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Climate-driven transformations: A framework for the sustainable urban landscape system to enhance heat resilience

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ABSTRACT

This study presents a transformative framework for building sustainable urban landscapes that are resilient to the escalating heat stress challenges exacerbated by global warming and urban heat islands. In contrast to traditional research that views landscapes as passive cooling tools, ignores heat damage, and adopts a static perspective on landscape heat resilience, this study innovatively redefines landscapes as dynamically sustainable systems, emphasizing their ability to withstand, recover from, and adapt to extreme heat and focusing on the dynamics of their cooling efficiency. The need for resilient landscape systems to support urban vitality and environmental health is argued by parsing the interconnections between landscape, climate, and human activities, detailing how user behavior patterns, exposure times, and demographic characteristics can inform planning and management. The framework follows the logic of the landscape industry and forms a pathway through the entire cycle, including heat vulnerability assessment, resilient landscape planning, spatial design, heat management practices, and post-evaluation. Heat vulnerability is assessed using tools such as remotely sensed data, meteorological observations, drone thermal imagery, and ground-based monitoring systems, with measures such as land surface temperature, vegetation indices, and thermal comfort indicators. Facing potential obstacles like financial constraints, technical difficulties, and political resistance, the framework employs cost-effective designs, adaptive technologies, and policy incentives to ensure feasibility. The study's insights contribute to a broader understanding of landscape heat resilience, providing actionable guidance to enhance urban landscapes' thermal comfort, ecological robustness, and overall resilience in the face of intensifying climate and impacts.

1. Introduction

Global warming and urban heat islands (UHI) are intensifying heat stress on urban ecosystems, with future heat waves expected to become more severe and frequent (Cui et al., 2024; Santamouris & Kolokotsa, 2015). Regional disparities are pronounced: while cold stress decreases

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in higher latitudes, tropical and subtropical regions face sharp increases in heat stress frequency and duration (Hamed et al., 2024). Heat waves have intensified particularly in tropical and polar regions, with hotspots in the Middle East, North Africa, and Mediterranean (Zhang et al., 2022), while South America shows rising heat stress hours across climate zones (Miranda et al., 2024). These extreme heat events damage infrastructure, cause financial losses, and disproportionately affect vulnerable populations, while increased reliance on mechanical cooling creates negative feedback loops of energy demand (He, 2023; Xu et al., 2016). This underscores the urgent need for sustainable, climate-sensitive urban heat mitigation strategies.

Nature-based solutions (NBS) offer a sustainable approach to urban heat mitigation by modifying urban surface energy balances through vegetation and water systems (Augusto et al., 2020). Defined as cost-effective, nature-supported responses that deliver environmental, social, and economic benefits (Qiu et al., 2021; Stange et al., 2022), NBS include green roofs, urban forests, and vegetated facades that enhance evapotranspiration, improve albedo, and provide shading. These measures help create cooler microclimates and reduce the impact of extreme heat (Li & He, 2025).

In this study, “landscape” refers to both natural and artificial outdoor systems in urban contexts, including vegetation, water, built structures, and open spaces that support human activities. As key carriers of nature-based solutions (NBS), their thermal performance depends on design, construction, and management. Promoting NBS can reshape urban landscape form and perception, influencing both microclimate and public acceptance (Raymond et al., 2023). Understanding this interaction helps build a positive feedback loop that supports thermal comfort and livable spaces. Artificial components, such as shading structures and paving materials, also contribute to outdoor heat mitigation (Santamouris et al., 2012).

However, landscapes are increasingly vulnerable to heat. Vegetation may decline, water bodies dry out, and materials degrade during extreme events (Esperon-Rodriguez et al., 2025). Blue-green infrastructure faces risks like desiccation, wildfires, and structural fatigue (Cai et al., 2012), while poor material choices or excessive irrigation can worsen environmental degradation (Gober et al., 2009). These threats highlight the need to go beyond mitigation and integrate resilience and recovery strategies.

While existing research highlights the cooling function of landscapes, it often overlooks their ability to recover from heat-induced damage. In practice, urban landscapes—such as green roofs and street vegetation—are vulnerable to degradation during extreme heat, leading to performance loss and safety concerns (Haase & Hellwig, 2022; Percival, 2023). Without timely recovery strategies, these systems may fail to deliver climate services and could even worsen heat exposure risks (Gräf, Immitzer, Hietz, & Stangl, 2021; Kraemer & Kabisch, 2022).

To bridge this theoretical and practical gap, this study proposes a framework for landscape heat resilience that integrates heat resistance and self-organizing capacity as interdependent elements of an adaptive system. Rather than viewing landscapes as static assets, we conceptualize them as dynamic systems that buffer and respond to thermal stress through spatial, ecological, and operational mechanisms.

The objectives of this study are threefold:

i) Define “heat resilience” within sustainable urban landscapes, clarifying its scope and functions;
ii) Explore the coupled dynamics between landscape form, urban heat, and human activity, revealing landscapes’ dual role in heat formation and mitigation;
iii) Develop a full-cycle implementation pathway—covering data acquisition, planning, design, operation, and post-evaluation—for informed, resilient landscape management.

2. The role of landscape in urban heat

2.1. Landscape

Landscape serves as a "second nature" that supports human outdoor activities and reconnects people with natural systems. It is comprised of an integrated network of blue-green infrastructure (e.g., parks, rivers, and vegetated corridors) and grey infrastructure (e.g., buildings, roads, and public facilities). Effective planning, design, and management are key to maintaining these spaces. Urban green systems comprise diverse types—such as parks, residential greens, transport corridors, and peri-urban buffers. Landscapes provide essential ecosystem services, including air purification, microclimate regulation, and biodiversity support, as well as social benefits like aesthetics, mobility, leisure, cultural expression, and public well-being.

2.2. Transformative interactions in sustainable landscape systems for heat resilience

Landscape heat resilience emerges from the dynamic interactions between three interconnected subsystems: landscape, urban heat, and human activity (Fig. 1). These elements form a feedback triangle where each component simultaneously influences and responds to the others, creating complex adaptive cycles that determine the thermal performance and livability of urban environments.

2.2.1. Mutual feedback between landscape and urban heat

Urban landscapes and urban heat are tightly interconnected through mutual feedback. Landscape features—such as vegetation, water, surface materials, and spatial form—shape local thermal conditions, while urban heat stressors like elevated temperatures and moisture deficits affect landscape health and performance.

Vegetation serves as the primary thermal regulator through multiple cooling mechanisms. Shading provision reduces direct solar radiation, while evapotranspiration creates localized cooling through moisture release (Lenzholzer & Brown, 2016). Green spaces with dense canopy coverage, vertical greening systems, and water bodies provide cooling through evapotranspiration and shading, with reduced heat storage (Zhai, Ren, Xi, Tang, & Zhang, 2021). At the material level, surfaces with high albedo or permeability facilitate heat dissipation (Cao et al., 2020), while spatial attributes—including vegetation height, spacing, and connectivity—influence airflow patterns and shading effectiveness, directly shaping the intensity of localized heat islands (Lucchi et al., 2024).

Conversely, persistent heat stress creates vegetation stress and ecosystem degradation. Prolonged heat exposure and moisture deficits lead to plant wilting, reduced biodiversity, and increased irrigation demands (Boucher-Lalonde et al., 2012; Percival, 2023). Soil desiccation and vegetation fragmentation amplify these stresses, while hardscape elements experience material degradation—cracking or warping under extreme temperatures—reducing both functionality and aesthetic value (Esperon-Rodriguez et al., 2025; Gräf, Immitzer, Hietz, & Stangl, 2021).

This bidirectional feedback has direct implications for heat resilience. Landscapes must not only regulate heat but also withstand and recover from heat stress. Accounting for this dynamic is essential to designing systems that integrate heat resistance with self-organizing capacity, enabling long-term adaptive performance under climate extremes.

2.2.2. Mutual feedback between landscape and human activity

The relationship between landscape and human activity is inherently reciprocal. Urban landscapes provide essential thermal, ecological, and social functions, while being continuously reshaped by human behavior and land-use decisions—especially under growing heat stress.

Access to shaded streets, parks, and vegetated corridors enhances thermal comfort, encourages outdoor activity, and reduces heat-related

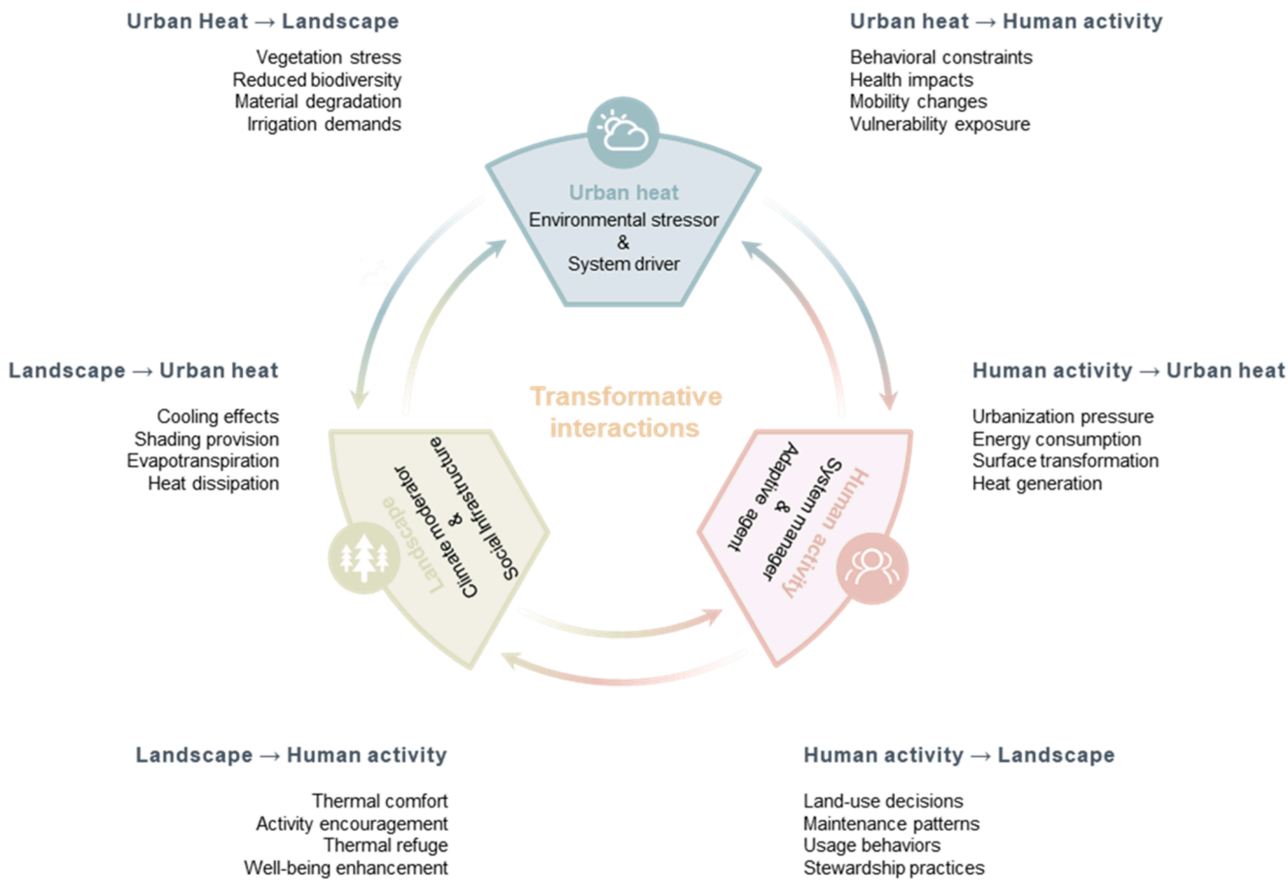

Fig. 1. Transformative interactions in sustainable landscape systems for heat resilience.

stress (Douglas et al., 2017; Sandifer et al., 2015). In hot climates, vegetated environments help reduce dependence on mechanical cooling and promote well-being (Sanusi & Bidin, 2020). Beyond physical comfort, landscapes also support cultural and psychological benefits, contributing to urban resilience and equity (Mahmoud, 2011).

At the same time, human activity strongly influences landscape resilience. Urban expansion often replaces green cover with impervious surfaces, intensifying heat accumulation. Aesthetic preferences or poor usage patterns—like overuse during heatwaves or vandalism—can degrade landscape quality and impair ecological function (Raymond et al., 2023). Conversely, proactive behaviors—such as tree planting, community gardening, and user-informed design—can enhance vegetation health and promote stewardship (Astell-Burt & Feng, 2019). In heat-vulnerable areas, incorporating user behavior, mobility patterns, and thermal needs into planning ensures that landscapes function effectively as thermal refuges (Chen et al., 2021).

