

Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs

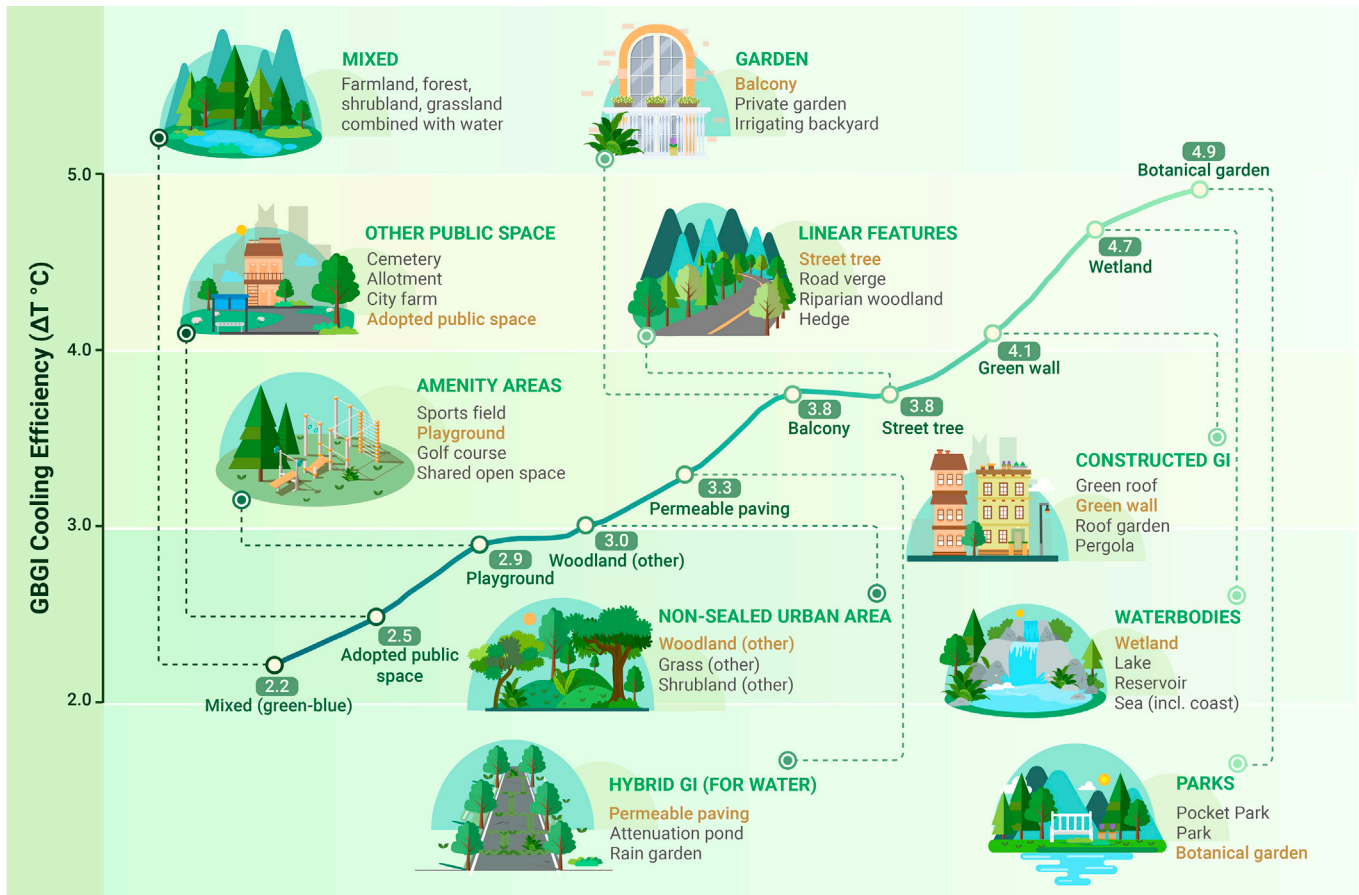
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- This review focuses on how to mitigate the risk of urban overheating by green-blue-grey infrastructure (GBGI).
- Fifty-one GBGI types in 10 key categories assessed by monitoring > modeling > remote sensing > mixed methods.
- Highest cooling efficiency: botanical garden > wetland > green wall > street trees.
- New GBGI implementation should consider future climate impact, multifunctional co-benefits, and unintended consequences.



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The combination of urbanization and global warming leads to urban overheating and compounds the frequency and intensity of extreme heat events due to climate change. Yet, the risk of urban overheating can be mitigated by urban green-blue-grey infrastructure (GBGI), such as parks, wetlands, and engineered greening, which have the potential to effectively reduce summer air temperatures. Despite many reviews, the evidence bases on quantified GBGI cooling benefits remains partial and the practical recommendations for implementation are unclear. This systematic literature review synthesizes the evidence base for heat mitigation and related co-benefits, identifies knowledge gaps, and proposes recommendations for their implementation to maximize their benefits. After screening 27,486 papers, 202 were reviewed, based on 51 GBGI types categorized under 10 main divisions. Certain GBGI (green walls, parks, street trees) have been well researched for their urban cooling capabilities. However, several other GBGI have received negligible (zoological garden, golf course, estuary) or minimal (private garden, allotment) attention. The most efficient air cooling was observed in botanical gardens ($5.0 \pm 3.5^\circ\text{C}$), wetlands ($4.9 \pm 3.2^\circ\text{C}$), green walls ($4.1 \pm 4.2^\circ\text{C}$), street trees ($3.8 \pm 3.1^\circ\text{C}$), and vegetated balconies ($3.8 \pm 2.7^\circ\text{C}$). Under changing climate conditions (2070–2100) with consideration of RCP8.5, there is a shift in climate subtypes, either within the same climate zone (e.g., Dfa to Dfb and Cfb to Cfa) or across other climate zones (e.g., Dfb [continental warm-summer humid] to BSk [dry, cold semi-arid] and Cwa [temperate] to Am [tropical]). These shifts may result in lower efficiency for the current GBGI in the future. Given the importance of multiple services, it is crucial to balance their functionality, cooling performance, and other related co-benefits when planning for the future GBGI. This global GBGI

heat mitigation inventory can assist policymakers and urban planners in prioritizing effective interventions to reduce the risk of urban overheating, filling research gaps, and promoting community resilience.

