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Urban Forestry and Green Infrastructure for Climate Resilience

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ABSTRACT

Urban areas face escalating climate risks—rising temperatures, extreme precipitation, flooding, and deteriorating air quality—that demand urgent, scalable nature-based responses. This review synthesizes interdisciplinary evidence to evaluate the role of urban forestry and green infrastructure as nature-based solutions for building urban climate resilience. We examine the biophysical mechanisms through which trees and green infrastructure regulate urban climates, including shading, evapotranspiration, infiltration, and carbon assimilation, and assess how these processes generate critical ecosystem services: heat island mitigation, stormwater attenuation, carbon sequestration, air quality improvement, and biodiversity enhancement. Evidence from international case studies demonstrates that increasing urban tree canopy cover by 10–30% can reduce ambient air temperatures by 1–4°C, while green infrastructure such as bioswales and rain gardens can intercept 40–80% of stormwater runoff. Carbon sequestration in urban forests ranges from 0.2 to 2.0 Mg C ha^{-1} yr^{-1}, depending on species composition and management. We further examine the socio-ecological dimensions of urban forestry, including community well-being, thermal comfort, and health co-benefits. However, the delivery of these services is contingent on appropriate species selection, spatial configuration, canopy structure, and adaptive governance. We identify critical knowledge gaps, particularly the limited economic valuation of urban ecosystem services, insufficient evidence from Global South cities, and the need for fine-scale spatial modelling. We conclude that integrating urban forestry and green infrastructure into climate-resilient planning frameworks requires strengthened empirical evidence, equity-sensitive design, and cross-sectoral governance to realise their full potential as systemic climate solutions.

Keywords Urban forestry, Green infrastructure, Climate resilience, Urban heat island mitigation, Ecosystem services, Nature-based solutions.

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INTRODUCTION

Urban centres around the world are becoming increasingly exposed to the growing effects of climate change and require resilient and adaptive planning strategies (Gorjian 2025). Green infrastructure and urban forestry represent a nature-based approach to increase urban resilience to extreme heat, flooding, and air pollution, delivering multiple co-benefits through ecological processes (Brašanac-Bosanac *et al.* 2022; Umoh *et al.* 2024). We synthesize the urban forestry and green infrastructure literature to critically assess mechanisms related to climate change adaptation, quantify relevant ecosystem services, and highlight research gaps (Aleha *et al.* 2024; Salih and Nagy 2024). Despite the increasing attention on urban climate resilience, specific implementation strategies, defining features and criteria of success for green infrastructure are still under debate (Meerow 2017). This review critically assesses the effectiveness of a range of urban green infrastructure components such as urban forests, green roofs, and permeable surfaces in providing quantifiable climate adaptation outcomes in a variety of urban typologies and socio-ecological settings (Demuzere *et al.* 2014).

Defining urban forestry, green infrastructure, and climate resilience

The proliferation of terms such as “green infrastructure,” “urban forestry,” “nature-based solutions,” and “ecosystem services” often leads to conceptual ambiguity within the literature, necessitating a clear delineation of these interlinked concepts for rigorous scientific discourse (Jia and Turcu 2025). Specifically, urban forestry is defined as the planned management of tree populations in urban areas for environmental, economic, and social benefits and green infrastructure is broadly defines as “a planned network of natural and semi-natural areas” that is intended to provide a diversity of ecosystem services, such as moderating climate and enhancing urban resilience (Meemrot *et al.* 2024). This conceptual understanding is essential for the development of robust frameworks that effectively combine these approaches into urban planning and climate adaptation measures given their proven ability to mitigate the heat island effect, mitigate the effects of stormwater and increase biodiversity (Albers *et al*. 2021; Ashinze *et al.* 2024; Pandey and Ghosh 2023). Green infrastructure means integrating natural and semi-natural systems, such as urban forests, parks, green roofs, and vegetated corridors, into urban landscapes to provide crucial ecosystem services, including carbon sequestration, air purification, stormwater management, and thermal regulation (Khalifi *et al*. 2025). The potential of nature-based solutions for promoting urban resilience through addressing urban heat islands and related challenges that can be directly addressed by shading and evapotranspiration through varied vegetated spaces (Yuan 2024). Such strategic multiscale integration of green features, ranging from storm water planters and green roofs at the site level to urban forests and parkways at the city scale, is essential to preserve the natural hydrological functioning by absorbing, infiltrating and storing water and effectively respond to the vulnerability issues caused by the intensification precipitation and flood events (Shade *et al.* 2020; Tauhid 2018). Climate resilience refers to urban systems' ability to anticipate, absorb, accommodate, and adapt to climate change impacts quickly and effectively while maintaining critical functions and components (Reynolds *et al*. 2021). Nature-based solutions offer a framework for achieving this resilience, as they are based on nature-inspired interventions to address societal challenges that result in environmental, social, and economic co-benefits in an urban context (Zarei and Shahab 2025). We will, in this review, assess the pathways through which urban forestry and green infrastructure (GI) enable climate resilience, estimate the quantification of the resulting ecosystem services, and identify knowledge deficits that will inform future research and policy pathways (Segura *et al.* 2024). The conceptual integration of these three pillars and their cascading pathways to urban climate resilience is illustrated in Fig 1.