Recognizing this feedback loop is key to adaptive planning. Human behaviors reshape landscapes, and in turn, landscapes influence how people live and cope with heat. Designing for this mutual influence ensures landscapes evolve alongside shifting urban needs and climate realities.

2.2.3. Feedback between human activity and urban heat

Human activity both contributes to and is shaped by urban heat. At various scales, from urban design to daily behavior, anthropogenic actions intensify heat stress—while rising temperatures, in turn, constrain human movement, comfort, and health (Huang et al., 2024b).

Urbanization transforms vegetated surfaces into impervious materials, reducing albedo and evapotranspiration, thereby strengthening urban heat island (UHI) effects (Rizwan et al., 2008). Dense building layouts lower sky view factors and hinder natural ventilation, while widespread air conditioning and transport emissions further elevate local temperatures, creating a self-reinforcing feedback loop of heat and energy use.

Urban heat also impacts behavior. Rising temperatures reduce outdoor activity, shift mobility patterns, and heighten risks for vulnerable populations, including the elderly, children, and those with chronic illnesses (Sampson et al., 2013). Prolonged exposure can lead to dehydration, fatigue, reduced cognitive function, and productivity loss (Mahmoud, 2011; Orlov et al., 2020; Sanusi & Bidin, 2020).

In areas lacking shade or green infrastructure, these effects are magnified, exacerbating social inequalities and increasing reliance on energy-intensive cooling (Sanusi & Bidin, 2020). Adaptive interventions—such as passive cooling design, shaded public spaces, and behavior-informed planning—can help turn this feedback from negative to regenerative.

Understanding the interaction between heat and human behavior is vital for climate-resilient urban design. Integrating exposure data, vulnerability profiles, and behavioral insights supports equitable, adaptive responses in increasingly heat-stressed cities.

3. Approach to framework development

This study conducts a framework review to develop a structured approach to enhancing landscape heat resilience in sustainable urban environments. Rather than relying on empirical methods, it draws on a systematic and integrative literature review to synthesize existing knowledge, identify gaps, and construct a conceptual model. The following outlines the review process.

To ensure the relevance and specificity of the literature, a systematic search was conducted in Scopus and Web of Science. A Boolean search strategy was employed, combining landscape-related terms with heat resilience-related terms using the "AND" operator, in order to retrieve studies that simultaneously address both aspects.

The landscape-related terms include: landscape, nature-based solutions, green infrastructure, blue infrastructure, outdoor environment, park, and urban design/planning.

The heat resilience-related terms include: heat resilience, thermal resilience, heat mitigation, thermal mitigation, heat adaptation, thermal adaptation, heat stress, thermal comfort, heat vulnerability, thermal vulnerability, heat risk, thermal risk, heat exposure, thermal exposure, urban heat, and urban microclimate.

This structured search strategy was designed to enhance the precision of the literature selection process and ensure the inclusion of interdisciplinary studies that link landscape-based approaches with strategies for mitigating urban heat and enhancing climate resilience.

The initial search yielded a total of 9581 articles. After removing duplicates and non-peer-reviewed sources, 4897 records remained. Titles and abstracts were then screened based on their relevance to both landscape-based strategies and heat resilience in urban environments. Articles were excluded if they focused solely on either landscape or heat-related issues without establishing a clear connection between the two, or if they addressed rural rather than urban contexts. Full-text screening was subsequently conducted for 1697 articles that met the inclusion criteria. Finally, 105 articles were selected for inclusion, prioritizing highly cited and recently published studies due to the large volume of relevant literature.

The framework was developed in stages: (i) defining core concepts (Section 4.1), (ii) establishing hierarchical objectives bridging theory and practice (Section 4.2), and (iii) proposing implementation pathways informed by landscape planning, urban climatology, and sustainability literature (Section 5).

4. Landscape heat resilience system for sustainable urban environments

4.1. The connotation of heat resilience in landscapes

In the face of intensifying climate change, landscape heat resilience has emerged as a critical framework for sustainable urban environments. Unlike conventional approaches that treat landscapes as passive cooling agents, landscape heat resilience refers to the dynamic capacity of urban landscape systems to withstand, adapt to, and recover from extreme heat events while maintaining their ecological integrity and social functions. This resilience encompasses two interdependent dimensions: heat resistance and self-organizing capacity.

Heat resistance addresses how landscape components withstand elevated temperatures through strategic design interventions. Effective resistance requires optimizing vegetation layouts, selecting heat-tolerant materials, and configuring spatial arrangements that mitigate urban heat island effects and promote microclimatic regulation.

Self-organizing capacity represents the system's ability to autonomously restore ecological functions following heat stress. This dimension emphasizes designing landscapes with intrinsic adaptability, enabling natural processes to facilitate recovery through ecological connectivity and diversity.

The integration of both dimensions is essential for urban sustainability. Heat-degraded landscapes can trigger cascading impacts—elevated temperatures, biodiversity loss, increased energy demand, and reduced livability—particularly affecting vulnerable communities. Therefore, embedding comprehensive resilience capacity into landscape planning is critical for ensuring both immediate urban safety and long-term climate adaptation.

4.1.1. Heat resistance

Heat resistance encompasses how landscapes endure extreme temperature fluctuations through two interrelated dimensions: exposure and vulnerability. These dimensions reveal complex interactions between natural systems and human interventions (Depietri, 2020; Yu et al., 2021).

Exposure represents the degree and spatial extent of landscape subjection to elevated temperatures, influenced by internal and external factors. Internally, vegetation cover provides crucial cooling through shading, significantly reducing heat exposure. Topographical features (valleys versus open areas) influence heat distribution and retention, while soil type and moisture content determine heat absorption and release capacity. Externally, climate change and UHI effects increase extreme heat frequency, elevating exposure risk. Microclimatic conditions create spatial variability in heat stress experience.

Vulnerability encompasses the sensitivity of both natural and artificial landscape elements to heat stress. For blue-green infrastructure, this is expressed as ecological degradation: heat and drought can cause plant mortality, reduce biodiversity, and deplete water resources, with limited ecological connectivity hindering recovery. For grey infrastructure, vulnerability involves both material and systemic failures. High temperatures can lead to discoloration, cracking, and deformation of materials. More critically, extreme heat can cause pavement buckling, thermal expansion in bridges and railway tracks, and place significant strain on energy grids due to heightened cooling demands. Additionally, the layout of built elements, such as dense building configurations, can trap heat and exacerbate local stress, compromising the functionality of critical urban systems. Inadequate heat warning systems intensify these vulnerabilities across all landscape types during extreme events.

4.1.2. Self-organizing capacity

Self-organizing capacity refers to a system's ability to autonomously restore functional and structural balance following stress without relying solely on external interventions (Shen et al., 2023). In landscape heat resilience, this emphasizes not merely returning to pre-disturbance states, but adapting and re-establishing critical services—microclimate regulation, biodiversity support, and thermal comfort—after extreme heat events. This capacity depends on internal feedback mechanisms and varies with landscape composition, ecological connectivity, and regenerative resources availability.

Natural elements possess inherent self-organizing mechanisms through ecological processes like seed dispersal, root sprouting, and nutrient cycling under favorable conditions (Vloon et al., 2022). Artificial elements lack regenerative potential and require human maintenance. Parks exemplify this contrast: heat-tolerant shrubs may regenerate within one growing season, restoring cooling functions (Urban et al., 2023), while damaged artificial elements need external resources for functionality recovery.

Evaluating self-organizing capacity requires assessing: (i) recovery level—fraction of pre-event canopy signal regained, and (ii) recovery cycle—time until stabilization (Fig. 2). Multi-temporal studies show three-band Slope vegetation index (SVI) outperforms two-band NDVI/EVI by suppressing soil, asphalt, and water backgrounds, accurately

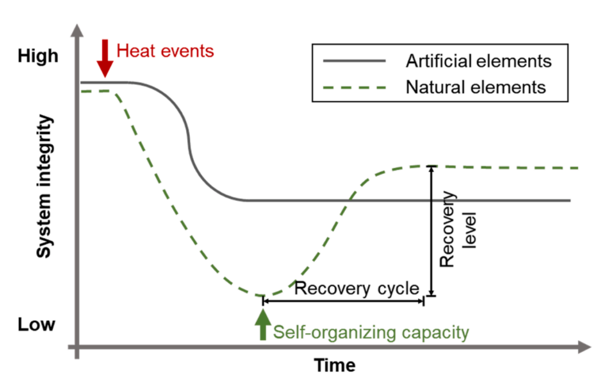

Fig. 2. Differentiated self-organizing responses of natural and artificial elements after heat events.

tracking vegetation stress and rebound in heterogeneous urban mosaics (Zhao, Pan, Ren et al., 2024, 2024).

$$SVI = \rho_{NIR} - \left(\rho_{green} + \frac{\rho_{SWIR1} - \rho_{green}}{\lambda_{SWIR1} - \lambda_{green}} \times (\lambda_{NIR} - \lambda_{green})\right) \tag{1}$$

where ρ is surface reflectance (sr) and λ is band centre-wavelength (μm).

To accurately account for seasonal vegetation dynamics in the assessment of recovery, the recovery level (RL_t) using SVI at any checkpoint t is defined as:

$$RL_t = \frac{SVI_t - SVI_{post}}{SVI_{baseline,\ t} - SVI_{post}} \times\ 100\% \tag{2}$$

Where:

SVI_t is the SVI value at the observation checkpoint t.

SVI_{post} is the SVI value from the first cloud-free scene acquired ≤7 days after extreme heat events, representing initial post-disturbance vegetation state.

$SVI_{baseline,t}$ is the phenological baseline representing historical average SVI for the same calendar period as checkpoint t. This baseline derives from multi-year (5–10 years) historical data from years without significant heat events, reflecting expected SVI for healthy vegetation during that time period. Observation checkpoints include +30d, +90d, and +180d post-event (Rynkiewicz et al., 2025; Zhang et al., 2024).

Recovery studies show RL curves flatten when increment between consecutive composites falls below 2 %—coinciding with field-measured LAI and ecological recovery. The first date meeting this condition (Δt = one composite, e.g., 30 days) defines the recovery cycle.

This SVI-based framework provides robust, replicable methodology for measuring self-organizing capacity across urban settings. However, due to inherent differences in landscape composition, ecological connectivity, and built environment context, urban areas experiencing identical extreme heat intensity may exhibit significantly different self-organizing capacity outcomes.

4.2. Objectives of landscape heat resilience systems

Climate change and UHI pose unprecedented challenges to urban landscapes, necessitating clear heat resilience objectives in landscape planning. We identify three hierarchical objectives transforming passive heat response into proactive adaptation (Fig. 3):

1) Maintaining structural integrity: Preserve landscape stability under heat stress through robust self-protection mechanisms preventing or enabling recovery from heat damage to vegetation (mortality, wilting) and infrastructure (material degradation, deformation).
2) Sustaining essential functions: Ensure continuous ecosystem services and social benefits delivery during heat stress, maintaining landscape capacity to provide environmental services and support human activities despite heat perturbations.
3) Providing cooling benefits: Maximize landscape microclimate regulation potential. Resilient landscapes actively modify local thermal conditions, serving as critical cooling agents protecting other urban systems during heat waves.

These objectives represent progressive shift from survival to active urban heat adaptation contribution. When unmet—due to delayed recovery, design failure, or inadequate institutional support—vulnerabilities cascade through urban systems, causing intensified UHI effects, increased health risks, degraded infrastructure performance, and growing social inequities. This reinforces designing landscapes that resist heat stress while enabling autonomous and policy-supported recovery as integral components of holistic urban adaptation strategies.

5. Pathways to implementing landscape heat resilience systems

Most existing frameworks adopt fragmented approaches treating landscapes as static cooling tools, overlooking dynamic capacities for heat resistance and self-organizing recovery. Our proposed framework explicitly integrates these core aspects—heat resistance (exposure and vulnerability) and self-organizing capacity (recovery level and cycle)—into a systematic implementation process (Fig. 4).

