minimal maintenance requirements under subtropical climatic conditions [5, 12, 14].

Instrumentation included precision-grade thermocouples (± 0.1 °C), soil moisture sensors, and pyranometers installed at uniform grid points across both roofs. Ambient air temperature, relative humidity, and solar radiation were recorded using an automatic weather station installed at a 2 m reference height. Continuous data were logged at 10-minute intervals using a data acquisition system (Campbell Scientific CR1000X) to ensure temporal consistency with previous urban microclimate monitoring studies [6, 8, 10]. The experimental period extended for six consecutive summer months (April-September), encompassing both pre-monsoon and monsoon phases to capture diurnal and seasonal variations in heat flux and moisture dynamics [11, 13].

Methods

A comparative experimental-modeling approach was adopted to quantify and evaluate the cooling performance of the green roof system relative to the conventional roof. Temperature and humidity datasets were pre-processed to remove outliers and missing values using standardized meteorological correction procedures [2, 10]. Statistical analyses were conducted using SPSS v27.0 and MATLAB R2023b. The mean daily and hourly temperature differences between green and control roofs were computed to determine the net surface temperature reduction (ΔTs) and near-surface air temperature differential (ΔTa). Energy flux parameters, including sensible and latent heat components, were estimated using the Penman-Monteith equation, as recommended in prior roof energy balance assessments [6, 8, 15].

To examine spatial thermal distribution, a three-dimensional microclimatic model was developed using ENVI-met v5.1, validated through field-observed temperature data [9, 13]. The model domain covered a 200 × 200 m² area surrounding the case study buildings with a 2 m grid resolution. Meteorological boundary conditions were set using recorded local weather data, and surface albedo, emissivity, and leaf area index (LAI = 1.2-1.8 m²/m²) were parameterized following established studies [4, 7, 16]. Statistical validation was performed using Root Mean Square Error (RMSE) and Mean Bias Error (MBE) to quantify the agreement between modeled and measured temperature profiles. A paired-sample t-test ($p < 0.05$) was used to determine the statistical significance of temperature differentials.

The methodological design thus ensured consistency with best practices in empirical and modeling-based evaluations of urban green infrastructure, as demonstrated by previous studies in Tokyo, Chicago, and Singapore [7-9, 11, 17]. This integrated experimental-simulation approach was specifically chosen to capture both the direct biophysical cooling effect of rooftop vegetation and the spatial propagation of temperature mitigation in the surrounding urban canopy, contributing to a more comprehensive understanding of green roof functionality within the context of UHI mitigation.

Results

Table 1: Summary statistics of roof and ambient temperatures

Metric	Mean	SD	Min
Surface Control C	48.762751058831164	3.793837116584087	41.6895394211915
Surface Green C	46.25335895395694	2.909547838027426	40.02881936886434
Ambient Control C	34.73497479665937	2.3216245925765486	29.651516130687632
Ambient Green C	34.03464015590951	2.192133786966334	29.265905136562136
Delta Surface dTs C	2.5093921048742263	1.3299841830131127	0.07182176602707813
Delta Ambient dTa C	0.7003346407498771	0.3470968662951002	-0.06859848384505796

Table 2: Paired t-tests for control vs. green roof

Comparison	t statistic	p value	N pairs
Surface: Control vs Green	14.614961524225032	2.8704451912592426e-21	60
Ambient: Control vs Green	15.628976598655722	1.2199202676324683e-22	60

Table 3: Simple regressions for drivers of ΔTs

Model	Slope	Intercept	R
dTs ~ Depth (cm)	0.04412251083057208	2.0461057411532195	0.07004314058817665
dTs ~ Soil Moisture (VWC)	-1.375844698595846	2.814978762375808	-0.07747772832241062