Fig. 1. Conceptual integration of urban forestry, green infrastructure, and climate resilience. The figure 1 illustrates how urban forestry, green infrastructure, and nature-based solutions drive key ecosystem functions, including carbon sequestration, thermal regulation, stormwater management, and air purification, through biophysical processes such as shading, evapotranspiration, and infiltration. These functions generate ecosystem services that support climate mitigation, adaptation, biodiversity enhancement, hydrological stability, and human well-being. Together, these pathways contribute to urban climate resilience

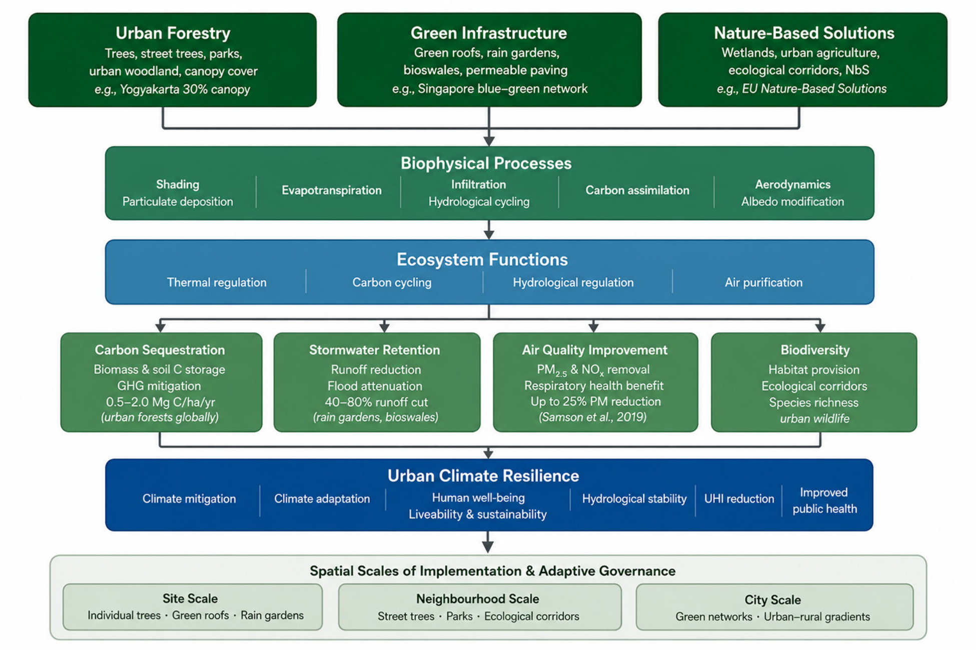

Fig. 1. Conceptual integration of urban forestry, green infrastructure, and nature-based solutions. Three green-intervention domains drive biophysical processes and ecosystem functions, yielding four ecosystem-service outputs (carbon sequestration, stormwater retention, air-quality improvement, biodiversity) that collectively build urban climate resilience across site, neighbourhood, and city scales under adaptive governance.

across site, neighborhood, and city scales, supported by adaptive governance and iterative planning.

Resilience theory in urban ecosystems

Resilience theory in urban ecosystems: an urgent need to understand how cities respond to increasing threats to life on Earth from storm events, heat waves, and other stresses (Mosleh *et al.* 2023). This understanding includes ecological resilience, which is understood as: the capacity of ecological systems to absorb disturbance and reorganise and adapt during change, and social-ecological resilience, which includes ecophysiological and sociophysiological adaptive capacities (Huff *et al.* 2020). This framework extends to an understanding of urban ecosystem functioning as a consequence of organismal interactions and life history characteristics which support essential functions such as soil stabilization, water retention and radiation reflectance (Kabisch *et al.* 2017). This integrated interplay of processes underlies how urban green infrastructure can provide ecosystem services that strengthen the resilience of urban areas to disturbances (White *et al*. 2023). Hence, the implementation of such infrastructure needs to move on from static design to temporally responsive systems that combine ecological performance with governance needs by conceptualizing mechanisms of urban planting as a time-dynamic instrument of microclimate response and systemic adaptation to compound climate risks (Jiang and Zhai 2025). The interaction of trees and other vegetation with the urban environment contributes to modifications of microclimates, the hydrological cycle, and biodiversity. These modifications provide tangible benefits in the form of ecosystem services(Privitera 2024; Ivanova *et al.* 2026). In evaluating urban forestry, this contribution will highlight specific interactions through literature that quantitatively assess the effects of urban forests on temperature, stormwater runoff, and biodiversity. The will also further describe how these services can enhance resilience in urban climate through means such as energy savings, improved air quality and human well-being and reveal gaps in knowledge in long-term, replicated studies across multiple cities (Piana *et al.* 2021). Moreover, we will explore how different species and/functions diversity of urban forests determine their resistance and resilience against climate related stressors, such as drought and high temperatures (Esperón-Rodríguez *et al.* 2025).