INTRODUCTION

Heatwaves are of great concern to society as they negatively impact human health, economy, and natural ecosystems.^{1–4} While there is no universal definition of heatwaves, they are generally defined as episodes where the air temperature exceeds certain thresholds over days or weeks.^{5,6} These hazards are extensive meteorological phenomena, typically spanning continents and involving vast amounts of heated air. The extreme heat phenomenon arises from a combination of factors, including rising urban density, elevated summer air temperatures, and intensified anthropogenic activities, resulting in surplus heat generation and reduced albedo and transpiration cooling. Consequently, it leads to elevated day-time temperatures during summer and, notably, warmer nights as well.⁷ Globally, heatwaves have substantially increased in frequency and intensity since the 1950s due to climate change, and are now considered by scientific and other professional communities to be a direct consequence of rising greenhouse gas concentrations in the Earth's atmosphere.^{2,8–11} Between 1998 and 2017, heatwaves were responsible for the global deaths of more than 166,000 individuals, with more than 70,000 fatalities, concomitant drought and subsequent crop failure, leading to an economic loss of EUR 16 billion^{12,13} during the August 2003 heatwave in Europe.¹⁴ There was a significant increase in the annual number of hours experiencing heat stress in South America between 1979 and 2020.¹⁵ The rate of increase varied depending on the Köppen-Geiger class, ranging from +1.16 h per year to +8.25 h per year. In the last two decades, all the cities analyzed not only

witnessed more consecutive hours under heat stress compared with the preceding two decades, but also experienced a greater persistence of these conditions. A heat-related mortality burden of 62,862 deaths was attributed to the record hot summer of 2022 in Europe, emphasizing the need for enhanced heat surveillance, prevention plans, and long-term adaptation strategies.¹⁶ A record-breaking air temperature of 40.3°C was noted on July 19, 2022, in the UK.¹⁷ In July 2023, the world experienced the hottest month on record, with widespread heatwaves across many countries in the northern hemisphere.¹⁸ Wu et al.¹⁹ analyzed data from 717 locations across 36 countries and reported the increased mortality rates due to climate change-induced temperature variability and temperature rise, while Campbell et al.²⁰ in their global review of health impacts focused on vulnerable populations. Xu et al.²¹ studied mortality under different heatwave definitions and accounting for different climatic contexts and different socio-demographic characteristics of the study populations to provide a more nuanced perspective than a simple heatwave duration and intensity analysis would yield. For example, the health of a given population is a strong determinant of the outcome of heatwave events and the severity should be viewed through the lens of a health-based metric.²² However, while health impacts are critically important, there is a greater impact on human wellbeing that reaches into altered daily patterns of behavior and myriad social, and ultimately economic, consequences.²³ More frequent and intense hot extremes are expected to persist in the 21st century.²⁴ On land, temperature extremes will increase faster compared with the increase in global mean (land and ocean combined) temperature due to accelerating global climate change from anthropogenic emissions. This necessitates transitioning to renewables, fortifying carbon sinks, and resilient adaptation strategies.²⁵ Thus, the increasing frequency, amplitude, and duration of heatwaves forces governments to take action against the increasing risk of heat-related mortality and morbidity. The increasing implementation of cooling centers^{26–29} is a clear indicator that governments are beginning to take action to protect their populations from extreme heat.

As acknowledged by the International Panel on Climate Change,²⁴ green and blue urban infrastructure elements are particularly effective in reducing air temperatures in cities. Green-blue-grey infrastructure (GBGI), which includes vegetation-based (green = trees, grass, hedges, etc.), water-based (blue = pools, ponds, lakes, rivers, etc.), and engineered (gray = green walls, green facades, and roofs) structures, have been widely proposed to mitigate the impact of urban overheating and decrease energy consumption.³⁰ They have the potential to play a vital role in improving the quality of life for urban residents, enhancing biodiversity, mitigating climate change impacts, and promoting overall sustainability.³¹ GBGI, especially its green component, can regulate urban heat and may promote a more comfortable and cooler urban environment^{32–35} through various mechanisms such as evaporation,^{36,37} transpiration, shading,^{38,39} and thermal insulation.^{40,41} Blue infrastructure, which includes water bodies such as ponds, canals, rivers, streams, lakes, and wetlands, absorbs heat and cools the surrounding area through evaporation. Different forms of green infrastructure have been found effective in keeping urban environments cool. For example, Tan et al.⁴² used a regional modeling approach for the Chicago metropolitan area and reported that green roofs reduce the near-surface temperature by 14% compared with solar panel roofs. Likewise, Blanco et al.⁴³ found that green vegetated walls recorded up to 7.7°C lower surface temperature than the uncovered concrete wall during summertime in Valenzano (Bari), Italy. Coutts et al.⁴⁴ highlighted that street trees can cool summer daytime air temperatures by up to 1.5°C, yet reported that the cooling effect of trees during extreme heat events was not significant between streets with and without trees. Street trees were also shown to significantly lower surface temperatures in cities across Europe.⁴⁵ Several urban heat mitigation studies have also assessed the potential of urban water management for improving urban cooling through the retention of water in the urban environment.^{29–31,46–48} As an example, the integration of natural water features within cities can effectively cool surrounding areas such as lakes and ponds (10%–50% cooler inside between 30 and 200 m than at edges), rivers (5%–15% cooling effect), and urban wetlands (5%–20% cooling effect).^{49,50} High amounts of tree canopy cover, green space, green roofs and walls, and open space have been reported to decrease urban heat through evapotranspiration cooling.^{51,52} The combined use of multiple heat mitigation measures has been proposed to substantially decrease urban air temperatures.^{52–54} Haddad et al.⁵⁴ quantified the benefits of city-scale heat mitigation measures to human health, energy consumption, and peak electricity demand. They reported that the best-performing mitigation scenarios were those that combined cool mate-

rials, shading, and greenery to reduce the peak ambient air temperature by 2.7°C in comparison with areas without GBGI interventions. Sadeghi et al.⁵⁵ analyzed the impact of urban greening infrastructure strategies (tree cover, green roofs, and green areas) on the Universal Thermal Climate Index (UTCI) under 3 scenarios across 10 weather stations in Sydney, Australia. UTCI measures the impact of urban heat on human comfort and health, considering meteorological variables (air temperature, humidity, wind speed, and radiation). It helps to explain and address the challenges posed by heat in cities. Their simulation study showed that planting 2 million well watered trees in the Sydney Basin could decrease the urban daily average UTCI by 0.2°C–1.7°C during a heatwave. Additionally, the health impact assessment revealed a potential decrease in heat-related deaths by up to 11.7 per day across Sydney. This is in addition to the numerous other health and wellbeing benefits that GBGI provides through ecological ecosystem services.⁵⁶

Table 1 provides an overview of past review articles that focused on the heat mitigation potential of green (e.g., trees, parks, grass, pocket park, sports field, golf course, city farms, playgrounds, riparian woodland), blue (e.g., ponds, sea, reservoir, wetlands, lakes, rivers, canals, and streams), or engineered (e.g., green roofs, green walls, roof garden) interventions. The majority of these past reviews have focused on the cooling effect of different forms of green infrastructure^{42,57–59} while others examined blue infrastructure in the context of urban heat mitigation.⁶⁰ However, none of these studies has systematically assessed the direct urban cooling benefits of the many various forms of urban GBGI alongside the co-benefits these GBGI interventions offer. Most reviews focused on investigating trees, followed by green roofs, parks (or other large green areas), and vertical greenings while numerous other GBGI such as gardens (botanical, heritage, nursery, zoological, rain, backyard), sports fields, vegetated balconies, water-based solutions (wetland, reservoir, estuary/tidal, river, lake, pond, sea, water canal/ditch) were not within their scope. Therefore, the novelty of this paper lies in the systematic assessment of a comprehensive list of 51 GBGI types under 10 main categories, based on the typology of Jones et al.⁶¹ Furthermore, this review offers a comprehensive analysis of GBGI effectiveness against heatwaves in various climate zones and sub-climate conditions; and it explores the dependence of GBGI effectiveness on multiple potentially influencing factors (e.g., population density, altitude, city area, spatial scale, GBGI-area to city-area ratio, temporal trends, monitoring location, and surrounding environment). This allows us to draw insights for optimizing GBGI strategies for different conditions.