The pathway begins with detailed vulnerability assessment clarifying landscape exposure and vulnerability, forming the basis for enhancing heat resistance through planning and design interventions. Strategic planning and spatial design steps directly minimize exposure, mitigate vulnerability, and optimize ecological conditions promoting efficient recovery. Recognizing that extreme heat events may exceed natural recovery thresholds, the framework includes targeted operational management applying artificial interventions, ensuring rapid restoration when landscapes' intrinsic self-organizing capacities prove insufficient. Finally, rigorous post-evaluations continuously assess landscape performance, informing adaptive improvements that strengthen capacities for both resistance and autonomous recovery under future climatic

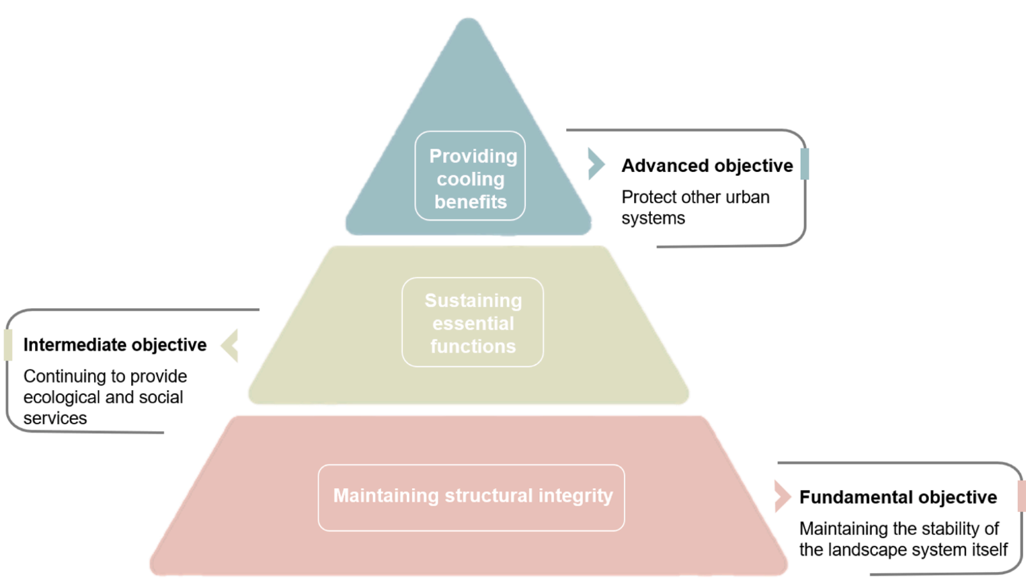

Fig. 3. Objectives of landscape heat resilience systems.

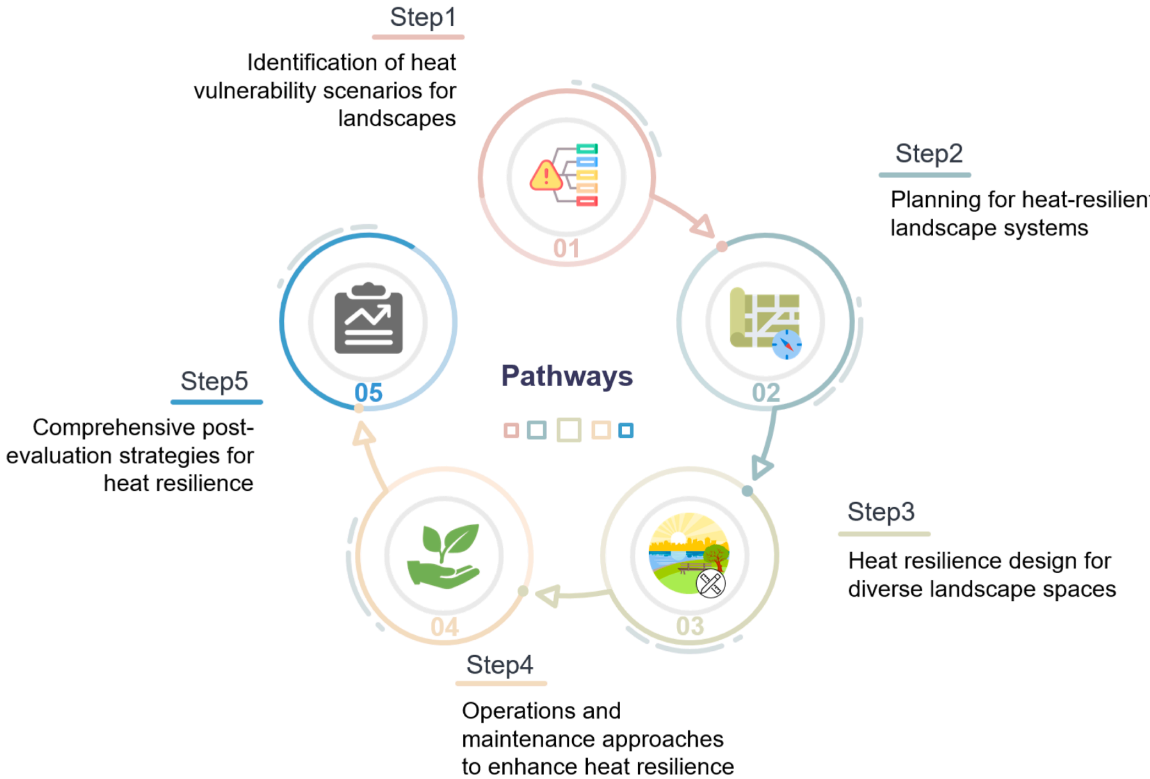

Fig. 4. Pathways to implementing landscape heat resilience systems.

stresses.

5.1. Identification of heat vulnerability scenarios for landscapes

Effectively identifying heat vulnerability scenarios is fundamental to enhancing landscape heat resistance by characterizing exposure and vulnerability at multiple scales. We propose a multi-scale downscaling framework integrating urban-scale thermal analyses, district-level microclimate characterization, site-specific monitoring, and predictive climate simulations to evaluate and prioritize heat resilience strategies (Fig. 5).

At the urban scale, heat exposure patterns are assessed using remote sensing and open-source datasets—LST, vegetation indices, land cover, and population density—to identify areas with highest exposure and vulnerability (Chen et al., 2023). Macro-level analyses prioritize strategic interventions addressing critical hotspots. In Seville, Spain, Landsat 9 data with Local Climate Zone mapping identified 11 % of residential areas as high heat hotspots (Sola-Caraballo et al., 2025). In Alabama, USA, LST integration with population density and social vulnerability metrics produced effective city-scale heat vulnerability

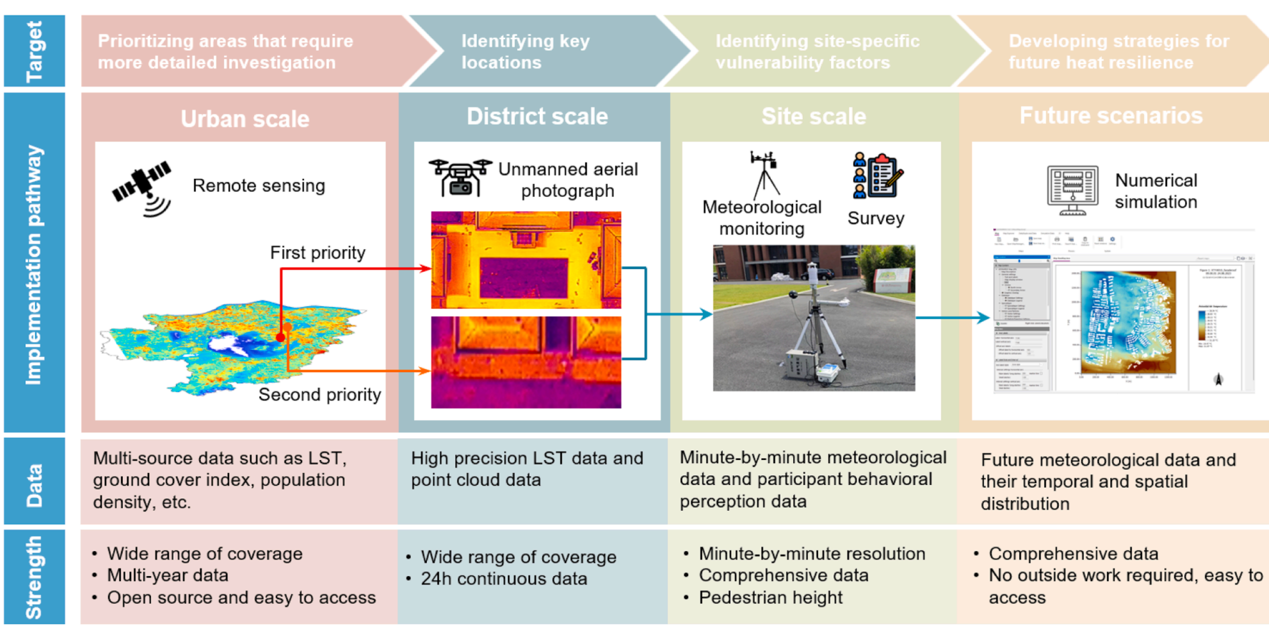

Fig. 5. Heat vulnerability identification framework based on multi-source data and scale transitions.

maps (Fall, Coulibaly, Quansah, & El Afandi, 2023).

At the district scale, vulnerability is refined through high-resolution thermal imaging and drone-collected point cloud data, identifying critical microclimatic zones with sparse vegetation or poor ventilation requiring targeted strategies. Continuous 24-hour drone monitoring captures dynamic heat exposure variations at neighborhood levels. Dimitrov et al. (2024) developed UAV-based approaches detecting microscale urban heat islands and ranking intervention areas based on local temperature differentials.

At the site scale, minute-by-minute meteorological monitoring integrates with user questionnaires and behavioral observations to characterize vulnerability through environmental conditions and human thermal experiences. This provides pedestrian-level insights enabling highly localized interventions enhancing specific landscape heat resistance. Kim and Brown (2022) combined weather stations and cameras to obtain thermal conditions in a street canyon and analyzed their effects on pedestrian behavior.

Predictive scenario modeling using ENVI-met, WRF, and CFD enhances heat resilience planning by anticipating vulnerability pattern evolution under different climate trajectories. Liu et al. (2025) proposed a downscaling framework combining WRF-UCM and ENVI-met to predict pedestrian-layer air temperature and humidity with high accuracy, supporting future heat vulnerability distribution predictions.

5.2. Planning for heat-resilient landscape systems

Effective planning of heat-resilient landscape systems requires addressing two core resilience dimensions: heat resistance through reduced landscape exposure and vulnerability, and self-organizing capacity through enhanced recovery level and shortened recovery cycles. Our methodology systematically integrates spatial heterogeneity of three essential landscape elements—impervious surfaces, green spaces, and water bodies—with advanced multi-source remote sensing indicators and physical parameter models. This integration enables precise quantitative analysis and spatial representation of each element's capacity to withstand heat stress and autonomously recover following extreme heat events (Fig. 6).

Building upon the Local Climate Zone (LCZ) classification framework, we introduce an enhanced indicator system at the fundamental parameter level (including building height, building density, NDBI, NDVI, and MNDWI) (Zou et al., 2025). This system provides targeted improvements specifically designed to strengthen landscape resistance and recovery capabilities.

The framework addresses three critical urban elements through dynamic parameter integration. Water bodies incorporate surface area to depth ratio, hydrologic connectivity, evapotranspiration rate, and water temperature, moving beyond static measures like MNDWI to explicitly model dynamic cooling potential and support rapid ecological recovery. Green spaces are characterized through aspect ratio, ecological connectivity, leaf area index (LAI), and evapotranspiration rate to maximize heat resistance and self-organizing capacities, directly informing strategies to enhance vegetative cover and ecological connectivity. Impervious surfaces utilize new indicators including surface reflectance, specific heat capacity, windward surface density, and building curvature, surpassing traditional two-dimensional analysis to address how building morphology intensifies urban heat island effects.

A hybrid modeling approach coupling surface energy balance equations and fluid dynamics quantifies landscape resilience performance. The water body system simulates thermal diffusion pathways through hydrologic connectivity networks, delineating cooling radiation zones based on temperature gradients. The green space system dynamically simulates shading and evapotranspiration cooling effects using LAI and solar altitude angle models combined with canopy turbulence exchange modeling. The impervious surface system captures synergistic impacts of building curvature, reflectance, and thermal capacity, illustrating how building morphologies amplify local heat intensity and informing morphological planning strategies.

Implementation of this integrated methodology is achieved through GIS platform overlay analysis. By combining cooling capacity index (CCI) and effective radius (ER) data for blue-green cooling sources with high-temperature heat-source distribution (Han et al., 2023), a comprehensive thermal risk level map is generated to explicitly guide planning and decision-making processes. This approach enables targeted interventions that systematically strengthen both resistance and self-organizing recovery capabilities of urban landscape systems.