Mechanisms of climate regulation by urban forestry and green infrastructure

In this section, we critically discuss the biophysical processes of urban forestry and green infrastructure mediated climate regulation by addressing how individual elements of evapotranspiration, shading, and aerodynamic processes interact and combine to influence urban heat island mitigation, and urban-scale temperature. The cooling effects of urban trees are strongly driven by shading and evapotranspiration, which are in turn influenced by tree characters, spatial patterns, and climatic conditions (Alonzo *et al.* 2025). The potential effectiveness of urban green infrastructure to alleviate urban heat island is a function of the growth of permeable nature, enhanced tree canopy and/or need for green space in high solar radiation environments (Doussard and Delabarre 2023). Optimal tree-species mix for maximum thermal amelioration: importance of crown architecture and water use efficiency under anticipated drought and heat stress provision (Kraemer and Kabisch 2022). Moreover, the structural traits of urban trees such as canopy density and leaf area index affect greenhouse gas emissions and temperature, and thereby the urban heat island effect, with certain species reducing ambient air temperatures by as much as 0.9°C under specific configurations (Ali *et al*. 2021). Additionally, urban cooling can also be aided by selective planting: research in hundreds of European cities shows that a 16–18% increase in tree cover might result in an average temperature decrease of 0.4–1.0 °C (Oukawa *et al.* 2025).

Urban heat island mitigation

The improvement is mostly provided by the biophysical interactions of shading that screens the solar input and evapotranspiration as a latent heat loss, modifying surface and mean air temperature (Cordeiro *et al.* 2023). Both mechanisms are heavily dependent on tree properties (crown structure, leaves area) and the urban context (canyon geometry, material properties) (Wu *et al.* 2024). More explicitly, the effectiveness of shade is directly proportional to crown architecture and leaf area density and other species-specific capabilities for capturing radiation, while ET rates are strongly dependent on stomatal conductance, water stress and the innate species-specific response to heat (Samson *et al.* 2019; Wang *et al.* 2021). The potential of trees for cooling is also influenced by tree height, canopy form and foliage density, continuous shade canopies achieve large energy savings through the reduction of solar heat input to building façades (Giyasova 2021; WESTENDORFF 2020). Moreover, due to its combined shading and evapotranspiration, tree shade can be more effective at lowering urban temperatures than built infrastructure shade, and canopy characteristics such as Leaf Area Index and Crown Projected Area are important factors that contribute to the superior cooling effect of trees (Reitberger *et al*. 2024). On the other hand, surface impermeability of artificial urban areas, such as asphalt and concrete, tends to absorb and reemit the solar radiation, which is positively related to the urban heat island (Hwang *et al.* 2015). Empirical evidence from global studies demonstrates that a 10% increase in urban tree canopy cover can reduce mean radiant temperature by 0.5–2.0°C (Li *et al.* 2024a). In Singapore, a strategic increase in canopy cover from 29% to 38% reduced outdoor thermal discomfort by 18% (Tan *et al.* cited in Gao *et al.* 2024). A study across 19 European cities found that parks reduced maximum air temperatures by up to 2.8°C compared to surrounding built-up areas, with cooling effects extending up to 100 m into adjacent neighborhoods (Kraemer and Kabisch 2022). In desert cities such as Abu Dhabi, irrigated green infrastructure reduced summer surface temperatures by up to 4°C relative to unplanted control plots (Gao *et al.* 2024). These findings confirm that the magnitude of UHI mitigation is strongly modulated by background climate, tree species, and urban morphology (Li *et al*. 2024a; Alonzo *et al.* 2025).

Carbon sequestration and storage

Beyond the immediate thermal regulation benefits, urban forestry plays a pivotal role in climate change mitigation through carbon sequestration and long-term storage within biomass and soils (Deng *et al.* 2019). This ecosystem service, by lowering atmospheric CO_2 concentrations and reducing the greenhouse effect, directly reduces the major contributor(s) to global climate change at the global scale (Orlandi *et al.* 2022). Additionally, the difference between high percent tree cover in urban green spaces maximizes trees' carbon sequestration capacities by allowing them to absorb greater quantities of carbon than release into the atmosphere (Solomou *et al.* 2018). Although the total amount of carbon stored is limited in urban forests by available space within the cities, a management strategy in place, nice growing conditions and good water resources can increase carbon storage rates and storage capacity (Wilson *et al.* 2022). Moreover, urban trees mitigate the effects of climate change by assimilation and sequestration and by lowering direct and indirect greenhouse gas emissions in cities (Locosselli and Buckeridge 2023). Quantitative assessments reveal that urban trees globally sequester between 0.2 and 2.0 Mg C ha^{-1} yr^{-1}, depending on species composition, age structure, and management regime (Borelli *et al.* 2023). A comprehensive analysis of 33 US cities estimated total urban forest carbon storage at 643 million tonnes, with sequestration rates averaging 25.6 Tg C yr^{-1} (Wilson *et al.* 2022). In the ChangZhuTan urban agglomeration in China, ecosystem services supply—including carbon sequestration—declined by 12.3% in newly urbanized zones compared to old urban areas, underscoring the importance of proactive green planning in growing cities (Li *et al.* 2024b). In India, urban forest patches in Guwahati demonstrated carbon stocks of 45–68 Mg C ha^{-1}, comparable to tropical secondary forests, highlighting the high mitigation potential of urban greenery in rapidly urbanizing Asian cities (Athokpam *et al.* 2024). These figures underscore that urban forestry is not merely an amenity but a measurable contributor to national carbon budgets.