This review article aims to comprehensively consolidate and interpret the existing scientific studies related to GBGI, with the ultimate goal of creating a global GBGI database that encompasses their direct advantages such as urban heat mitigation, as well as their co-benefits, which include managing other natural hazards, addressing societal issues, or enhancing biodiversity. The specific objectives are to (1) conduct a systematic review of the literature assessing GBGI's effectiveness in urban heat mitigation and the availability of information about their co-benefits and potential drawbacks, (2) emphasize the most effective and extensively researched GBGI approach for addressing urban heating out of the 51 GBGI types that were evaluated, (3) identify areas of knowledge that are currently underdeveloped, and (4) suggest guidelines for the planning, implementation, monitoring, and evaluation of GBGI for maximum urban cooling benefits. We aim to emphasize that our systematic review is designed to provide a comprehensive analysis of the entire spectrum of research in this domain, rather than focusing solely on recent papers. Our systematic review is designed to address specific research questions (i.e., what is the efficacy of the broad range of GBGI used in urban environments? Which GBGI types are most and least efficient and what are the challenges associated with the GBGI intervention assessments for urban heating?) through a stepwise analysis of the data extracted from the relevant research papers that were identified through a predefined search and a consistent data extraction criterion.

MATERIALS AND METHODS

The review adopts a classification presented by Jones et al.⁶¹ and expands it to 51 GBGI types under 10 broad categories: gardens, parks, amenity areas, linear features/routes, constructed green infrastructure (GI) on infrastructure, hybrid GI (for water), water bodies, other non-sealed urban areas, other public spaces, and mixed (green-blue). Apart

Table 1. Summary of the most relevant review articles since 2019 on the multiple benefits of GBGI for urban heat adaptation and mitigation

GBGI type (location)	Key findings	Authors
Green roofs and green walls (Mexico)	Examined green roofs and green walls, along with their energy, thermal, and environmental benefits, considering factors such as vegetation, climate, substrate, configuration, and green roof policies in Mexico. The primary focus was the assessment of surface and interior temperatures as critical parameters.	Ávila-Hernández et al. ⁶²
Green roofs (US)	Examined the impact of cool roofs, green roofs, and solar panel roofs on near-surface temperature and cooling energy demand. The effectiveness of green roofs reduced temperature by 14% compared with solar panel roofs.	Tan et al. ⁴²
Urban and peri-urban forests (Global)	Confirms dendrochronology as a valuable tool for evidence-based decision-making in urban planning. It has broad geographical applicability and diverse applications, including climate risk assessment, cultural heritage preservation, environmental pollution evaluation, and tree management.	Miyahara et al. ⁶³
GI shading, water-sensitive urban design (Australia)	Reviewed different components of heat vulnerability (e.g., exposure, sensitivity, and adaptive capacity) and mitigation options in Australia. GI and water-sensitive urban design have proven to be efficient in reducing the impacts of heat in Australia.	Adnan et al. ⁶⁴
Economic, social, environmental and cultural benefits of BGI	Emphasizes the ability of GBGI to deliver multifunctionality, meeting a number of needs, priorities, and objectives on various scales, from communities to cities to strategies, making it a critical infrastructure that is heavily dependent on design and planning. It introduces the 'four capitals' approach to help frame engineering that is synergistic with system interdependency.	Bader et al. ³¹
Gardens, green roofs, vertical greening systems, public parks, urban trees, and forests (Nigeria).	Examined the current state of urban GI in Nigeria, such as domestic gardening, green roofs, vertical greening systems, public parks, and urban forests and highlighted the benefits, disadvantages, barriers, and opportunities of GI to improve environmental quality and enhance the quality of life in Nigeria's rapidly expanding cities.	Adegun et al. ⁵⁹
Trees, green roofs, vertical greenings, and water bodies (Global)	Evaluated papers for their modeling, validation, and scenario simulation process for the heatwave mitigation benefits of urban GI and BI and concluded that GBGI design should incorporate appropriate implantation location, arrangement, and orientation to optimize the shaded area for improving the cooling effect.	Liu et al. ⁶⁵
Tree canopy cover (Global)	Collected empirical data at ground level for below-canopy surface temperature and transpiration cooling of trees' canopy density. Tree canopy cover can provide shading, reduce local air temperatures, and create a cooler and more comfortable environment, particularly for pedestrians. Trees that provide dense shade at least over paved surfaces should be prioritized since every unit of leaf area index led to around 4°C of surface cooling.	Rahman et al. ⁵⁸
Green-blue (waterbodies, greenspaces, and parks) (Global)	Reviewed cooling efficiency of BGI (waterbodies, greenspaces, and parks) and identified influencing factors on the cooling effect of GBGI like size, shape, connectivity, and climate variations.	Yu et al. ⁶⁶
Blue space (ponds, lakes, rivers, canals streams) (Global)	Analyzed thermal effects of static blue spaces on the UHI and showed that the size and shape of blue spaces are important variables for the cooling achieved in an urban environment.	Ampatzidis and Kershaw ⁶⁰
Small, medium, and large-sized urban parks (Global)	Reviewed the cooling effects of urban green spaces in recent years and reported that the highest cooling effect distance and cooling effect intensity are for large urban parks with an area of more than 10 ha.	Aram et al. ⁵⁷
Nature-based solutions (Global)	Assessed the impact of extreme hydro-meteorological hazards, such as floods, landslides, droughts, heatwaves, and storm surges, and highlighted the significant risk reduction achieved through the implementation of GBGI. Specifically, the hybrid approach for flood mitigation and the green approach for heat mitigation emerged as the most effective solutions. However, the effectiveness of GBGI depends on its architecture, typology, green species, and environmental conditions.	Debele et al. ³²
Nature-based solutions (Global)	Reviewed different methodologies incorporating exposure, vulnerability, and adaptation interaction for hydro-meteorological risk (flood, drought, and heatwaves) assessment, focusing on mitigation effectiveness of GBGI.	Sahani et al. ³³
Nature-based solutions (Global)	Underscores the importance of incorporating ecological principles into urban planning, with a focus on integrating GI, biodiversity conservation, and NBS to promote resilient and sustainable cities and highlighted the critical role of collaborative stakeholder engagement in ensuring effective implementation, fostering urban sustainability, and maintaining ecological integrity	Heymans et al. ⁵⁷