5.3. Heat resilience design for diverse landscape spaces

The design of landscape spaces plays a critical role in directly enhancing urban heat resilience by strategically strengthening their capacities for heat resistance (reducing exposure and vulnerability) and self-organizing recovery (improving recovery level and shortening recovery cycle). Recognizing that different landscape typologies exhibit distinct thermal responses and resilience capacities, this section systematically synthesizes resilience mechanisms from previous studies and proposes targeted optimization pathways for enhancing each typology's

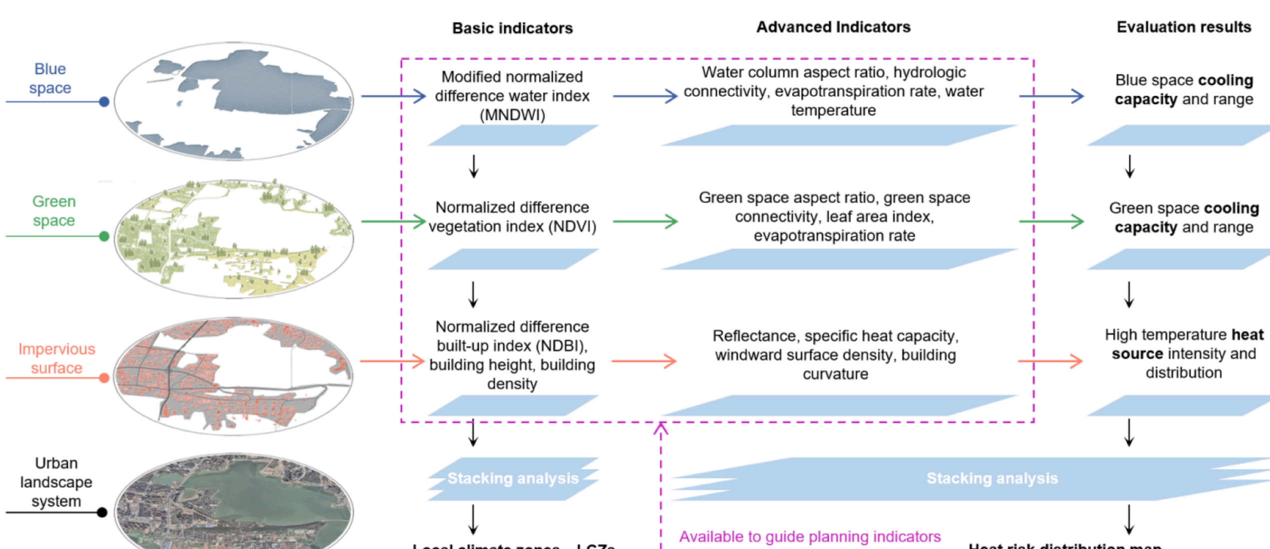

Fig. 6. Heat-resilient landscape planning based on multi-source data and hybrid thermal models.

heat resilience (Fig. 7).

5.3.1. Urban parks

Urban parks are central to green infrastructure, providing cooling benefits through their size and spatial layout. Moderately sized, elongated parks can significantly reduce surrounding temperatures, challenging the common belief that larger parks have greater cooling effects (Chen et al., 2012). Vegetation configuration is essential for optimizing cooling (Q. Li et al., 2024). Employing native plant species adapted to local climatic conditions can effectively improve both vegetation recovery level and shorten recovery cycles following heat stress (Parmesan & Hanley, 2015). Incorporating water bodies covering significant park areas (>70 %) can further augment heat resistance through evapotranspiration and air circulation, creating stable microclimatic conditions (Deng et al., 2023; Sharma et al., 2016). Integrated blue-green systems, such as wetlands, optimize synergistic cooling and ecological recovery, significantly enhancing parks' autonomous resilience capabilities (Li et al., 2024b).

5.3.2. Residential green spaces

The heat resilience of residential areas hinges on the synergistic design of green spaces and the built environment (grey infrastructure). High building density and impervious surfaces are known to exacerbate heat stress, increasing cooling energy demand by 20–30 % compared to well-vegetated areas (Qi & He, 2023). Therefore, a holistic approach that integrates both green and grey strategies is essential.

Resilience can be enhanced by directly addressing the grey infrastructure itself. This includes adopting passive cooling designs for buildings, such as optimizing orientation for natural ventilation and using external shading devices (e.g., awnings and louvers) to minimize solar heat gain. Furthermore, innovative materials for building envelopes play a crucial role; strategies such as cool roofs and high-reflectance facades can significantly reduce heat absorption and transfer into the building, thereby lowering indoor temperatures and cooling energy demands (Tyagi & Danish, 2025).

The deep integration of green and grey elements offers further benefits. Rooftop gardens and vertical greening systems should be viewed not just as aesthetic additions, but as direct modifications to the thermal performance of buildings. They provide an insulating layer that reduces energy consumption while actively cooling the surroundings through evapotranspiration (Nasr, El Zakhem, Hamami, El Bachawati, & Belarbi, 2024; Pisello, 2017) . This synergy is critical, as plants themselves can experience stress from heat radiated by grey infrastructure, such as air conditioning units (Qin, 2015), necessitating careful selection of heat-tolerant species.

Ultimately, a comprehensive strategy combining passive building design, advanced materials, and integrated green systems can systematically reduce heat exposure and vulnerability in residential spaces. Supporting these physical designs with adaptive technologies like smart irrigation and drought-resistant plant selection ensures both the resistance of the built environment and the self-organizing recovery capacity of the living landscape (Kim et al., 2023; Livesley et al., 2021; Qi et al., 2021; Tan et al., 2020).

5.3.3. Green transportation corridors

Green transportation corridors are critical for urban heat resilience,

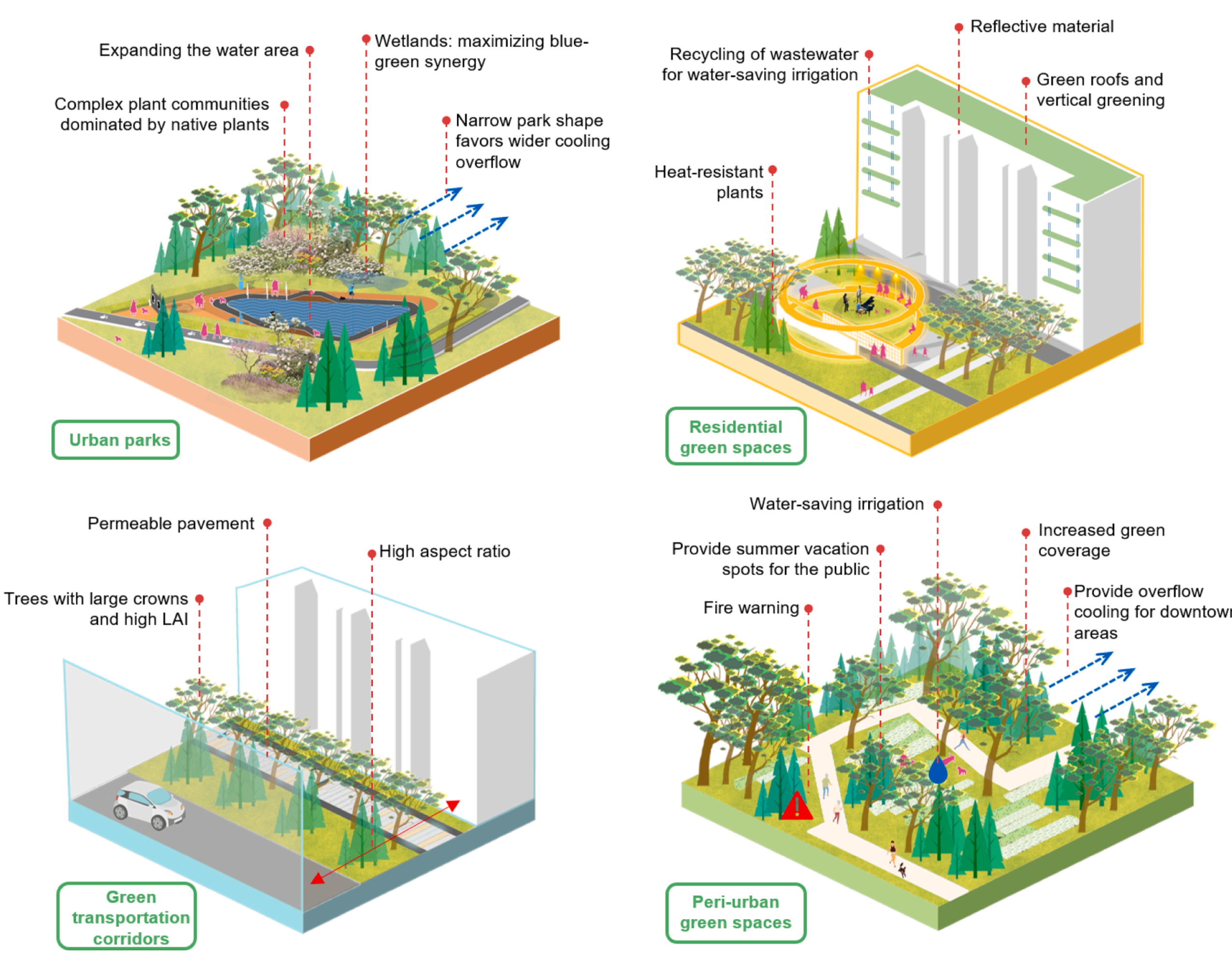

Fig. 7. Typology-based heat resilience design strategies for landscape spaces.

requiring an integrated design of both green and grey infrastructure to protect pedestrians and ensure system functionality (Li & He, 2025). While vegetative components like street trees can significantly reduce local temperatures (by up to 2.3 °C) (Shashua-Bar et al., 2006), their effectiveness is amplified when combined with resilient grey infrastructure design.

A key strategy is the use of advanced materials for surfaces. Instead of conventional asphalt, cool pavements with high solar reflectance should be employed to lower surface temperatures, reduce heat storage, and improve pedestrian thermal comfort (Muniz-Gäal et al., 2020). The design of heat-resilient street furniture is also crucial, such as bus shelters with insulated or green roofs and ample shaded seating areas.

Furthermore, vegetation plays a protective role for the grey infrastructure itself. Strategically placed trees not only shade pedestrians but also cool the microenvironment around critical roadside equipment, such as utility boxes and communication nodes, thereby reducing their risk of overheating and failure during heatwaves. Therefore, a holistic approach that combines the optimization of street canyon geometry, the use of advanced materials, the strategic design of street furniture, and the selection of multi-layered, heat-tolerant vegetation is essential. This integration systematically reduces heat exposure and vulnerability for both people and infrastructure, enhancing the corridor's overall resilience and self-organizing capacity (Karimimoshaver, Khalvandi, & Khalvandi, 2021; Morakinyo et al., 2020; Shamsaei et al., 2022; Sharifi, 2021).

5.3.4. Peri-urban green spaces

Peri-urban green spaces, typically located at the urban fringe, serve as crucial buffers against heat extremes by providing substantial vegetative cover that reduces exposure and enhances local microclimates. These areas—such as shelterbelts, ecological farmland, or urban-edge forest patches—are physically situated within the city's ecological infrastructure, though often spatially close to rural boundaries. Their dense vegetation and ecological diversity contribute significantly to reducing urban vulnerability by moderating temperature gradients and providing temporary cooling refuges during heat waves (Amorim-Maia et al., 2023; Kirschner et al., 2023). While climate change increases their vulnerability through heightened fire risk and drought, targeted design strategies—such as fire breaks, fire-resistant planting, and smart irrigation—can enhance their heat resistance. These measures also support self-organizing recovery capacity, enabling rapid ecological regeneration after disturbances and strengthening the long-term resilience of the urban ecological network (Miller et al., 2024).

5.4. Operations and maintenance approaches to enhance heat resilience

Operational management and maintenance practices are essential components of landscape heat resilience, playing a crucial role particularly when extreme heat events surpass landscapes' inherent self-organizing recovery capacities. Proactive operational interventions can significantly reduce landscape exposure and vulnerability (heat resistance), while targeted maintenance enhances ecological recovery by improving the recovery level and reducing the recovery cycle (self-organizing capacity). Thus, effectively integrating spatial transformation, maintenance practices, and supportive governance policies—supplemented by precise human activity data (e.g., user vulnerability and activity patterns)—is crucial for reliably maintaining and enhancing resilience during and after heat events (Fig. 8).