Stormwater and flood regulation

Urban forests and green infrastructure effectively mitigate stormwater runoff and improve flood regulation by enhancing infiltration, interception, and evapotranspiration, and thus, decreasing the volume and velocity of surface flows (Borelli *et al*. 2023). This is a result of the compounded effects of canopy interception which diminishes the direct effect of rainfall on impervious surfaces and increased soil permeability leading to increased subsurface infiltration and groundwater recharge (Aditya and Ningam, 2021). Specifically, the complex root structures of trees enhance the soil which in turn, improves hydraulic conductivity and reduces bulk density, improving the soil's water absorption and retention capacity (Rahim *et al.* 2024). These processes reduce peak stormwater flows, ease strain on urban drainage systems, and lessen the magnitude and frequency of site-level flooding events, forming a cornerstone of urban hydrological resilience (Singh *et al*. 2020). Additionally, urban trees also regulate climate by intercepting particulate matter and gaseous pollutants including precursors to ground level ozone; thereby improving the urban air quality and co-delivering these measures co-benefits for health (Sabir *et al.* 2024). Nature-based solutions to climate resilience in cities: urban green infrastructure for people, nature, and climate. In addition to the direct benefits to climate resilience, urban green infrastructure also plays key role in maintaining and improving urban biodiversity through creation of ecosystem habitat and ecological corridors. Thus, the overall impact of green infrastructure on increasing biodiversity and ecological connectivity cannot be overlooked when considering the drivers and benefits of green infrastructure. Addressing urban water and heat challenges, water and offsetting some of the impacts of climate change and supporting biodiversity and ecosystem services are just some of the roles green infrastructure can play to address environmental challenges in the city. As such, urban forestry and green infrastructure can indeed effectively contribute to multiple forms of sustainability and resilience in the city, because it provides multi-faceted benefits to people, nature, and the climate. (Guarino *et al.* 2024). Quantified assessments show that bioretention cells and rain gardens can intercept 40–80% of annual stormwater runoff, with peak flow reductions of up to 70% during high-intensity storm events (Mosleh *et al.* 2023). A case study in Lausanne, Switzerland demonstrated that nature-based stormwater solutions reduced combined sewer overflow events by 35% annually, while simultaneously providing biodiversity co-benefits (Doussard and Delabarre 2023). In tropical cities, where intense monsoonal rainfall poses acute flood

Table 1. Mechanisms, ecosystem services, and resilience outcomes of urban forestry and green infrastructure.

Thematic Component	Key Mechanisms / Processes	Ecosystem Services Generated	Quantitative / Empirical Indicators	Resilience Contribution
Urban Heat Island Mitigation	Shading (solar interception), evapotranspiration (latent heat flux), aerodynamic exchange, reduced sensible heat flux	Thermal regulation, microclimate cooling	0.4–1.0°C reduction with 16–18% canopy increase; up to 0.9°C species-specific cooling; lower surface temperatures (30–35°C vs 45–60°C)	Reduced heat stress, lower mortality risk, improved thermal comfort
Carbon Sequestration and Storage	Photosynthetic assimilation, biomass accumulation, soil organic carbon storage	Climate change mitigation, greenhouse gas reduction	Increased carbon uptake in high canopy cover areas; enhanced storage under optimal management and water availability	Reduced atmospheric CO_2 concentrations; long-term climate stabilization
Stormwater and Flood Regulation	Canopy interception, root-mediated infiltration, increased hydraulic conductivity, evapotranspiration	Runoff reduction, groundwater recharge, hydrological stability	Reduced peak flow, delayed runoff response, improved soil permeability	Reduced flood risk, improved urban hydrological resilience
Air Quality Regulation	Deposition of particulate matter, gaseous pollutant absorption, ozone precursor reduction	Improved air quality, public health protection	Reduction in PM2.5 deposition; decreased ground-level ozone formation	Reduced respiratory risk; enhanced urban liveability
Biodiversity and Ecological Function	Habitat provision, ecological corridors, structural diversity (LAI, crown density), species richness	Biodiversity enhancement, ecosystem functioning	Increased avian and insect diversity; improved ecological connectivity	Greater ecological stability and adaptive capacity
Socio-Ecological Co-benefits	Integration of ecological and social systems, multifunctional green spaces, community engagement	Public health improvement, social cohesion, reduced energy demand	Reduced building cooling demand; improved mental well-being indicators	Strengthened social-ecological resilience and adaptive governance
Multiscale Integration	Site-level (green roofs, bioswales), neighborhood-level (street trees), city-scale (urban forest networks)	Integrated ecosystem service delivery	Cumulative canopy cover expansion; distributed cooling effects	System-level resilience across spatial scales
Design and Management Strategies	Climate-resilient species selection, crown architecture optimization, water-use efficiency, adaptive governance	Sustained ecosystem service performance	Species-specific performance under drought and heat stress	Long-term resilience under compound climate stressors