from heat mitigation, five more co-benefits were identified: enhanced recreational opportunities, ambient noise reduction, flood and drought risk mitigation, improvements in air and water quality, and biodiversity. Detailed GBGI design and implementation principles, along with global GBGI challenges, have been covered in earlier reviews (Table 1) and, therefore, are beyond the scope of our review. The PRISMA methodology⁶⁸ was adopted for the systematic review of the literature (Figure S1). This methodology helped us to uncover geographical and temporal trends in the origin of studies, as well as knowledge voids in the existing literature. The sample for organizing the datasets obtained from the reviewed papers for each of the 51 sub-categories is presented in Table S1. Our literature search consisted of five stages (Section S1). (1) Search terms were developed based on objectives and GBGI categories (Table S2). (2) peer-reviewed literature in the English language and published between 2010 and 2023 were searched via Boolean search term combinations (Table S2) utilizing Web of Science, Science Direct, Scopus, and Google Scholar for their first 20 pages of results. This yielded a total of 27,486 publications (Fig-

ure 1A). (3) Removing duplicates and screening based on GBGI inclusion criteria left 1,512 publications for further screening (Figure 1B) and full-text retrieval eligibility (Figure 1C). Eventually, 202 publications (0.74% of the originally identified 27,486 publications) were chosen for meta-analysis (Figures 1D and 1E). (4) Relevant data (e.g., location, type of GBGI, co- and dis-benefits, and knowledge gaps) were extracted from the selected studies (Table S2). (5) The number of studies available for each of the GBGI sub-categories was categorized into six scale conditional performance classes (Table S3). The data hence obtained were analyzed using descriptive statistics on R project software.⁶⁹ Of the selected 202 publications, 64.7% solely discussed heat mitigation as their main ecosystem service; the rest discussed the co-benefits.

We categorized all the papers into four main Köppen-Geiger climate classification zones: temperate, continental, dry, and tropical (Figure S2). Each zone was further divided into three spatial scales based on the cooling observed: micro-scale (<2 km), meso-scale (>2 km <1,000 km), and macro-scale (>1,000 km). Furthermore, we tagged each study location

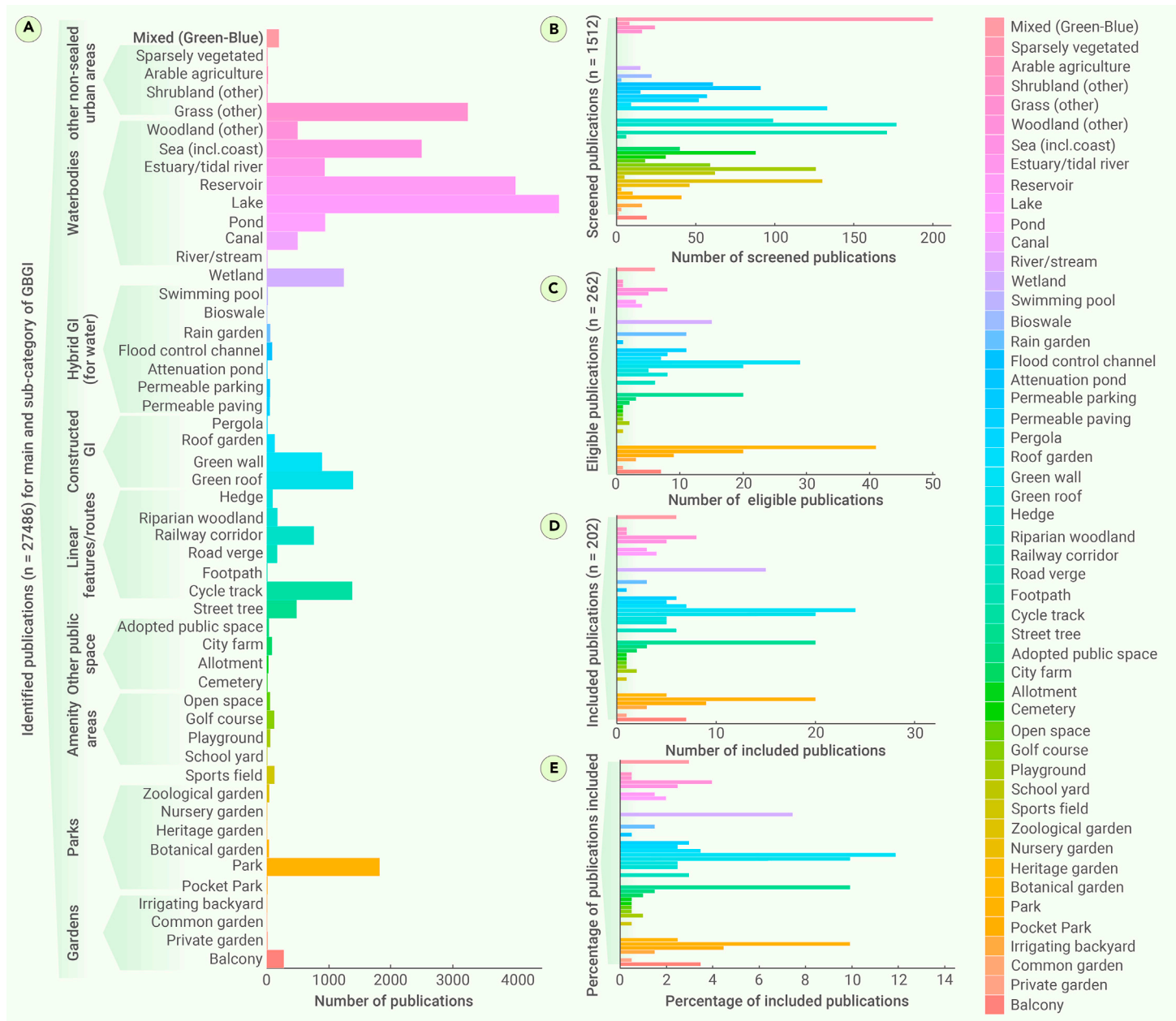


Figure 1. The literature availability across the 10 primary types of GBGI and their 51 subcategories The number of (A) identified, (B) screened, (C) eligible, and (D) included publications for meta-analysis, and (E) the percentage of included publications for each of the 51 GBGI sub-categories (shown at the y axis of A), falling under the 10 main GBGI categories (shown as bold text in A). A detailed list of the GBGI main and sub-categories is listed in Table S3.

of monitored or modeled temperatures with specific types of GBGI. To assess the potential effects of climate change on cooling efficiency, we categorized each paper into two groups based on their study time frames: past and future. Moreover, we conducted an analysis comparing the migration of GBGI systems between different Köppen-Geiger climate zones in the present and future climate conditions (Section [urban GBGI and climate change](#)). The future climate condition is analyzed under the largest emission scenario of RCP8.5⁷⁰ which covers 2071–2100.