5.4.1. Spatial transformation

Spatial transformation explicitly targets enhancing landscape heat resistance by significantly reducing exposure and vulnerability, especially in densely built or outdated urban areas. Traditional landscape designs frequently lack adequate shading, airflow, and vegetation cover, resulting in elevated heat exposure. Spatial transformations—such as implementing rooftop gardens, vertical greening systems, and micro-parks—directly reduce local heat vulnerability, positioned based on human activity and vulnerability data (e.g., locating micro-parks near playgrounds or rooftop gardens on low-income housing). In areas challenged by limited water access, heat- and drought-tolerant plant species further reduce vulnerability by ensuring sustained vegetation health under extreme heat (Sadok et al., 2021). Incorporating reflective materials, misting systems, and closed-loop water features provides additional artificial cooling interventions, effectively reducing heat exposure beyond the landscape's natural capacity (Cuce & Riffat, 2016; Harmáčková et al., 2022). Combined applications of vegetation, shading structures, and soil amendments further support enhanced recovery by fostering ecological stability, ensuring sustained landscape resilience

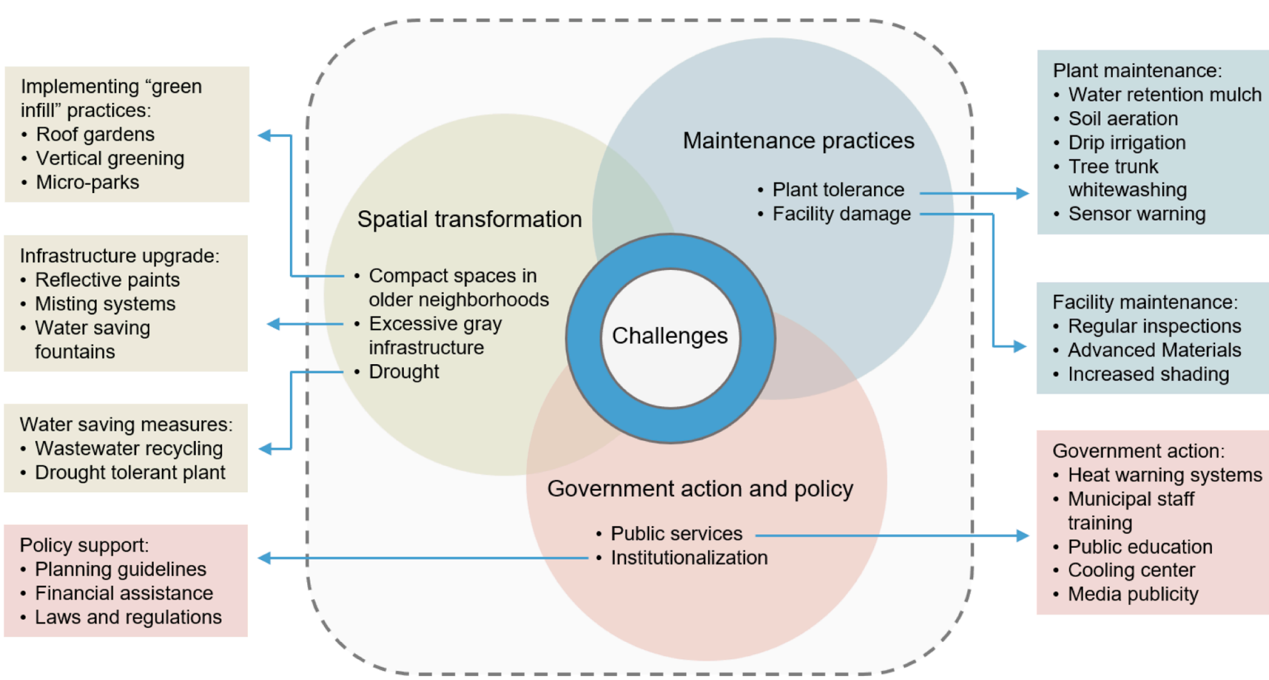

Fig. 8. Strategies for managing and maintaining heat resilient urban landscapes.

and rapid ecological recovery after heat disturbances (Amores et al., 2023).

5.4.2. Maintenance practices

Maintenance practices are crucial to long-term landscape resilience, directly enhancing self-organizing recovery capacity by maintaining healthy vegetation and resilient infrastructure. Extreme heat stress frequently leads to vegetation wilting, reduced canopy density, and infrastructure deterioration, significantly increasing landscape vulnerability and lengthening recovery cycles. Targeted maintenance measures—such as applying water-retaining mulches, soil aeration, and organic amendments—directly mitigate heat stress effects, enhancing ecological recovery levels and reducing vegetation recovery cycles (Cheung et al., 2024; Demirel & Kavdır, 2013). Reflective materials applied to tree trunks minimize direct heat damage, further enhancing vegetation resilience (Ophardt & Hummel, 2020). Continuous monitoring of radiation, temperature, and moisture via sensor networks facilitates proactive management, quickly identifying and addressing vulnerabilities, particularly in landscapes frequented by vulnerable populations (e.g., elderly) (Sato et al., 2024). Regular inspections and maintenance of structural elements (e.g., green walls, awnings) additionally ensure continuous heat resistance and robust self-organizing capacity, providing timely artificial interventions when landscape conditions exceed natural recovery thresholds (Zhao et al., 2023).

5.4.3. Government action and policy support

Governmental policies significantly enhance landscape heat resilience by addressing heat resistance and supporting self-organizing recovery through strategic institutional frameworks. Proactive measures, such as early heat-warning systems utilizing predictive analytics, alert landscape managers to extreme heat threats, facilitating timely artificial interventions and prioritizing protection of vulnerable communities (Cui et al., 2024). Strengthening local municipalities' operational capabilities, particularly in smaller cities, enhances their preparedness and responsiveness, directly improving landscape resistance during heat extremes. Public awareness and educational campaigns explicitly address community vulnerability, reducing exposure by informing citizens about heat mitigation and safety practices. Building emergency infrastructure systems—including establishing cooling centers, shaded seating areas, and water stations in high-traffic urban zones—further reduce community heat vulnerability, especially during heatwaves exceeding landscapes' inherent cooling capabilities (Kearl & Vogel, 2023). Policies mandating green infrastructure integration (e.g., water-efficient landscaping, mandatory shade provisions) and financial incentives (e.g., tax credits for green roofs) institutionalize proactive resilience-building practices, enhancing landscapes' capacities to withstand and recover from extreme heat events (Liberalesso et al., 2020). Finally, community involvement in policy development ensures inclusive decision-making, further aligning governance frameworks with diverse community needs and strengthening overall landscape heat resilience (Chapman & Schott, 2020).

5.5. Comprehensive post-evaluation strategies for heat resilience

Post-evaluation is essential for ensuring sustained landscape heat resilience. This evaluation integrates advanced microclimate monitoring technologies, user feedback mechanisms, and routine inspection practices, thereby establishing a dynamic feedback loop that continuously informs adaptive landscape management and improves future resilience outcomes (Fig. 9).

5.5.1. Microclimate monitoring with advanced technologies

Advanced monitoring technologies, including weather stations and drone-based thermal imaging systems, significantly enhance our ability to measure, evaluate, and optimize landscape heat resistance. Drones equipped with thermal sensors precisely identify landscape areas with elevated heat exposure and vulnerability, pinpointing hotspots where existing cooling strategies may be inadequate or failing (Duffy et al., 2021). These detailed aerial assessments guide targeted interventions aimed specifically at reducing exposure and vulnerability. Additionally, ground-based weather stations continuously record microclimatic data. This high-resolution, real-time data directly supports the proactive management and adaptive maintenance of landscapes, ensuring interventions effectively reduce heat vulnerability and maintain optimal conditions for ecological recovery, thus enhancing landscapes' self-organizing capacity following heat disturbances.

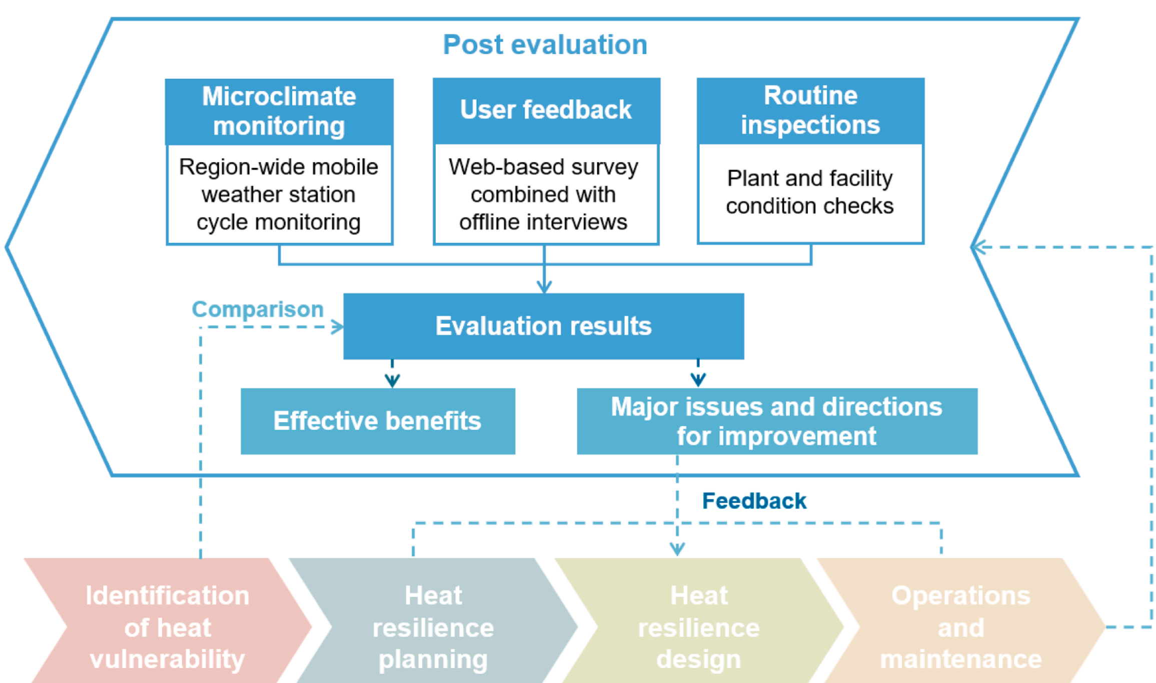

Fig. 9. Workflow for post evaluation of urban landscape heat resilience.

5.5.2. User feedback as a driver of adaptation

User feedback plays a critical role in evaluating the effectiveness of heat resilience strategies, particularly by providing real-world insights into landscape performance concerning human exposure and perceived vulnerability during heat events. Surveys, interviews, and online engagement platforms directly capture user experiences and highlight specific resilience gaps, such as insufficient shading, uncomfortable conditions, or inadequate cooling infrastructure. When feedback reveals shortcomings, landscape architects, climate specialists, and local policymakers collaborate promptly to pinpoint underlying causes and implement targeted improvements. Quick adaptive adjustments, such as altering maintenance practices, enhancing vegetation cover, or adding shading structures, immediately reduce user vulnerability and enhance local heat resistance. Continuous engagement with community members ensures interventions remain aligned with public needs and expectations, significantly reinforcing long-term resilience through adaptive co-management.

5.5.3. Routine inspections for long-term resilience

Regular and rigorous routine inspections are crucial for maintaining and enhancing landscapes' heat resilience over time. Consistent monitoring of plant health provides timely indications of stress—such as wilting, reduced canopy density, or reduced vegetation vigor—allowing landscape managers to proactively enhance vegetation recovery levels and reduce recovery cycles through targeted maintenance interventions, such as increased irrigation, organic soil amendments, and proactive plant replacements. Similarly, regular inspections of structural components—such as misting systems, shading devices, and reflective surfaces—ensure these artificial resilience-supporting features remain fully functional, especially when landscape conditions exceed natural recovery capacities. Heat-induced wear and deterioration of landscape features can significantly compromise heat resistance; thus, continuous preventive maintenance and timely repairs are essential. Staff training in advanced technology usage, microclimatic data interpretation, and adaptive management techniques further supports effective implementation of interventions, systematically strengthening both heat resistance and self-organizing capacity through ongoing adaptive management and continuous improvement.

6. Discussion

6.1. Redefining landscape heat resilience: a complex adaptive systems perspective

This study redefines landscape heat resilience from the perspective of complex adaptive systems by explicitly integrating two critical resilience dimensions: heat resistance (addressing exposure and vulnerability) and self-organizing capacity (focusing on recovery level and recovery cycle). Through a comprehensive analysis of landscape-climate-human interactions, we highlight that traditional landscape frameworks predominantly emphasize immediate cooling functions, often neglecting landscape vulnerability and intrinsic ecological recovery dynamics after heat stress (Huang et al., 2024b). In contrast, our framework explicitly considers landscapes as dynamic, adaptive socio-ecological systems, inherently responsive to climatic conditions and human activities. By incorporating detailed vulnerability assessments and emphasizing the importance of autonomous ecological recovery, this new perspective expands beyond the conventional static role of landscapes as passive cooling elements (Zou & Zhang, 2021). Instead, landscapes are viewed as active agents capable of dynamically reducing vulnerability, enhancing local microclimatic conditions, and supporting ecological and social recovery through self-organizing mechanisms (Nazarian et al., 2022).