risk, urban forests in Guwahati, India retained approximately 58% of incident rainfall through canopy interception and litter-layer infiltration (Athokpam *et al.* 2024). The hydrological performance of green infrastructure is, however, strongly scale-dependent; Sayah *et al.* (2021) demonstrated that spatial variability in rainfall distribution generates significant uncertainty (±30%) in model-predicted NbS performance, emphasising the need for distributed monitoring and adaptive management frameworks. A study across Multan, Pakistan found that expanding urban forest cover by 20% could reduce annual urban flood damage by an estimated USD 12 million (Aleha *et al.* 2024), illustrating the economic as well as ecological value of green stormwater management.

Air quality regulation

Beyond the ecological and hydrological advantages, urban forests enhance urban air quality by absorbing gaseous pollutants and through deposition of particulates (as shown in Table 1), reducing health risks from air pollution to respiratory health and improving liveability in urban areas. The removal of air pollutants and cooling effects of urban trees together create a healthier urban space, especially reducing formation of ground-level ozone.(Santamouris and Osmond 2020). This pollutant removal, together with carbon sequestration and stormwater management, underscores that urban greening is an important tool for multi-dimensional environmental enhancement and public health promotion in cities (Kumar *et al.* 2025). In addition to they are of an important ecological value, urban forests also enhances the image and perceived quality of neighborhoods, as well as to promotes mental health and social cohesion in urban communities (Staddon *et al.* 2018). Therefore, integrating urban forestry and green infrastructure into urban planning frameworks is crucial for fostering sustainable, resilient, and healthy cities that can effectively adapt to the multifaceted challenges posed by climate change (Csete and Poyraz 2022; Janowiak *et al.* 2021). This holistic approach that takes into account both ecological and social benefits highlights the importance of urban green infrastructure in sustainable urban climate resilience management (Pauleit *et al*. 2018). Quantitative evidence indicates that urban trees can remove 711,000 metric tonnes of air pollution annually across the United States, with associated health benefits valued at USD 3.8 billion per year (Samson *et al.* 2019). Particulate matter ($PM_{2.5}$) concentrations can be reduced by 10–25% in street canyons with dense tree canopy compared to bare streets, with broadleaf species such as Platanus x hispanica demonstrating superior pollutant capture capacity due to their high leaf area index and rough surface texture (Sabir *et al.* 2024). In urban areas of Pakistan, monitoring across different land use zones found $PM_{2.5}$ concentrations 34% lower in green-space-dominated zones compared to commercial districts (Sabir *et al.* 2024). A meta-analysis of 52 European cities confirmed that a 1% increase in urban green cover was associated with a 0.08 μg m^{-3} decrease in ambient NO_2 concentration (Kumar *et al.* 2025). However, it is important to note that some tree species emit biogenic volatile organic compounds (BVOCs) that can exacerbate tropospheric ozone formation under high-temperature, high-NOx conditions—highlighting the importance of species selection in urban air quality management (Samson *et al.* 2019; Wu *et al.* 2024).

Biodiversity and ecological function in urban green spaces

Urban green infrastructure (a network of green spaces) is becoming recognized as a key element of urban ecosystems that provides habitat for flora and fauna and vital ecosystem services that enhance urban resilience (Athokpam *et al.* 2024; Dipeolu *et al.* 2020). This infrastructure, encompassing diverse elements like trees, green roofs, and wetlands, supports ecological functions ranging from local climate regulation to critical habitat provision (Hanna *et al*. 2022; Staddon *et al.* 2018). These greening features have a substantial role in the preservation of bird habitats, insect prey, and microorganisms, thus enhancing biodiversity of the cityscape (Ashinze *et al.* 2024; Pandey and Ghosh 2023). Ecological enrichment is especially important in light of the increasing effects of urbanization on natural habitats and the growing importance of green urban spaces as a component of regional biodiversity (Edeigba *et al*. 2024). Such varied green environments as parks, gardens, green roofs, wetlands, and street trees are essential components of sustainable and ecological urban planning that provide remarkable benefits to society and health, and reduce the effects of climate change and improve urban life quality (Athokpam *et al.* 2024). These spaces also offer significant social and psychological benefits, fostering community well-being and providing essential recreational opportunities (Kifayatullah *et al.* 2025). Case studies from Mediterranean cities demonstrate that semi-natural green infrastructure patches support 40–60% higher plant species richness than conventional urban parks, underscoring the value of ecological complexity in urban design (Guarino *et al.* 2024). A global analysis of 54 cities found that tree species richness was the strongest predictor of urban heat island mitigation magnitude, with each additional tree species contributing a 0.12°C reduction in maximum urban temperatures—a finding that argues for diversity-conscious urban planting strategies (Wang *et al*. 2021). In the UK, urban green corridors supporting pollinator communities were found to increase crop yields in peri-urban agricultural zones by up to 18% through enhanced ecosystem service delivery (Segura *et al.* 2024). Urban forests in Northeast India—including community-managed sacred groves in Manipur and Assam—harbor endemic plant species absent from managed parks, demonstrating that indigenous and community-led green spaces contribute disproportionately to urban biodiversity (Athokpam *et al.* 2024). These findings collectively argue for a biodiversity-sensitive, functionally diverse approach to urban greening that moves beyond monoculture street tree planting towards ecologically complex, multi-layered green infrastructure networks.