To characterize the impact of various parameters on the cooling efficiency of GBGI under different climate zones, four main factors are considered: (a) population density, (b) the ratio of the area covered by GBGI intervention to the total town/city area, (c) altitudes (above mean sea level), and (d) temporal scale. These parameters are correlated with the cooling potential of GBGI interventions within four distinct climate zones. Population density (per square kilometer) and the altitude of each location where GBGI is implemented are obtained from the World Cities Database.⁷¹ Additionally, the areas of GBGI and the respective city or town, as well as temporal scales, are extracted from each reviewed paper. The cooling ratio is then calculated by dividing the area of GBGI intervention by the total town or city area, providing insights into the spatial scale of the intervention in relation to the urban environment.

MECHANISMS OF TEMPERATURE AND HEAT STRESS REGULATION BY GBGI

GBGI, especially its green component, can regulate urban heat³⁵ through evaporation,^{36,37} transpiration, shading,^{38,39} and thermal insulation.^{40,41} Blue infrastructure absorbs heat and cools the surrounding area through evaporation (Section S2).

Mechanisms of temperature and heat stress regulation by GI

Trees and plants help in the reduction of heat by providing shade and decreasing the amount of direct sunlight reaching the ground, therefore lowering surface temperatures and mitigating the urban heat island (UHI) effect via creating a cooler micro-climate.^{38,39,72} Additionally, during evapotranspiration plants release moisture, which further cools the surrounding air by converting sensible heat into latent heat.⁷³ Parks can act as natural air conditioners through several mechanisms,^{74–76} including the formation of micro-scale centripetal thermal system (park breeze) that generate low-level advection currents that draw air from cooler green toward warmer urban areas.⁷⁷ Other GI elements,

such as green roofs, green walls, and roof gardens, provide insulation, decrease heat absorption by buildings, and promote evaporative cooling (heat absorption, as water changes from liquid to a gas state in the air stream).^{78–81} Vegetation also contributes to the dissipation of heat by acting as windbreaks, modifying airflow patterns, and facilitating natural ventilation.

Mechanisms of temperature and heat stress regulation by blue infrastructure

Blue infrastructure (BI) actively mitigates heat effects by cooling the surrounding environment⁷⁷ through processes such as evapotranspiration, shading, the albedo effect, groundwater recharge, and temperature buffering.^{82,83} BI can provide cooling during the day (acts as a heat sink by absorbing and storing heat from the surrounding environment), whereas it may lead to warming at night (re-releasing the heat due to water's higher heat capacity compared with the land surface).⁶⁰ Evaporation from water bodies also helps to cool the air, creating a micro-climate with lower temperatures and thereby helping to mitigate the UHI effect.⁸⁴ Larger urban water bodies can also generate cool breezes that further lower the ambient temperature and provide relief during hot weather through evaporative cooling.⁷⁷ Furthermore, surfaces of BI are less reflective and more absorptive for solar radiation due to low albedo (0.05–0.10) than forests (0.1–0.2) or snow (8.8–0.95), especially under calm conditions; thus, there is less heating of the immediate surroundings,⁸⁵ helping to mitigate heat build-up and contributing to the cooling of the surrounding area. However, water's lower albedo does not always guarantee cooler surrounding areas as it absorbs heat, affecting the local climate. It retains more solar energy, leading to increased humidity and moderated temperatures nearby. The overall impact relies on factors like water's heat capacity, air movements, and local weather complexities, making direct temperature comparisons challenging. Some of the BI such as wetlands, ponds, lakes, swales, and rain gardens also act as natural sponges, storing water and releasing it during high air temperatures, thereby moderating temperatures in the vicinity by increasing water availability for evaporation through groundwater recharge.³⁷

GLOBAL MAPPING OF GBGI STUDIES FOR URBAN HEAT MITIGATION

Temporal and spatial trends

Analysis of publication trends offers insight into how knowledge evolves, aids in understanding context, identifies gaps, ensures credibility, and supports well informed decisions, enhancing the depth and accuracy of analysis. Figure S3A illustrates the chronological trends of publications from 2010 to 2023 included in this review. A general increase in the number of publications investigating GBGI portrays a growing interest and research activity on the topic for urban heat mitigation and other benefits. This can be attributed to heightened concerns about climate change and impacts on urban heat, propelling a global shift toward sustainable urban planning and environmental considerations.⁸⁶ This surge might also be driven by the proven effectiveness of GBGI in mitigating heat and its associated benefits, prompting increased attention and research efforts.⁸⁷ While the earlier years (2010–2016) saw a relatively low count of publications, with a range of 1.9% ($n = 4$) in 2010 to 5.5% ($n = 11$) in 2016, a substantial linear increase ($R^2 = 0.69$; $p < 0.05$) was observed worldwide after 2016 with 8.9% ($n = 18$) in 2017, peaking at 28.2% ($n = 57$) in 2022. Overall, the trend indicates a growing interest and research activity for the use of GBGI for urban heat mitigation and associated benefits. The peak in 2022 is likely partially attributable to the coronavirus disease 2019 pandemic, with many countries imposing lockdown and movement restrictions, which raised awareness of the benefits and motivating research into GBGI.^{88–90}

The spatial trends of GBGI studies were scrutinized to systematically evaluate and help identify geographical areas with varying research focuses the distribution of GBGI studies, focusing on their effectiveness against heat within different global regions (Figure 2). This analysis offers insights into specific regional needs, effective practices, and potential transferability of solutions across different locations. Most of the GBGI studies originated from Asia (51.1%), primarily from China (29.95%), followed by Europe (30.4%), Australia (7.5%), and North America (7.0%). Far fewer studies have been carried out in South America (1.8%), Africa (1.8%), and Oceania (New Zealand, 0.4%) (Figure 2). The prevalence of GBGI in Asia and Europe (81%) can be attributed to various factors.

The type of GBGI studied varied across continents. For example, in Asia, wetlands (14.7%) and parks (12.9%) were the most frequently studied GBGI types

for combating urban overheating. In contrast, the most common GBGI measures reported in Europe were street trees (18.8%), green walls (15.9%), and green roofs (13.0%) (Figure 2). In Australia, green wall studies were prominent (17.6%), alongside irrigating backyards, parks, street trees, and green roofs, which constituted 58.8% of the total GBGI studies. In North America, parks (31.3%), street trees (18.8%), and wetlands (12.5%) made up approximately 62.5% of GBGI interventions described. The disparity in types of GBGI studied across continents likely stems from diverse regional contexts, climate conditions, and urban planning priorities. This reflects the varying environmental needs and urban challenges specific to each continent, shaping the focus on different types of GBGI interventions best suited to tackle urban overheating in their respective regions. For instance, in Asia, the extensive development of GBGI (wetlands, parks, and green spaces) are a response to challenges posed by rapid urbanization, cultural preferences that prioritize green areas for community activities,⁹¹ and environmental goals focused on biodiversity conservation, improved air quality, and mitigating the UHI effect.⁹² Government initiatives in Asian countries prioritize large park creation as part of urban planning and environmental policies,⁹³ reflecting a comprehensive approach to addressing challenges associated with urban development. In Europe, GBGI strategies involve diverse approaches, such as integrating GI into urban areas, implementing river restoration projects for water quality improvement, adopting agroecology and sustainable agriculture practices, and emphasizing biodiversity conservation through protected areas and Natura 2000 networks. These strategies align with broader EU environmental goals, notably Horizon 2020 projects and the European Green Deal.⁹⁴ Interestingly, this shows an increasing interest in the widespread application of the heat mitigation benefits provided by GBGI in low-income and lower-middle-income, relatively less developed, and highly populated continents such as Asia and Africa (total 52.9%). Comparatively, the most developed continents such as Europe, Australia, and North America (total 44.9%) demonstrated a lower but similar number of studies. The varying representation in GBGI research by different continents may be attributed to various factors, such as resource availability for research, different competing regional priorities, socio-economic challenges, lack of GBGI benefits awareness, and number of established academic or research institutions focusing on GBI research.⁹⁵ Africa and South America have initiated some interest in GBGI research for urban heat mitigation. Williams et al.⁹⁶ reported on the effectiveness of adaptive responses to climate change in Africa, finding that the fewest actions were reported for cities, with only a 5% response rate.