6.2. Uniting landscapes for urban cooling and resilience

Integrating diverse urban landscapes—including parks, residential areas, transportation corridors, and peri-urban green spaces—is essential for creating a cohesive urban cooling and resilience network (Rezaei et al., 2024). Unlike traditional fragmented planning methods (Aram et al., 2020; Xiong & He, 2024), a unified approach fosters synergistic effects that systematically strengthen both landscape resistance and recovery capacities. Strategically linking parks with residential areas maximizes shade, reduces vulnerability through evapotranspiration cooling, and promotes ecological connectivity that enhances landscapes' self-organizing capacity. Similarly, carefully designed green transportation corridors improve airflow and shading, directly lowering local exposure and vulnerability to heat (Q. Q. Li et al., 2024). Consequently, our holistic approach explicitly integrates planning, design, operational management, and evaluation stages, ensuring landscape resilience across multiple spatial scales and typologies.

6.3. Contextualizing resilience strategies

Effective implementation of heat resilience strategies must be tailored explicitly to local contexts, directly addressing the variability in landscape vulnerability and recovery capacities across different climatic and socio-ecological conditions (Joshi & Teller, 2024). For instance, the design and implementation of green roofs differ significantly between tropical and arid climates due to variations in exposure, plant species suitability, and ecological recovery potentials. Similarly, distinct landscape types (parks, residential green spaces, transportation corridors, peri-urban green spaces) inherently have varied resilience objectives. Parks prioritize cooling, ecological connectivity, and social recovery; residential spaces aim to minimize local vulnerability and improve human thermal comfort; transportation corridors emphasize pedestrian exposure reduction and ecological recovery; and peri-urban green spaces prioritize fire prevention and ecosystem health. Recognizing these contextual nuances allows landscape managers and planners to clearly set resilience objectives, optimize local heat resistance, and systematically enhance self-organizing recovery capacities (Huang et al., 2024a).

6.4. Rethinking plant selection and biodiversity

Current landscape management practices primarily emphasize native species, potentially overlooking resilient non-native species capable of effectively reducing vulnerability and enhancing recovery under changing climatic conditions. A more flexible approach—integrating both native and carefully selected non-native plant species with high heat and drought tolerance—can significantly improve biodiversity, ecological stability, and self-organizing recovery capacity following heat events (Alberti, 2024). Promoting polycultures and companion planting can optimize resource utilization, reduce ecological vulnerability, and enhance overall landscape resilience by improving ecological connectivity, accelerating vegetation recovery levels, and shortening recovery cycles after disturbances (Molénat et al., 2023).

6.5. Integrating social equity resilience planning

Social equity must be integral to heat resilience strategies due to the heightened vulnerability experienced by marginalized populations, such as low-income residents, the elderly, and children (Ballester et al., 2023; Bedi et al., 2022; Sandholz et al., 2021). Often, these groups face compounded vulnerability from insufficient landscape infrastructure, further increasing heat exposure and vulnerability (Astell-Burt & Feng, 2019; Nesbitt et al., 2019). Explicitly prioritizing resilience interventions—such as community gardens, shaded playgrounds, accessible cooling centers, and barrier-free shaded seating—directly addresses social vulnerability and supports autonomous community recovery following extreme heat events (Cheng et al., 2021; Pfautsch et al., 2022). Age-friendly landscape features, particularly in schools and elderly care centers (Huang et al., 2021; Ma et al., 2021), further reduce exposure, support ecological and social recovery, and significantly enhance community-level self-organizing capacities (Jiao et al., 2023; Kükrer & Eskin, 2021; Otto & Thieken, 2024).

6.6. Revisiting the temporal and spatial linkages of policy

Current climate policy efforts predominantly address global-scale warming through long-term emission reduction targets, yet often overlook short-term, localized vulnerabilities and recovery needs (Azam et al., 2022; Emodi et al., 2019). Recognizing the increasing frequency and intensity of heatwaves (Li & Zha, 2020), policies must also explicitly support short-term, spatially targeted interventions—such as temporary shading structures, cooling centers, and targeted vegetation enhancement—to quickly reduce immediate landscape vulnerability. These localized measures can significantly lower heat exposure and vulnerability in priority areas, while simultaneously supporting self-organizing recovery through adaptive ecological strategies. Combining short-term targeted interventions with long-term strategic planning ensures that immediate landscape resilience needs are addressed without compromising longer-term sustainability and adaptive capacity (Turner et al., 2023).

6.7. Bridging the gap between research and application

A significant gap persists between advanced landscape resilience research and its practical application. This gap stems from two primary challenges: the complexity of accessing and interpreting high-resolution climate and landscape data, and the difficulty of applying sophisticated resilience modeling tools (e.g., WRF, ENVI-met) in real-world scenarios (Liu et al., 2021). To bridge this gap, the development of accessible, coherent decision-support tools and digital platforms is critical. These platforms can significantly simplify real-time monitoring, resilience evaluation, and adaptive landscape management practices, enabling practitioners to readily integrate strategies that explicitly strengthen landscape resistance and facilitate rapid ecological recovery after heat disturbances.

6.8. Aligning landscape heat resilience with sustainable development goals (SDGs)

Our landscape heat resilience framework explicitly aligns with multiple United Nations Sustainable Development Goals (SDGs), systematically addressing urban sustainability, climate adaptation, public health, biodiversity, and collaborative governance (Jia et al., 2024).

SDG 3 (Good health and well-being): Reducing heat exposure and vulnerability through shaded spaces, cooling centers, and misting systems, enhancing public health resilience especially for vulnerable populations.

SDG 11 (Sustainable cities and communities): Comprehensive resilience planning reduces heat vulnerability, improves ecological recovery, and enhances urban sustainability (He et al., 2024).

SDG 13 (Climate action): Directly supports proactive climate adaptation through urban forests and water-based cooling strategies that reduce vulnerability and strengthen ecological recovery capacities.

SDG 15 (Life on land): Incorporating diverse, heat-tolerant vegetation significantly enhances biodiversity, ecological connectivity, and self-organizing recovery capacity, protecting terrestrial ecosystems from climate-driven disturbances.

SDG 17 (Partnerships for the goals): Promotes collaborative governance through inclusive, adaptive decision-making platforms that explicitly integrate resilience assessment, stakeholder engagement, and targeted landscape interventions.

6.9. Integrating green and grey infrastructure for holistic resilience

Effective heat resilience requires the deep integration of green and grey infrastructure, treating them as synergistic partners rather than competitors. This integration is twofold. First, green and grey systems become mutually supportive at a functional level. Green infrastructure provides multiple cooling and ecological benefits, such as stormwater management and biodiversity support (Meerow & Newell, 2017; Nilon et al., 2017), while also shielding grey infrastructure from extreme heat. For instance, tree canopies protect pavements and building facades from solar radiation. In return, grey systems, like smart irrigation or stormwater harvesting structures, provide the essential water and support needed to sustain the health and cooling capacity of urban vegetation (Livesley et al., 2021).

Second, this integrated approach yields powerful social-ecological synergies. Aligning heat interventions with community priorities through participatory design can create multifunctional spaces. Community gardens, shaded gathering areas, and other cooling infrastructures not only reduce heat exposure but also promote social cohesion, physical activity, and mental well-being (Clarke et al., 2023). This ensures that investments in resilience create landscapes that are simultaneously cooler, more ecologically robust, and socially inclusive, directly addressing the core goals of urban sustainability.

7. Conclusions

Amid intensifying climate challenges, this study presents a comprehensive framework for enhancing landscape heat resilience, grounded in two core dimensions: heat resistance (reducing exposure and vulnerability) and self-organizing capacity (improving recovery level and shortening recovery cycle). Unlike traditional views of landscapes as passive cooling tools, this framework redefines them as adaptive systems capable of actively withstanding, recovering from, and adapting to heat stress while sustaining essential ecological and social functions.

This study proposes a full-cycle implementation pathway comprising five stages: (1) identifying heat vulnerability scenarios, (2) planning urban landscape systems, (3) designing resilient landscape spaces, (4) managing and transforming landscape spaces, and (5) conducting thorough post-evaluation. This model supports data-driven, adaptive, and participatory landscape governance, enabling interventions to evolve with climate dynamics.

The framework also acknowledges regional disparities. Cities vary in climatic conditions, governance capacity, and socioeconomic resources. For instance, resource-constrained regions like Jakarta face infrastructural limits, while dense cities such as Tokyo require complex coordination (Ufaira et al., 2023; Yu et al., 2024). Thus, flexibility and inclusiveness are essential for contextual adaptation.

By centering resistance and recovery within a cohesive system, this study offers a strategic roadmap for designing and managing climate-resilient landscapes. It bridges theoretical understanding and practical application, contributing to urban sustainability, social equity, and climate adaptation across diverse settings.

CRediT authorship contribution statement

Boze Huang: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Jinda Qi:** Writing – review & editing, Validation, Investigation, Conceptualization. **Minal Pathak:** Writing – review & editing, Conceptualization. **Ayyoob Sharifi:** Writing – review & editing, Formal analysis. **Ali Cheshmehzangi:** Writing – review & editing, Validation. **Shady Attia:** Writing – review & editing, Validation, Conceptualization. **Andreas Matzarakis:** Writing – review & editing, Validation, Conceptualization. **Amirhosein Ghaffarianhoseini:** Writing – review & editing, Conceptualization. **Geun Young Yun:** Writing – review & editing, Methodology, Funding acquisition. **Amos Darko:** Writing – review & editing, Project administration. **Xiao Liu:** Writing – review & editing, Project administration. **Bao-Jie He:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing 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.

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Data availability

Data will be made available on request.