Socio-ecological dimensions of urban forestry and climate resilience

Integration of urban forestry and green infrastructure in socio-ecological systems is key to climate resilience: socio-ecological systems as intermediaries between natural and human worlds (Herath and Bai 2024). This holistic viewpoint recognizes urban green spaces as more than just ecological resources, but rather, as essential elements of human health and incorporate community-building, public health, and environmental awareness of the city habitants (Kusam 2024). The interdisciplinary perspective of green infrastructure shows the necessity of making use of comprehensive assessment tools considering both ecological and social aspects to something, looking at coherences and tensions between the different functions and services that urban greening can produce (Ocokoljić *et al.* 2024). This requires an integrative, interdisciplinary approach to urban planning, whereby social science and ecological principles are combined, to successfully capture the co-benefits that are possible (Vargas-Hernández and Zdunek-Wielgołaska 2020). These co-benefits often encompass improvements in human well-being through opportunities for physical activity, social engagement, and stress reduction, alongside ecological gains like enhanced biodiversity and microclimate regulation (Delgado-Capel and Cariñanos 2020; Tongyun *et al.* 2024). Such a collaborative approach requires an understanding of how human values and community action interact with ecological concepts to guide the development of resilient urban forest ecosystems (Xie *et al.* 2024). The integrated biophysical mechanisms underpinning these socio-ecological outcomes are conceptualised in Fig. 2. Quantitative evidence links urban green space access directly to measurable health outcomes: a landmark study of 290 European cities found that a 10% increase in urban green space was associated with a 4% reduction in all-cause mortality and a 6% reduction in cardiovascular mortality (White *et al.* 2023). In Singapore, long-term resident surveys found that proximity to parks (within 400 m) was associated with 18% lower rates of depressive symptoms and 12% higher self-reported well-being scores compared to residents without nearby green access (Herath and Bai 2024). Economic co-benefits are equally significant: urban trees in the United States provide an estimated USD 18.3 billion annually in energy savings through building shading and cooling, alongside property value uplifts averaging 7–15% for residences adjacent to mature tree canopy (Wilson *et al.* 2022). These socio-economic dimensions strengthen the policy case for urban forestry investment as a multi-sectoral public good, linking environmental, health, and economic governance frameworks.

Fig. 2. Integrated biophysical mechanisms of climate regulation by urban forestry and green infrastructure. The figure is organized into six analytical strata that sequentially represent the vertical and functional integration of processes governing urban climate regulation. Stratum 1 depicts atmospheric forcing, including incoming shortwave radiation, outgoing longwave radiation, wind speed, and turbulent exchange within the urban boundary layer, framed by the surface energy balance equation ($Rn = H + LE + G$). Stratum 2 contrasts impervious and vegetated surfaces, highlighting differences in permeability, thermal inertia, albedo, and sensible heat flux that underpin urban heat island dynamics. Stratum 3 details tree physiological and microclimatic mechanisms, including shading, evapotranspiration, stomatal conductance, crown architecture, leaf area index, and root-mediated infiltration processes that modulate latent heat flux and groundwater recharge. Stratum 4 synthesizes functional climate regulation outputs, namely heat island mitigation, carbon sequestration in biomass and soils, stormwater peak reduction, air pollutant removal, and biodiversity support. Stratum 5 illustrates downstream socio-ecological co-benefits such as reduced energy demand, improved public health, enhanced thermal comfort, social cohesion, and urban livability. Stratum 6 emphasizes multiscale spatial integration across site, neighborhood, and city