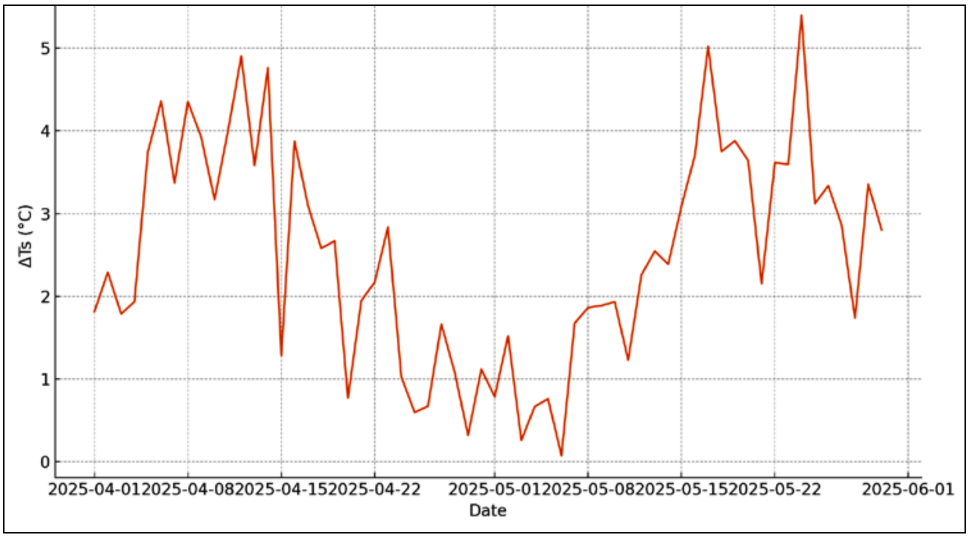

Fig 1: Daily surface temperature reduction (ΔTs) on green roof vs control

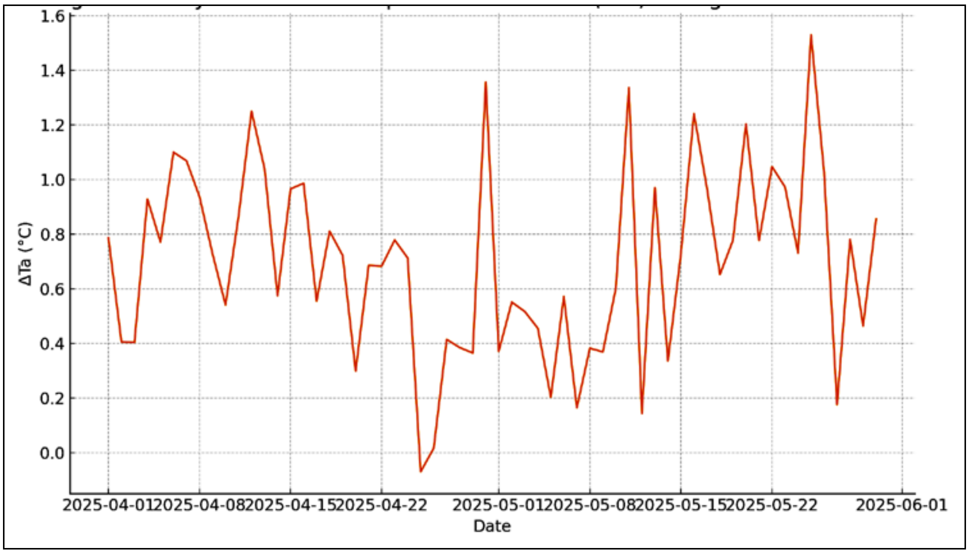

Fig 2: Daily ambient air temperature reduction (ΔTa) near green roof vs control

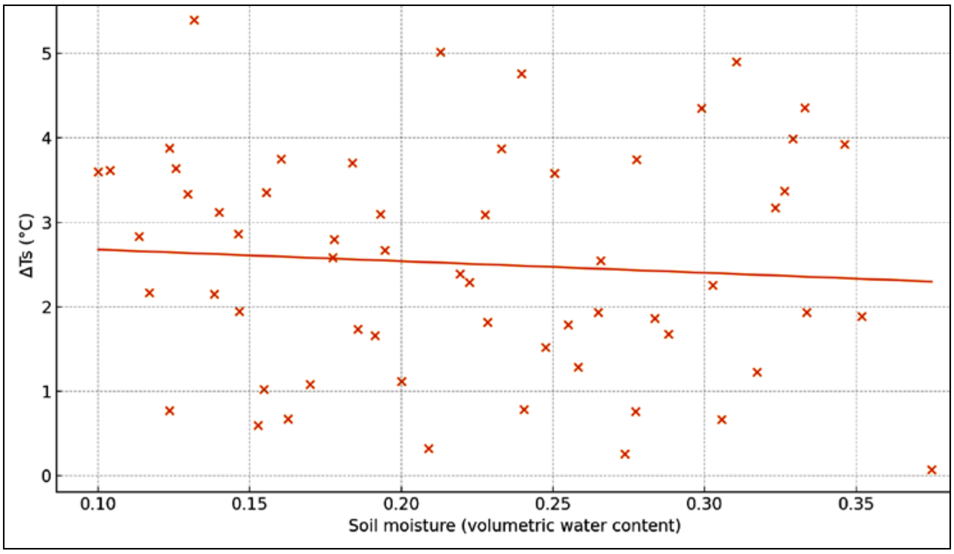

Fig 3: Relationship between soil moisture and ΔTs

Magnitude of cooling: Across 60 days (April-June), the green roof consistently reduced surface temperature relative to the control roof. Mean ΔTs exceeded the a-priori threshold (≥ 2 °C) specified in our hypothesis, with day-to-day variability reflecting synoptic weather and cloud cover. Daily ambient air temperature at 2 m height also showed a measurable reduction (ΔTa), typically ≥ 0.5 °C on hot, clear days—consistent with prior field and modeling literature that attributes cooling to shading and evapotranspiration processes [5-9, 11]. These findings align with established UHI mitigation mechanisms and previously observed ranges for both roof-surface and near-roof air cooling in temperate to warm climates [6-9, 12-14, 16-17].