References

Alberti, M. (2024). Cities of the Anthropocene: Urban sustainability in an eco-evolutionary perspective. *Philosophical Transactions of the Royal Society B, 379*(1893), Article 20220264.
Amores, T. R. P., Ramos, J. S., Delgado, M. G., Medina, D. C., Cerezo-Narvaéz, A., & Domínguez, S.Á. (2023). Effect of green infrastructures supported by adaptative solar shading systems on livability in open spaces. *Urban Forestry & Urban Greening, 82*, 127886.
Amorim-Maia, A. T., Anguelovski, I., Connolly, J., & Chu, E. (2023). Seeking refuge? The potential of urban climate shelters to address intersecting vulnerabilities. *Landscape and Urban Planning, 238*, Article 104836.
Aram, F., Solgi, E., Garcia, E. H., & Mosavi, A. (2020). Urban heat resilience at the time of global warming: Evaluating the impact of the urban parks on outdoor thermal comfort. *Environmental Sciences Europe, 32*, 1–15.
Astell-Burt, T., & Feng, X. J. J.n.o (2019). *Association of urban green space with mental health and general health among adults in Australia, 2*(7). e198209-e198209.
Augusto, B., Roebeling, P., Rafael, S., Ferreira, J., Ascenso, A., & Bodilis, C. (2020). Short and medium-to long-term impacts of nature-based solutions on urban heat. *Sustainable Cities and Society, 57*, Article 102122.
Azam, A., Rafiq, M., Shafique, M., & Yuan, J. H. (2022). Mitigating carbon emissions in China: The role of clean energy, technological innovation, and political-institutional quality. *Frontiers in Environmental Science, 10*, Article 814439.
Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R. F., Pegenaute, F., Herrmann, F. R., Robine, J. M., … Achebak, H. (2023). Heat-related mortality in Europe during the summer of 2022. *Nature Medicine, 29*(7), 1857–1866.
Bedi, N. S., Adams, Q. H., Hess, J. J., & Wellenius, G. A. (2022). The role of cooling centers in protecting vulnerable individuals from extreme heat. *Epidemiology (Cambridge, Mass.), 33*(5), 611–615.
Boucher-Lalonde, V., Morin, A., & Currie, D. J. (2012). How are tree species distributed in climatic space? A simple and general pattern. *Global Ecology and Biogeography, 21* (12), 1157–1166.
Cai, W., Lengaigne, M., Borlace, S., Collins, M., Cowan, T., McPhaden, M. J., … Widlansky, M. J. (2012). More extreme swings of the South Pacific convergence zone due to greenhouse warming. *Nature, 488*(7411), 365–369.
Cao, Q., Liu, Y., Georgescu, M., & Wu, J. (2020). Impacts of landscape changes on local and regional climate: A systematic review. *Landscape Ecology, 35*, 1269–1290.
Chapman, J. M., & Schott, S. (2020). Knowledge coevolution: Generating new understanding through bridging and strengthening distinct knowledge systems and empowering local knowledge holders. *Sustainability Science, 15*(3), 931–943.
Chen, X., Su, Y., Li, D., Huang, G., Chen, W., & Chen, S. (2012). Study on the cooling effects of urban parks on surrounding environments using Landsat TM data: A case study in Guangzhou, southern China. *International Journal of Remote Sensing, 33*(18), 5889–5914.
Chen, G., Lam, C. K. C., Wang, K., Wang, B., Hang, J., Wang, Q., & Wang, X. (2021). Effects of urban geometry on thermal environment in 2D street canyons: A scaled experimental study. *Building and Environment, 198*, Article 107916.
Chen, Y., Yang, J., Yu, W., Ren, J., Xiao, X., & Xia, J. C. (2023). Relationship between urban spatial form and seasonal land surface temperature under different grid scales. *Sustainable Cities and Society, 89*, Article 104374.
Cheng, W., Li, D., Liu, Z., & Brown, R. D. (2021). Approaches for identifying heat-vulnerable populations and locations: A systematic review. *Science of The Total Environment, 799*, Article 149417.
Cheung, P. K., Nice, K. A., & Livesley, S. J. (2024). Impacts of irrigation scheduling on urban green space cooling. *Landscape and Urban Planning, 248*, Article 105103.
Clarke, M., Cadaval, S., Wallace, C., Anderson, E., Egerer, M., Dinkins, L., & Platero, R. (2023). Factors that enhance or hinder social cohesion in urban greenspaces: A literature review. *Urban Forestry & Urban Greening, 84*, 127936.
Cuce, P. M., & Riffat, S. (2016). A state of the art review of evaporative cooling systems for building applications. *Renewable and Sustainable Energy Reviews, 54*, 1240–1249.
Cui, Y., Yin, M., Cheng, X., Tang, J., & He, B.-J. (2024). Towards cool cities and communities: Preparing for an increasingly hot future by the development of heat-resilient infrastructure and urban heat management plan. *Environmental Technology & Innovation, 34*, Article 103568.
Demirel, K., & Kavdır, Y. (2013). Effect of soil water retention barriers on turfgrass growth and soil water content. *Irrigation Science, 31*, 689–700.
Deng, Y., Yao, Y., & Zhang, L. (2023). Analysis of urban wetland park cooling effects and their potential influence factors: Evidence from 477 urban wetland parks in China. *Ecological Indicators, 156*, Article 111103.
Depietri, Y. (2020). The social–ecological dimension of vulnerability and risk to natural hazards. *Sustainability Science, 15*(2), 587–604.
Dimitrov, S., Iliev, M., Borisova, B., Semerdzhieva, L., & Petrov, S. (2024). UAS-based thermal photogrammetry for microscale surface urban heat island intensity assessment in support of sustainable Urban development (A Case Study of Lyulin Housing Complex, Sofia City, Bulgaria). *Sustainability, 16*(5), 1766.
Douglas, O., Lennon, M., & Scott, M. (2017). Green space benefits for health and well-being: A life-course approach for urban planning, design and management. *Cities, 66*, 53–62.
Duffy, J. P., Anderson, K., Fawcett, D., Curtis, R. J., & Maclean, I. M. (2021). Drones provide spatial and volumetric data to deliver new insights into microclimate modelling. *Landscape Ecology, 36*, 685–702.
Emodi, N. V., Chaiechi, T., & Beg, A. (2019). Are emission reduction policies effective under climate change conditions? A backcasting and exploratory scenario approach using the LEAP-OSeMOSYS Model. *Applied Energy, 236*, 1183–1217.
Esperon-Rodriguez, M., Gallagher, R., Souverijns, N., Lejeune, Q., Schleussner, C.-F., & Tjoelker, M. G. (2025). Response to Guerin et al. Comment on 'Mapping the climate risk to urban forests at city scale. *Landscape and Urban Planning, 258*, Article 105324.
Fall, S., Coulibaly, K., Quansah, J., & El Afandi, G. (2023). Differential urban heat vulnerability: The tale of three alabama cities. *Urban Science, 7*(4), 121.
Gober, P., Brazel, A., Quay, R., Myint, S., Grossman-Clarke, S., Miller, A., & Rossi, S. (2009). Using watered landscapes to manipulate urban heat island effects: How much water will it take to cool Phoenix? *Journal of the American Planning Association, 76*(1), 109–121.
Gräf, M., Immitzer, M., Hietz, P., & Stangl, R. (2021). Water-stressed plants do not cool: Leaf surface temperature of living wall plants under drought stress. *Sustainability, 13* (7), 3910.
Haase, D., & Hellwig, R. (2022). Effects of heat and drought stress on the health status of six urban street tree species in Leipzig, Germany. *Trees, Forests and People, 8*, Article 100252.
Hamed, M. M., Alasow, A. A., & Shahid, S. (2024). Global Trends in Human thermal stress: A spatiotemporal analysis from 1940 to 2020. *Earth Systems and Environment, 1-13*.
Han, D., Xu, X., Qiao, Z., Wang, F., Cai, H., An, H., … Han, W. (2023). The roles of surrounding 2D/3D landscapes in park cooling effect: Analysis from extreme hot and normal weather perspectives. *Building and Environment, 231*, Article 110053.
Harmáčková, Z. V., Blättler, L., Aguiar, A. P. D., Daněk, J., Krpec, P., & Vačkářová, D. (2022). Linking multiple values of nature with future impacts: Value-based participatory scenario development for sustainable landscape governance. *Sustainability Science, 17*(3), 849–864.
He, T., Wang, N., Chen, J., Wu, F., Xu, X., Liu, L., … Qiao, Z. (2024). Direct and indirect impacts of land use/cover change on urban heat environment: A 15-year panel data study across 365 Chinese cities during summer daytime and nighttime. *Landscape Ecology, 39*(3), 67.
He, B.-J. (2023). Cause-related injustice, process-related injustice, effect-related injustice and regional heat action planning priorities: An empirical study in Yangtze River Delta and Chengdu-Chongqing urban agglomerations. *Landscape and Urban Planning, 237*, Article 104800.
Huang, B., Hong, B., Tian, Y., Yuan, T., & Su, M. (2021). Outdoor thermal benchmarks and thermal safety for children: A study in China's cold region. *Science of The Total Environment, 787*, Article 147603.
Huang, B., Dong, X., Tian, Y., Yin, M., Qiu, Y., & He, B.-J. (2024a). Experimental investigation of the thermal usability of outdoor environments in rideability, walkability, entertainmentability, exercisability and workability for urban heat mitigation, adaptation and governance. *Natural Hazards, 120*(2), 2005–2034.
Huang, H., Lu, Z., Fan, X., Zhai, W., Zhang, L., Xu, D., Liu, Z., Li, Y., Ye, X., & Qin, H. (2024b). Urban heatwave, green spaces, and mental health: A review based on environmental health risk assessment framework. *Science of The Total Environment, 948*, Article 174816.
Jia, K., Sheng, Q., Liu, Y., Yang, Y., Dong, G., Qiao, Z., … Han, D. (2024). A framework for achieving urban sustainable development goals (SDGs): Evaluation and interaction. *Sustainable Cities and Society, 114*, Article 105780.
Jiao, Y., Yu, Y., Yu, H., & Wang, F. (2023). The impact of thermal environment of transition spaces in elderly-care buildings on thermal adaptation and thermal behavior of the elderly. *Building and Environment, 228*, Article 109871.