Types of GBGI interventions

Figure S4A summarizes the number of studies available for each GBGI type and the corresponding studies for each of the 10 GBGI are shown in Figures S3B and S4B. More than three-quarters (75.7%) of all studies focused on only four GBGI types: constructed GI on gray infrastructure (27.7%), linear GI features and routes (17.8%), parks (16.8%), and waterbodies (13.4%). The remaining 24.2% of studies focused on six other GBGI categories: gardens (5.5%), other non-sealed urban areas (4.9%), hybrid GI for water (4.9%), other public space (3.5%), mixed (2.9%), and amenity areas (2.5%). Among the studied GBGI categories, green walls (11.9%), green roofs (9.9%), street trees (9.9%), and parks (9.9%) were the most studied (41.6% of the total). The second most studied (46.0%) GBGI sub-categories included woodland, lakes, wetlands, permeable paving, pergola (with vegetation), hedges, riparian woodlands, botanical gardens, road verges, pocket parks, and balconies. The least studied categories (12.4%) included private gardens, irrigated backyards, sports fields, playgrounds, golf courses, shared open spaces, cemeteries, allotments, city farms, adopted public spaces, permeable paving, attenuation ponds, reservoirs, shrublands, and grass. This distribution of research focus on different GBGI types highlights unequal attention to specific categories and underscores the need for more comprehensive research across various GBGI types to ensure a balanced understanding of their environmental impacts and benefits.^{95,97}

Effect of various parameters on the cooling efficiency of GBGI under different climate zones

Climate zones classified by the Köppen⁹⁸ encompass a range of environmental conditions that shape the characteristics of various regions across the globe. In this classification, there are five primary climate zones and 30

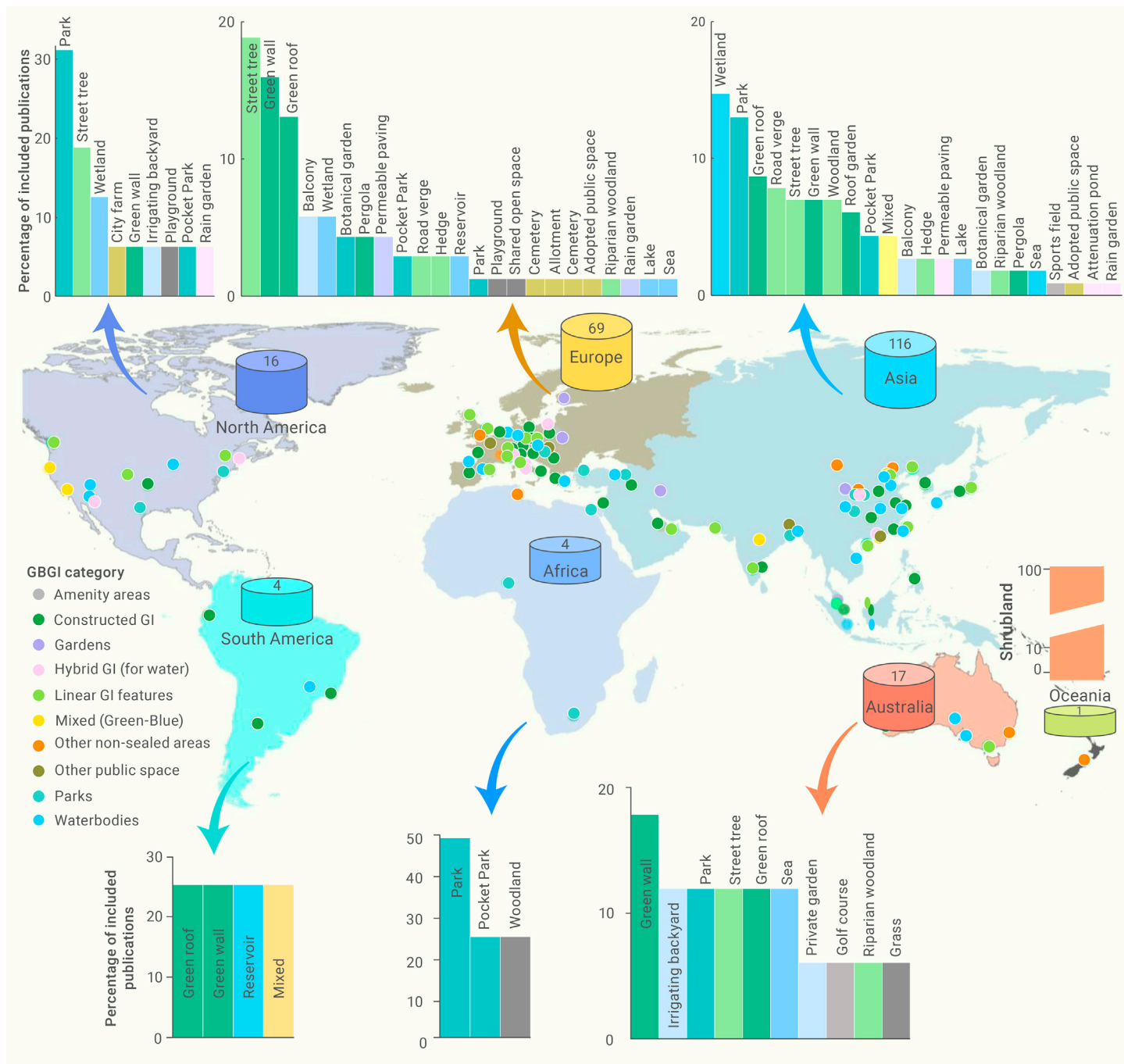


Figure 2. Geographical distribution of reviewed papers based on the number of GBGI categories, their location (latitude and longitude) by continent and number of publications by year The number in the magnetic disk and bar plot shows the number and percentage of GBGI sub-categories and types in each continent.