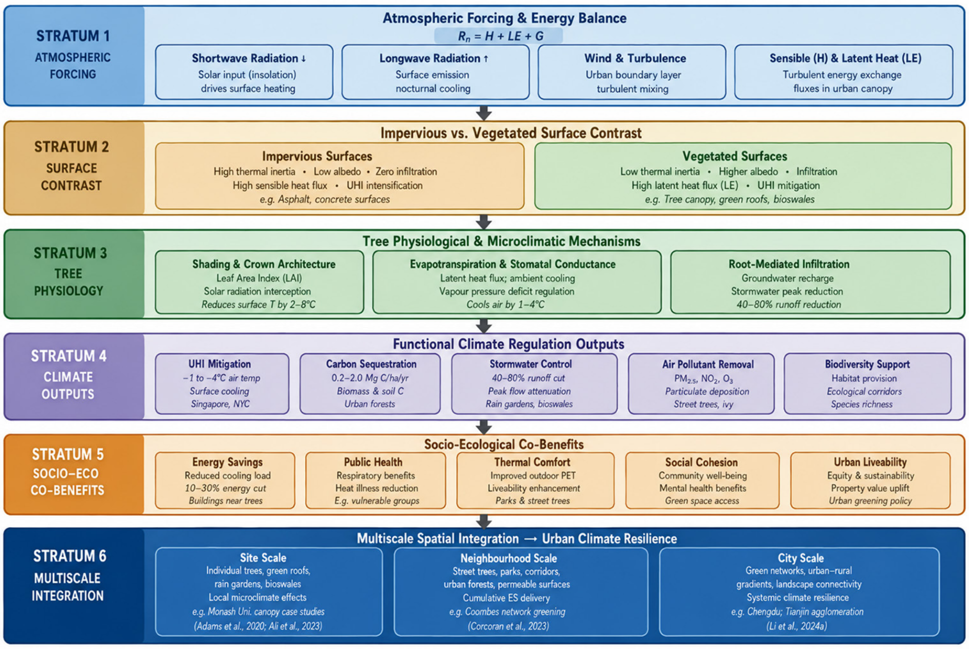

Fig. 2. Integrated biophysical mechanisms of climate regulation by urban forestry and green infrastructure, structured in six interacting strata: atmospheric forcing and energy balance, impervious–vegetated surface contrast, tree physiological and microclimatic mechanisms, functional climate-regulation outputs, socio-ecological co-benefits, and multiscale spatial integration delivering systemic urban climate resilience.

levels, underscoring that urban climate resilience emerges from the cumulative and spatially nested interactions of energy, hydrological, carbon, and ecological processes.

Design, planning, and management strategies for climate-resilient urban forests

Urban forestry and green infrastructure are crucial for climate resilience but may not tap their full potential unless design, planning and management are developed using ecological principles and governance that support adaptivity. To maximize the climate resilience co-benefits of urban forestry and green infrastructure: incorporate nature-based solutions into urban master plans; respond to the local ecological context; and design for socio-economic and ecological benefits using multi-function green spaces (Barron *et al.* 2019). An integrated cooling strategy requires an in-depth understanding of how specific species respond physiologically to urban stressors such as drought and heat, as these factors determine the cooling performance and sustainability of plantings (Rahman *et al.* 2024). This requires selecting climate-resilient species, including potentially non-native species when native species cannot sufficiently deliver essential ecosystem services within harsh urban landscapes (Carlin *et al.* 2025). Such decisions necessitate careful consideration of potential ecological impacts, including invasiveness, alongside the immediate benefits for urban thermal regulation (Hoyle and Sant'Anna 2020). Evidence-based design frameworks increasingly adopt the 3-30-300 rule—recommending that every urban resident can see at least 3 trees from their home, that every neighborhood has a minimum of 30% canopy cover, and that every resident lives within 300 m of a quality green space (Carlin *et al.* 2025). This framework, now formally adopted by cities including Singapore, Melbourne, and Oslo, provides a scalable benchmark for equity-sensitive urban forest planning. Spatial analysis using GIS-based equity mapping in Pakistan revealed that 68% of low-income neighborhoods fell below the 30% canopy threshold, compared to only 22% of high-income zones (Kifayatullah *et al.* 2025)—a finding that underscores the need to embed environmental justice principles within green infrastructure masterplans. Adaptive management approaches, which integrate real-time sensor networks for microclimate monitoring with species performance databases, have been shown to improve the cost-effectiveness of urban forest management by 25–40% over conventional prescriptive approaches (Janowiak *et al.* 2021; Rahman *et al*. 2024).

Limitations, trade-offs, and risks of urban forestry and green infrastructure

Urban forestry and green infrastructure offer clear and significant benefits; however, significant limitations, uncertainties, trade-offs, and risks associated with their implementation must be subjected to a rigorous and objective critical analysis. These constraints can emerge as spatial, resource allocation and management issues, and as ecological and social inter-related dynamics in the complex urban environment (Salmond *et al.* 2016). For example, urban trees can significantly alleviate the urban heat island effect (up to 2 C lower ambient temperatures and improved thermal comfort), but only if they are properly irrigated, particularly during heatwaves, to overcome the lower moisture availability in built-up environments (Cuce *et al.* 2025; Vo and Hu 2021). Without adequate watering, the evaporative cooling potential of urban trees diminishes, potentially leading to increased sensible heat flux from the canopy and surrounding impervious surfaces, thereby exacerbating localized thermal discomfort rather than mitigating it (Mabon *et al.* 2023). Moreover, the cooling effect of urban trees varies across species related to traits such as leaf area index and canopy architecture, which determine shading and transpiration rates (IPCC 2023). A life cycle assessment (LCA) of green roofs across 12 European cities found that the embodied carbon cost of installation offset the operational cooling benefits for an average of 8–15 years, implying that green infrastructure is most effective as a long-term climate investment rather than a short-term mitigation measure (Khalifi *et al.* 2025). Trade-offs between cooling benefits and water consumption are particularly acute in arid and semi-arid regions: irrigated urban trees in Riyadh, Saudi Arabia required 350–450 litres per tree per day during peak summer, raising critical questions about water security in water-stressed cities (Gao *et al.* 2024). Pollen emissions from flowering urban trees represent an underappreciated public health risk: allergenic species such as Platanus, Betula, and Cupressus are responsible for increasing rates of allergic rhinitis in European cities, with urban warming extending pollen seasons by 10–27 days over the past three decades (Reitberger *et al.* 2024). Social equity dimensions are equally important: Shade *et al.* (2020) demonstrated that urban greening initiatives in US cities disproportionately benefited high-income neighborhoods, a pattern termed "green gentrification," where improved amenity values drive displacement of low-income residents. Recognising and designing around these trade-offs is essential for urban forestry to fulfil its potential as an equitable climate resilience tool.