Joshi, M. Y., & Teller, J. (2024). Assessing urban heat island mitigation potential of realistic roof greening across local climate zones: A highly-resolved weather research and forecasting model study. *Science of The Total Environment, 944*, 173728.
Kükrer, E., & Eskin, N. (2021). Effect of design and operational strategies on thermal comfort and productivity in a multipurpose school building. *Journal of Building Engineering, 44*, Article 102697.
Karimimoshaver, M., Khalvandi, R., & Khalvandi, M. (2021). The effect of urban morphology on heat accumulation in urban street canyons and mitigation approach. *Sustainable Cities and Society, 73*, 103127.
Kearl, Z., & Vogel, J. (2023). Urban extreme heat, climate change, and saving lives: Lessons from washington state. *Urban Climate, 47*, 101392.
Kim, S. W., & Brown, R. D. (2022). Pedestrians' behavior based on outdoor thermal comfort and micro-scale thermal environments. *Science of The Total Environment, 808*, Article 152143.
Kim, J. Y., Park, C. Y., Hyun, J. H., Kim, S. H., Yun, S. H., & Lee, D. K. (2023). Landscape design for improved thermal environment: An optimized tree arrangement design for climate-responsive outdoor spaces in residential buildings complexes. *Sustainable Cities and Society, 97*, 104762.
Kirschner, V., Macků, K., Moravec, D., & Maňas, J. (2023). Measuring the relationships between various urban green spaces and local climate zones. *Scientific Reports, 13*(1), 9799.
Kraemer, R., & Kabisch, N. (2022). Parks under stress: Air temperature regulation of urban green spaces under conditions of drought and summer heat. *Frontiers in Environmental Science, 10*, 849965.
Lenzholzer, S., & Brown, R. D. (2016). Post-positivist microclimatic urban design research: A review. *Landscape and Urban Planning, 153*, 111–121.
Li, Y., & He, B. J. (2025). Biophilic street design for urban heat resilience. *Progress in Planning, 199*, 100988.
Li, L., & Zha, Y. (2020). Population exposure to extreme heat in China: Frequency, intensity, duration and temporal trends. *Sustainable Cities and Society, 60*, Article 102282.
Li, Q., Zheng, J., Yuan, S., Zhang, L., Dong, R., & Fu, H. (2024a). RAV model: Study on urban refined climate environment assessment and ventilation corridors construction. *Building and Environment, 248*, Article 111080.
Li, Z., Liu, Q., Yan, K., Xiong, D., Xu, P., Yan, Y., & Lin, L. (2024b). Cooling effects of urban parks under various ecological factors. *Urban Climate, 58*, Article 102134. https://doi.org/10.1016/j.uclim.2024.102134
Liberalesso, T., Cruz, C. O., Silva, C. M., & Manso, M. (2020). Green infrastructure and public policies: An international review of green roofs and green walls incentives. *Land Use Policy, 96*, Article 104693.
Liu, Z., Cheng, W., Jim, C. Y., Morakinyo, T. E., Shi, Y., & Ng, E. (2021). Heat mitigation benefits of urban green and blue infrastructures: A systematic review of modeling techniques, validation and scenario simulation in ENVI-met V4. *Building and Environment, 200*, Article 107939.
Liu, J., Gao, H., Jia, R., Wang, R., Han, D., Liu, L., … Qiao, Z. (2025). A downscaling framework with WRF-UCM and LES/RANS models for urban microclimate simulation strategy: Validation through both measurement and mechanism model. *Building and Environment, 269*, Article 112361.
Livesley, S. J., Marchionni, V., Cheung, P. K., Daly, E., & Pataki, D. E. (2021). Water smart cities increase irrigation to provide cool refuge in a climate crisis. *Earth's Future, 9*(1). e2020EF001806.
Lucchi, E., Turati, F., Colombo, B., & Schito, E. (2024). Climate-responsive design practices: A transdisciplinary methodology for achieving sustainable development goals in cultural and natural heritage. *Journal of Cleaner Production, 457*, Article 142431.
Ma, X., Tian, Y., Du, M., Hong, B., & Lin, B. (2021). How to design comfortable open spaces for the elderly? Implications of their thermal perceptions in an urban park. *Science of The Total Environment, 768*, Article 144985.
Mahmoud, A. H. A (2011). Analysis of the microclimatic and human comfort conditions in an urban park in hot and arid regions. *Building and Environment, 46*(12), 2641–2656.
Meerow, S., & Newell, J. P. (2017). Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. *Landscape and Urban Planning, 159*, 62–75.
Miller, J., Böhnisch, A., Ludwig, R., & Brunner, M. I. (2024). Climate change impacts on regional fire weather in heterogeneous landscapes of central Europe. *Natural Hazards and Earth System Sciences, 24*(2), 411–428.
Miranda, V. F. V. V., dos Santos, D. M., Peres, L. F., Salvador, C., Nieto, R., Müller, G. V., … Libonati, R. (2024). Heat stress in South America over the last four decades: A bioclimatic analysis. *Theoretical and Applied Climatology, 155*(2), 911–928.
Molénat, J., Barkaoui, K., Benyoussef, S., Mekki, I., Zitouna, R., & Jacob, F. (2023). Diversification from field to landscape to adapt Mediterranean rainfed agriculture to water scarcity in climate change context. *Current Opinion in Environmental Sustainability, 65*, Article 101336.
Morakinyo, T. E., Ouyang, W., Lau, K. K.-L., Ren, C., & Ng, E. (2020). Right tree, right place (urban canyon): Tree species selection approach for optimum urban heat mitigation - development and evaluation. *Science of The Total Environment, 719*, Article 137461.
Muniz-Gäal, L. P., Pezzuto, C. C., Carvalho, M. F. H.d., & Mota, L. T. M. (2020). Urban geometry and the microclimate of street canyons in tropical climate. *Building and Environment, 169*, Article 106547.
Nasr, Y., El Zakhem, H., Hamami, A. E., El Bachawati, M., & Belarbi, R. (2024). Comprehensive assessment of the impact of green roofs and walls on building energy performance: A scientific review. *Energies, 17*(20), 5160.
Nazarian, N., Krayenhoff, E., Bechtel, B., Hondula, D., Paolini, R., Vanos, J., Cheung, T., Chow, W., de Dear, R., & Jay, O. (2022). Integrated assessment of urban overheating impacts on human life. *Earth's Future, 10*(8). e2022EF002682.
Nesbitt, L., Meitner, M. J., Girling, C., Sheppard, S. R. J. U. F., & Greening, U. (2019). *Urban green equity on the ground: Practice-based models of urban green equity in three multicultural cities, 44*, Article 126433.
Nilon, C. H., Aronson, M. F., Cilliers, S. S., Dobbs, C., Frazee, L. J., Goddard, M. A., O'Neill, K. M., Roberts, D., Stander, E. K., & Werner, P. (2017). Planning for the future of urban biodiversity: A global review of city-scale initiatives. *BioScience, 67* (4), 332–342.
Ophardt, M. C., & Hummel, R. L. (2020). *Environmental injury: Sunscald and sunburn on trees, 4* pp. 2–6). Washington State University Research and Extension Center Bulletin.
Orlov, A., Sillmann, J., Aunan, K., Kjellstrom, T., & Aaheim, A. (2020). Economic costs of heat-induced reductions in worker productivity due to global warming. *Global Environmental Change, 63*, Article 102087.
Otto, A., & Thieken, A. H. (2024). How do childcare centers cope with heat?–Findings of a mixed-method approach from three German cities. *Climate Risk Management, 44*, Article 100597.
Parmesan, C., & Hanley, M. E. (2015). Plants and climate change: Complexities and surprises. *Annals of Botany, 116*(6), 849–864.
Percival, G. C. (2023). Heat tolerance of urban trees – A review. *Urban Forestry & Urban Greening, 86*, Article 128021.
Pfautsch, S., Wujeska-Klause, A., & Walters, J. (2022). Outdoor playgrounds and climate change: Importance of surface materials and shade to extend play time and prevent burn injuries. *Building and Environment, 223*, Article 109500.
Pisello, A. L. (2017). State of the art on the development of cool coatings for buildings and cities. *Solar Energy, 144*, 660–680.
Qi, J., & He, B.-J. (2023). Urban Heat Mitigation Strategies. In A. Cheshmehzangi, B.-J. He, A. Sharifi, & A. Matzarakis (Eds.), *Climate Change and Cooling Cities* (pp. 21–44). Singapore: Springer Nature.
Qi, J., Ding, L., & Lim, S. (2021). *Toward cool cities and communities: A sensitivity analysis method to identify the key planning and design variables for urban heat mitigation techniques, 75*. Sustainable Cities and Society, Article 103377.
Qin, Y. (2015). A review on the development of cool pavements to mitigate urban heat island effect. *Renewable and Sustainable Energy Reviews, 52*, 445–459.
Qiu, Y., Schertzer, D., & Tchiguirinskaia, I. (2021). Assessing cost-effectiveness of nature-based solutions scenarios: Integrating hydrological impacts and life cycle costs. *Journal of Cleaner Production, 329*, Article 129740.
Raymond, C. M., Stedman, R., & Frantzeskaki, N. (2023). The role of nature-based solutions and senses of place in enabling just city transitions. *Environmental Science & Policy, 144*, 10–19.
Rezaei, T., Shen, X., Chaiyarat, R., & Pumijumnong, N. (2024). Effective cooling networks: Optimizing corridors for Urban Heat Island mitigation. *Remote Sensing Applications: Society and Environment, 36*, Article 101372.
Rizwan, A. M., Dennis, L. Y., & Chunho, L. (2008). A review on the generation, determination and mitigation of Urban Heat Island. *Journal of Environmental Sciences, 20*(1), 120–128.
Rynkiewicz, A., Hościło, A., Aune-Lundberg, L., Nilsen, A. B., & Lewandowska, A. (2025). Detection and quantification of vegetation losses with sentinel-2 images using Bi-temporal analysis of spectral indices and transferable random forest model. *Remote Sensing, 17*(6), 979.
Sadok, W., Lopez, J. R., & Smith, K. P. (2021). Transpiration increases under high-temperature stress: Potential mechanisms, trade-offs and prospects for crop resilience in a warming world. *Plant, Cell & Environment, 44*(7), 2102–2116.
Sampson, N. R., Gronlund, C. J., Buxton, M. A., Catalano, L., White-Newsome, J. L., Conlon, K. C., O'Neill, M. S., McCormick, S., & Parker, E. A. (2013). Staying cool in a changing climate: Reaching vulnerable populations during heat events. *Global Environmental Change, 23*(2), 475–484.
Sandholz, S., Sett, D., Greco, A., Wannewitz, M., & Garschagen, M. (2021). *Rethinking urban heat stress: Assessing risk and adaptation options across socioeconomic groups in bonn, 37*. Germany: Urban Climate, Article 100857.
Sandifer, P. A., Sutton-Grier, A. E., & Ward, B. P. (2015). Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: Opportunities to enhance health and biodiversity conservation. *Ecosystem Services, 12*, 1–15.
Santamouris, M., & Kolokotsa, D. (2015). On the impact of urban overheating and extreme climatic conditions on housing, energy, comfort and environmental quality of vulnerable population in Europe. *Energy and Buildings, 98*, 125–133.
Santamouris, M., Gaitani, N., Spanou, A., Saliari, M., Giannopoulou, K., Vasilakopoulou, K., & Kardomateas, T. (2012). Using cool paving materials to improve microclimate of urban areas–Design realization and results of the flisvos project. *Building and Environment, 53*, 128–136.
Sanusi, R., & Bidin, S. (2020). *Re*-naturing cities: Impact of microclimate, human thermal comfort and recreational participation. *Climate Change, Hazards and Adaptation Options: Handling the Impacts of a Changing Climate*, 545–562.
Sato, H., Mizoi, J., Shinozaki, K., & Yamaguchi-Shinozaki, K. (2024). Complex plant responses to drought and heat stress under climate change. *The Plant Journal, 117*(6), 1873–1892.
Shamsaei, M., Carter, A., & Vaillancourt, M. (2022). A review on the heat transfer in asphalt pavements and urban heat island mitigation methods. *Construction and Building Materials, 359*, Article 129350.
Sharifi, A. (2021). Co-benefits and synergies between urban climate change mitigation and adaptation measures: A literature review. *Science of The Total Environment, 750*, Article 141642.

Sharma, A., Conry, P., Fernando, H., Hamlet, A. F., Hellmann, J., & Chen, F. J. E. R. L. (2016). Green and cool roofs to mitigate urban heat island effects in the Chicago metropolitan area: Evaluation with a regional climate model. *Environmental Research Letters, 11*(6), Article 064004.

Shashua-Bar, L., Hoffman, M. E., & Tzamir, Y. (2006). Integrated thermal effects of generic built forms and vegetation on the UCL microclimate. *Building and Environment, 41*(3), 343–354.

Shen, J., Cong, S., Zhang, N., & Ma, Y. (2023). Reliability modelling and self-healing policy design for systems with limited resources. *Reliability Engineering & System Safety, 240*, Article 109537.

Sola-Caraballo, J., Serrano-Jiménez, A., Rivera-Gomez, C., & Galan-Marin, C. (2025). Multi-criteria assessment of urban thermal hotspots: A GIS-based remote sensing approach in a Mediterranean climate City. *Remote Sensing, 17*(2), 231.

Stange, E. E., Barton, D. N., Andersson, E., & Haase, D. (2022). Comparing the implicit valuation of ecosystem services from nature-based solutions in performance-based green area indicators across three European cities. *Landscape and Urban Planning, 219*, Article 104310.

Tan, P. Y., Wong, N. H., Tan, C. L., Jusuf, S. K., Schmiele, K., & Chiam, Z. Q. (2020). Transpiration and cooling potential of tropical urban trees from different native habitats. *Science of The Total Environment, 705*, Article 135764.

Turner, V. K., Middel, A., & Vanos, J. K. (2023). Shade is an essential solution for hotter cities. *Nature, 619*(7971), 694–697.

Tyagi, G., & Danish, M. (2025). Reflective building façades: The effect of albedo on outdoor thermal comfort–A case study of low-rise apartments. *Nature Environment and Pollution Technology, 24*(2), 1–13.

Ufaira, R., Amir, S., Indraprahasta, G. S., & Nastiti, A. (2023). Living in a hot city: Thermal justice through green open space provision. *Frontiers in Human Dynamics, 5*, Article 1237515.

Urban, J., Matoušková, M., Robb, W., Jelínek, B., & Úradníček, L. (2023). Effect of drought on photosynthesis of trees and shrubs in habitat corridors. *Forests, 14*(8), 1521. https://www.mdpi.com/1999-4907/14/8/1521.

Vloon, C. C., Evju, M., Klanderud, K., & Hagen, D. (2022). Alpine restoration: Planting and seeding of native species facilitate vegetation recovery. *Restoration Ecology, 30* (1), Article e13479.

Xiong, K., & He, B.-J. (2024). Planning for heat-resilient educational precincts: Framework formulation, cooling infrastructure selection and walkable routes determination. *Sustainable Cities and Society, 101*, 105183.

Xu, Z., FitzGerald, G., Guo, Y., Jalaludin, B., & Tong, S. (2016). Impact of heatwave on mortality under different heatwave definitions: A systematic review and meta-analysis. *Environment International, 89*, 193–203.

Yu, J., Castellani, K., Forysinski, K., Gustafson, P., Lu, J., Peterson, E., Tran, M., Yao, A., Zhao, J., & Brauer, M. (2021). Geospatial indicators of exposure, sensitivity, and adaptive capacity to assess neighbourhood variation in vulnerability to climate change-related health hazards. *Environmental Health, 20*, 1–20.

Yu, S., Lei, K. L., Li, D., Kim, Y. J., Nemoto, M., Gatson, S., … Brown, R. (2024). Plan integration for urban extreme heat: Evaluating the impacts of plans at multiple scales in Tokyo, Japan. *Urban Climate, 55*, Article 101888.

Zhai, J., Ren, J., Xi, M., Tang, X., & Zhang, Y. (2021). Multiscale watershed landscape infrastructure: Integrated system design for sponge city development. *Urban Forestry & Urban Greening, 60*, 127060.

Zhang, Y., Li, Q., Ge, Y., Du, X., & Wang, H. (2022). Growing prevalence of heat over cold extremes with overall milder extremes and multiple successive events. *Communications Earth & Environment, 3*(1), 73.

Zhang, X., Zhao, T., Xu, H., Liu, W., Wang, J., Chen, X., & Liu, L. (2024). GLC_FCS30D: The first global 30 m land-cover dynamics monitoring product with a fine classification system for the period from 1985 to 2022 generated using dense-time-series Landsat imagery and the continuous change-detection method. *Earth System Science Data, 16*(3), 1353–1381.

Zhao, Y., Sen, S., Susca, T., Iaria, J., Kubilay, A., Gunawardena, K., Zhou, X., Takane, Y., Park, Y., & Wang, X. (2023). Beating urban heat: Multimeasure-centric solution sets and a complementary framework for decision-making. *Renewable and Sustainable Energy Reviews, 186*, Article 113668.

Zhao, C., Pan, Y., Ren, S., Gao, Y., Wu, H., & Ma, G. (2024a). Accurate vegetation destruction detection using remote sensing imagery based on the three-band difference vegetation index (TBDVI) and dual-temporal detection method. *International Journal of Applied Earth Observation and Geoinformation, 127*, Article 103669. https://doi.org/10.1016/j.jag.2024.103669

Zhao, C., Pan, Y., & Zhang, P. (2024b). Development of a new indicator for identifying vegetation destruction events using remote sensing data. *Ecological Indicators, 166*, Article 112553. https://doi.org/10.1016/j.ecolind.2024.112553

Zou, M., & Zhang, H. (2021). Cooling strategies for thermal comfort in cities: A review of key methods in landscape design. *Environmental Science and Pollution Research, 28* (44), 62640–62650.

Zou, Q., Yang, J., Zhang, Y., Bai, Y., & Wang, J. (2025). Variation in community heat vulnerability for Shenyang City under local climate zone perspective. *Building and Environment, 267*, Article 112242.