sub-types. Because heatwaves are not a problem in the polar climate, which is characterized by extremely cold temperatures, no GBGI interventions are retrieved from this climate zone (Figure S5). Therefore, the GBGI presented in this study only covers 4 primary climate zones and 18 subtypes. Noteworthy examples (Table S4) were found in the analysis for specific climates. The majority (87%) of GBGI were found to be located in the temperate (67%) and continental (20%) climate zones, encompassing categories such as Cfb, Cfa, Cwa, and Dwa, characterized by warm, hot, and rainy summers (Figure S2). Within these climate categories, GBGI constructs such as GI on infrastructure, parks, and linear features and routes were the most frequently used, while the other 13% of GBGIs are located in tropical (Aw, Af) and dry (BWh, BSh) climate zones. In temperate climates (Cfa and Cfb sub-climate), wetlands and parks were the most effective for cooling due to evapotranspiration, shade, waterbodies, and the impact of green space, reducing temperatures by approximately 9°C–10°C (Figure S5). Wetlands showed efficient cooling at the meso-scale, often in natural surround-

ings, while parks excelled in micro-scale cooling, particularly near built-up areas emphasizing the crucial role of wetlands and parks in urban GI for temperate climates.⁹⁹

For continental climates (Dfb sub-climate), green walls and botanical gardens were notably efficient, achieving cooling of approximately 9°C–10°C nearby, likely due to their localized impact (Figure S5). Their effectiveness was observed mainly at the micro-scale but not at the meso-scale and/or macro-scale. However, parks also showed efficient cooling at the meso-scale due to their larger size and broader coverage, which allows them to exert a more significant influence over a wider area, thus demonstrating better cooling performance in the meso-scale environment compared with other GBGI types. Green roofs, situated within a mix of built and natural areas, and botanical gardens monitored inside and outside within built-up areas, showed significant cooling in the Dwa sub-climate of continental climates at an efficiency of approximately 10°C due to their ability to provide insulation, decrease heat absorption, and support evaporative

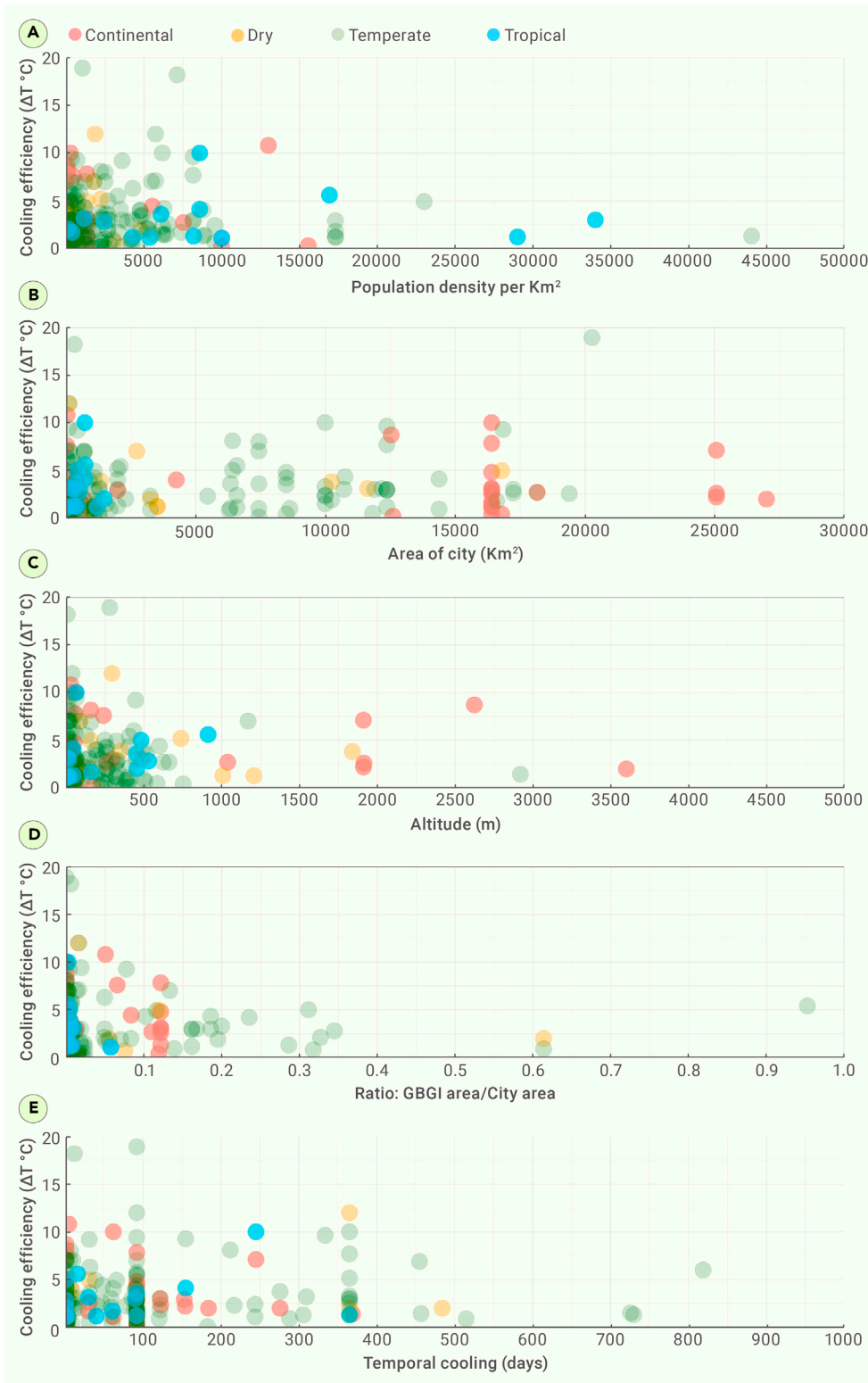


Figure 3. Scatterplot of GBGI cooling efficiency Scatterplot of GBGI cooling efficiency in different climate zones and against population density (A), area of city (B), ratio: area of GBGI/area of city (C), altitude (D), and temporal scale of cooling (E).

ated and discussed against population density, city area, altitude, and temporal duration of study (Figures 3 and S6; Table S5).

Population density. For the studied GBGIs, the population density ranges from 0.05 to 111,227/km², with a correlation value of 0.02 and a p value of 0.7 for cooling performance. Optimal heat management performance observed in low-population density cities suggests a balance between urban development and sustainable cooling strategies.¹⁰³ Studies conducted in tropical climates with dense urban populations demonstrated relatively reduced cooling efficacy (Figure 3A). In dry climates, such as those found in Mediterranean regions, the importance of BI becomes paramount because of less favorable conditions for GI.¹⁰⁴ Hence, the effectiveness of GBGI in this area may depend on water management strategies. Understanding the intricate relationship between cooling efficiency, population density, and climate zones is essential for tailoring sustainable urban development strategies that accommodate the unique characteristics of different regions.