Research gaps and future directions

Further research is required to measure the cooling benefit of individual green infrastructure elements, such as irrigation and water features, that have been less studied than vegetation density and shade (Bartesaghi-Koc *et al.* 2018). There is also a lack on identifying the minimum required treed area to achieve effective temperature decrease, thermal comfort and health benefits (An and Dedekorkut-Howes 2025). Moreover, the literature so far primarily covered developed areas and demands broader investigations from the Global South to consider various climatic contexts and urbanization regimes (Li *et al.* 2024a). Furthermore, integration of microscale climate models with mesoscale simulations are required to properly evaluate the benefits and ecological risks of urban greening (Gao *et al.* 2024). Future work should also explore the possibility of increased aeroallergens and disease vectors that may arise with increased urban vegetation expansion, even as medical and other health benefits increase (Heaviside 2020). Likewise, a significant gap in the current research relates to the development of robust, generalizable methods for measurement of the ecosystem services derived from urban forestry and green infrastructure in varied climatic zones and urban typologies (Karam 2023). Specifically, a holistic understanding of supply and demand for ecosystem services in multidimensional urban contexts is still missing, necessitating further studies that recognize ecosystems as central urban infrastructure (Sayah *et al*. 2021). A particularly critical gap is the near-absence of long-term performance monitoring datasets for urban green infrastructure in Global South cities, where the majority of future urban growth will occur (Uchôa *et al.* 2023). Existing evidence is skewed towards temperate, high-income city contexts, limiting generalisability to tropical and arid megacities in South Asia, Sub-Saharan Africa, and Latin America. The integration of remote sensing—including high-resolution LiDAR for three-dimensional canopy mapping and hyperspectral imagery for species identification—with machine learning frameworks offers a promising pathway to bridge these data gaps at scale (Xie *et al.* 2024). Future research should also develop standardized protocols for valuing urban ecosystem services in monetary terms, as the absence of consistent economic valuation methods currently prevents meaningful cost-benefit comparisons across city contexts (Herath and Bai 2024). Finally, given evidence that tree drought resilience varies substantially among species and provenance populations (Esperón-Rodríguez *et al.* 2025), proactive species trials under projected future climate conditions are urgently needed to build future-proof urban forest portfolios. Addressing these gaps demands transdisciplinary collaboration among urban ecologists, climate scientists, urban planners, public health researchers, and communities.

CONCLUSION

This comprehensive review underscores the critical role of urban forestry and green infrastructure as essential nature-based solutions for enhancing urban climate resilience. We provide a synthesis of international literature on the role of greening to combat urban heat islands, manage stormwater, sequester carbon and improve local biodiversity, thereby enriching healthier and more livable cities. A clearer understanding of ecosystem services and economic values for urban forest is crucial for the effective implementation of urban forest management and policy across the world, particularly in tropical contexts (Uchôa *et al*. 2023). We also identified a knowledge gap in the economic evidence for many urban ecosystem services, which for example can impede sound comparisons of the benefits of nature-based solutions in cost-benefit analyses and thereby support decisions on optimal urban planning and investment decisions. Future empirical research of the monetary benefits of green infrastructure should therefore be given priority to provide stronger economic arguments for green infrastructure development. At the same time, while many studies have identified benefits for such solutions in addressing urban heat, labor-intensive studies across different climate types are still needed as well as further validation of models that predict benefits of green infrastructure across different urban settings (i.e. across cities): to avoid biased understandings and justifications by means of over- or under-estimating potential benefits in local ecological settings. Such studies should incorporate robust methodologies for quantifying ecosystem service delivery, recognizing the complex interplay between ecological processes, urban planning, and socio-economic factors to ensure sustainable urban futures (Gulsrud *et al.* 2018). Moreover, accurate estimation of diverse land uses and the measurement of urban ecosystem services at a more detailed scale require high-resolution land cover and improved urbanization metrics to mitigate the potential inadequacies of low-resolution data which can result in underestimation (Li *et al*. 2024b). In the interests of promoting resource quality and ecosystem services, future research should aim to improve the remote sensing and Geo-spatial modelling of urban landscapes and ecosystem services at a fine-scale heterogeneity. These developments provide critical building blocks for more accurate measurements of urban ecosystem service provisioning and demand, to be used in planning and policy-making.

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