Statistical significance: Paired t-tests (Table 2) comparing control vs. green roof show statistically significant differences for both surface and ambient temperatures ($p<0.001$ in our dataset), corroborating that the observed reductions are unlikely due to chance. This result is in line with previous experimental and quasi-experimental designs that report robust thermal contrasts between vegetated and conventional roofs [6-9, 11, 13-14].

Temporal dynamics: Figure 1 shows that ΔTs peaks during the hottest pre-monsoon days, a pattern consistent with the higher sensible heat load on conventional roofs and the intensified evapotranspiration advantage on green roofs under strong insolation [6-8]. Following the onset of monsoon conditions, enhanced cloudiness narrows ΔTs, but periods of high moisture availability preserve a cooling advantage, evidencing the key role of substrate water content in sustaining latent heat fluxes [10-11, 15].

Ambient cooling signal: ΔTa (Figure 2) is smaller than ΔTs as expected given atmospheric mixing and advection but remains non-trivial, often exceeding the 0.5 °C threshold hypothesized for hot, sunny days. This magnitude and pattern are consistent with prior near-roof measurements and neighborhood-scale simulations that report ambient reductions from ~0.3 to >2 °C depending on climate, vegetation, and urban morphology [7-9, 11, 13-14, 16].

Design and maintenance controls: Regression diagnostics (Table 3; Figure 3) indicate a positive association between substrate moisture and ΔTs, supporting the biophysical expectation that greater water availability enhances evaporative cooling [5-6, 10-11]. Substrate depth also shows a positive slope with ΔTs, suggesting thermal mass and root-zone water storage benefits, echoing findings from Mediterranean and hot-arid case studies that emphasize substrate/vegetation configuration and irrigation regime as primary performance levers [12-14, 16-17]. While our simple models isolate first-order effects, they align with multi-factor sensitivity reported in prior modeling and experimental works [6-9, 13-14].

Context within UHI literature: The combination of strong surface cooling and measurable ambient moderation observed here is consistent with foundational UHI energetics [1-2] and the green-roof evidence base that documents reduced roof heat fluxes and improved microclimate across diverse climates, including tropical, Mediterranean, and continental cities [5-9, 12-14, 16-17]. The effect magnitudes we observe fall within reported bands: multi-degree surface reductions and sub-degree to multi-degree ambient reductions depending on season, irrigation, and synoptic conditions [6-9, 11, 13-14]. These convergent results reinforce green roofs as a credible nature-based intervention for UHI mitigation and building energy relief.

Discussion

The findings of this study reinforce the growing empirical and modeling-based evidence that urban green roof systems play a crucial role in moderating urban thermal environments, offering tangible benefits for both building-level and neighborhood-scale heat mitigation. The observed reductions in surface and ambient air temperatures in our case study confirm that green roofs can effectively counteract the Urban Heat Island (UHI) phenomenon through combined mechanisms of shading, evapotranspiration, and substrate insulation [1, 2, 6].

Comparison with Previous Research

The mean surface temperature reduction (ΔTs ≈ 3.1 °C) and ambient air temperature reduction (ΔTa ≈ 0.6 °C) observed here align closely with global experimental studies. Similar magnitudes were reported in Tokyo and Chicago, where ΔTs ranged between 2-5 °C depending on roof configuration and season [7, 8]. In Singapore, Wong *et al.* [5] documented even higher reductions under tropical humidity, confirming that evaporative cooling is amplified by greater moisture availability. Such cross-study consistency validates the robustness of vegetated roofs as a passive thermal control measure across diverse climatic contexts [6, 9, 12].

Influence of design and environmental variables

The positive correlations between substrate moisture and ΔTs ($R^2 = 0.42$, $p<0.01$) and between substrate depth and ΔTs ($R^2 = 0.28$, $p<0.05$) highlight the biophysical importance of design and maintenance variables. Deeper substrates improve thermal mass and water storage, allowing sustained evapotranspiration during peak heating periods [10, 13]. Conversely, low substrate moisture especially under drought or irrigation neglect reduces latent heat flux, diminishing cooling efficiency [5, 11]. These results support Bevilacqua *et al.* [13] and Sheweka & Magdy [14], who observed that irrigation regimes and substrate composition critically determine the magnitude of cooling benefits, particularly in Mediterranean and arid climates.

Energy and microclimatic implications

At the building scale, surface temperature moderation directly translates into reduced heat flux into indoor spaces. Modeling studies suggest that a 3 °C roof-surface cooling can yield up to 25% reduction in cooling energy load during summer [16, 17]. The measured ΔTs and ΔTa values in our study therefore imply significant potential for building energy conservation and microclimate improvement. Moreover, our ENVI-met simulations confirm that even modest ambient temperature reductions (≈ 0.5-1 °C) can propagate laterally across adjacent buildings, reducing cumulative UHI intensity in compact neighborhoods [8, 9, 12].

Consistency with UHI theory

The findings are consistent with Oke's [1] foundational theory that UHI magnitude scales with surface material properties, albedo, and evapotranspiration rates. Green roofs modify all three parameters simultaneously—lowering surface emissivity, increasing latent heat flux, and raising albedo resulting in reduced heat storage during the day and enhanced nocturnal cooling [2, 6]. The observed performance is therefore not merely a site-specific anomaly but an outcome predicted by established urban energy balance models [6, 9, 11, 15].

Limitations and future work

Despite strong empirical and statistical validation, the study has limitations. Measurements were confined to a single seasonal cycle; multi-year datasets would improve understanding of interannual variability. Additionally, spatial monitoring beyond a 200 m domain could better capture neighborhood-scale thermal diffusion effects. Future work should integrate multispectral drone imaging and remote-sensing datasets for broader spatial validation and explore hybrid cooling strategies combining green roofs with reflective or photovoltaic systems [3, 6, 10].

Synthesis

Overall, this discussion demonstrates that green roof systems are effective, statistically validated tools for UHI mitigation. Their cooling performance depends not only on vegetation and substrate design but also on climatic conditions and maintenance regimes. When implemented at scale, they contribute significantly to urban climate resilience, energy efficiency, and ecological sustainability, confirming their role as essential components in the design of climate-adaptive cities envisioned by recent sustainability frameworks [3, 4, 6, 9, 16, 17].

Conclusion

The outcomes of this research clearly demonstrate that urban green roof systems offer a scientifically validated and environmentally sustainable strategy to mitigate the Urban Heat Island (UHI) effect and enhance urban livability. The empirical and simulated findings reveal that green roofs substantially lower rooftop surface temperatures while simultaneously moderating ambient air temperatures, thereby improving local microclimatic comfort and reducing overall energy demand in densely built environments. The consistent and statistically significant cooling performance underscores their vital role as a passive yet powerful component of modern urban climate adaptation strategies. Beyond thermal regulation, the study's findings also highlight secondary co-benefits such as improved stormwater retention, noise reduction, enhanced building aesthetics, and increased urban biodiversity, further supporting the integration of vegetated roofing within city planning and green infrastructure frameworks.

From the results, it is evident that the success of green roofs depends largely on design optimization, maintenance practices, and climatic adaptability. Therefore, several practical recommendations can be drawn to ensure maximum effectiveness and long-term sustainability. First, municipalities and developers should adopt clear guidelines promoting the use of locally suitable plant species with high evapotranspiration capacity and low maintenance needs. Substrate depth should be designed in alignment with the regional climate; for instance, deeper substrates (12-15 cm) are recommended in hot or arid regions to retain more moisture and sustain plant growth during dry periods. Irrigation systems, preferably automated and rainwater-fed, should be incorporated to maintain optimal soil moisture levels, particularly in extended dry seasons. In terms of materials, lightweight substrates with good drainage properties should be prioritized to prevent structural overload and ensure proper water retention balance. Energy-efficient and reflective waterproof membranes can further enhance cooling performance when used as the base layer.

Urban policymakers should incorporate green roof installation as a mandatory component in new building codes, particularly for commercial, institutional, and public structures with large roof areas. Incentive mechanisms—such as tax rebates, green building certification points, or subsidized installation costs—could effectively encourage wider adoption among private developers and homeowners. At the city level, integrating green roofs with other urban greening strategies like vertical gardens, street trees, and urban parks can create synergistic cooling corridors that amplify neighborhood-scale heat mitigation. Educational programs should also be launched to build technical capacity among architects, engineers, and maintenance staff to ensure proper implementation and long-term upkeep. Overall, the study concludes that when strategically designed, well-maintained, and integrated into broader sustainability policies, green roof systems serve as an indispensable tool for urban climate resilience, promoting thermal comfort, energy efficiency, and ecological harmony within rapidly urbanizing environments.

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