GBGI versus city area. The larger urban areas, especially in continental, dry, and temperate climates, exhibited a positive correlation with noteworthy average cooling effects of 3.3°C (Figure 3B), suggesting substantial potential for GBGI implementation. In dry climates, the spatial extent of larger city areas amplifies opportunities for implementing GBGI, such as green roofs and permeable pavements,¹⁰⁵ enhancing average cooling efficiency to 3.4°C. GBGI interventions in tropical climates were primarily confined to smaller city areas, reaching up to 3°C cooling efficiency on average. This indicates the potential for expansion to larger extents for more significant cooling benefits. Tropical climates present distinctive challenges to GBGI implementation in larger city areas, where certain GBGI interventions may initially be confined to smaller urban spaces due to elevated humidity and heavy rainfall.¹⁰⁶ Nevertheless, the potential for expansion to larger extents hints at the prospect of significant cooling benefits in tropical climates. Figure 3C presents a comparison of the GBGI area with the studied city area,

cooling processes, especially in such particular climatic conditions.¹⁰⁰ In dry climates (BWh sub-climate), pocket parks and wetlands were the most effective, reducing temperatures at the micro-scale by 7°C and 12°C (Figure S5), respectively, allowing for a concentrated cooling effect of GI within arid environmental conditions.¹⁰¹ The high efficiency of roof gardens in tropical climates (Af sub-climate) was achieved up to approximately 10°C cooling. This is primarily due to their localized micro-scale impact, particularly when situated within or on top of buildings in densely built-up areas.¹⁰² In conclusion, the variability in GBGI effectiveness across climate zones underscores the need for region-specific strategies. Furthermore, GBGI effectiveness for urban cooling was associ-

with cooling efficiency ratios ranging from 0.0009 to 0.95. The correlation (*r*) value is 0.02, with a p-value of 0.8. A smaller ratio indicated a reduced GBGI area in comparison with the city area, with the most significant cooling effect observed for ratios of less than 0.3, especially evident in tropical regions. This signifies the optimal functioning of GBGI at the micro-scale, indicating the potential for expansion of GBGI interventions across different climatic contexts to cover the entire city area. The observed relationship between the GBGI area to city area/ratio and cooling efficiency aligns with past research in urban climatology.¹⁰⁷ The concept that a smaller ratio, indicative of GBGI smaller 0.2–0.3km² can provide effective cooling distribution,⁷⁷ results in greater cooling

benefits is consistent with the idea that localized greenery and shade provision can have a substantial impact on micro-climate regulation.¹⁰⁸ The prominence of enhanced cooling effects in tropical regions, particularly when the GBGI area-to-city area ratio falls below 0.3, resonates with research emphasizing the effectiveness of GI in equatorial climates.^{109,110} These findings suggest that the micro-climatic benefits derived from GBGI interventions are particularly pronounced in regions where the need for heat mitigation is more acute. Conversely, the diminishing cooling efficiency observed with increasing city size in temperate regions corresponds with studies highlighting the challenges of scaling up GI in larger urban areas.¹¹¹ The 99th percentile reaching a cooling ratio of 0.52 in temperate regions confirms the challenges posed by urban sprawl and the difficulty in maintaining a balance between urban development and environmental sustainability.¹¹²

Altitude. A considerable cooling impact was observed up to an altitude of 500 m across various climates (Figure 3D). The altitude ranges from 0 m to 3,600 m above mean sea level, with a correlation value of 0.02 and a p value of 0.8. However, a further increase in altitude did not yield a subsequent increase in the cooling efficiency of GBGI. Previous research suggested that high altitude is likely associated with a strong cooling effect of urban green space, but further research need to be conducted to confirm the findings.¹¹³ The impact of altitude on cooling by urban interventions, including GBGI, is complicated by many factors. Humidity decreases with altitude, and in drier climates the cooling effect of GBGI is stronger.¹¹⁴ Temperature also decreases with altitude, so urban environments in mountainous regions are cooler in general. In contrast, the downward solar radiation (irradiance) increases with altitude, as it is absorbed by clouds and other species in the atmosphere.¹¹⁵ So buildings and other urban surfaces in higher altitudes receive more direct heating from the sun than those at sea level. The dominant factor or net result will vary from place to place and will depend on local topography and climate conditions that also introduce variability.¹¹⁶ Urban planning and climate mitigation efforts should consider altitudes of the places for heat management by GBGI.²⁴ Water scarcity in dry climates poses challenges for sustainable urban cooling incorporating GBGI. Here, altitude may influence the availability of water resources for BI elements, thereby impacting the overall effectiveness of GBGI. While altitude may provide relief from heat in hot and humid tropical climates, the success of GBGI implementation could hinge on factors such as the prevalence of vegetation and water bodies.¹¹⁷

Temporal scale. Examining the temporal scale of cooling, the reported duration of cooling effects varied, ranging from a few hundred days to approximately 800 days, with the majority falling under 100 days. The correlation between cooling efficiency and temporal scale is 0.08, with a p value of 0.3. The association between the temporal scale and cooling efficiency shows a weak correlation, with data points scattered around the mean value of 136.1 days. For continental, dry, and temperate climates, the mean reported GBGI cooling efficiency is approximately 3.4°C over a monitored period of approximately 100–200 days in accordance to the typical duration of the summer or warmest season in these climate zones, lasting 3–5 months. GBGIs such as parks, green roofs, and green walls exhibited optimal cooling efficiency within these time frames, highlighting the relevance of considering climatic conditions in the design and planning of such interventions.¹¹⁸ Similarly, for the tropical climate zone, the mean reported GBGI cooling efficiency is approximately 3.0°C monitored over a duration of approximately 75 summer/hot days (Figure 3E). Furthermore, the cooling efficiency shows a better association with tropical climates, with a correlation coefficient of 0.3, although it is not statistically significant.

Studies conducted for longer periods were predominantly observed in temperate and a few dry climates. Notably, GBGI efficiency seemed to decrease when studied for more than 400 days. This might be due to the degrading health of GBGI after summer. In arid or dry climates, water-efficient GBGI solutions can limit the hindrance in GBGI health caused due to water availability issues. In particular, the combination of gray infrastructure supporting water conservation and drought-resistant GI becomes paramount for localized cooling in water-scarce regions.

This comprehensive analysis reveals that the effectiveness of GBGI for urban cooling varies significantly based on climatic zones, population density, city area, altitude, and temporal duration of study. The findings indicate a preference for GBGI interventions in cities with lower density and larger areas, showcasing the potential for scalability and enhanced effectiveness of GBGI, especially in tropical regions when expanded to cover larger city extents. The limitations in

denser urban settings and the reduced effectiveness over longer temporal scales highlight key areas for future research and considerations in implementing GBGI for urban cooling strategies.

Co- and dis-benefits of GBGI intervention

Figures 4A–4C show the availability of studies based on a six-point scale evidence-based classification on co-benefits and dis-benefits, respectively. GBGI interventions possess the potential to deliver multiple co-benefits, encompassing, for example, stormwater management, carbon sequestration, and improved air quality and urban resilience to hazards such as urban overheating. However, GBGI may occasionally have dis-benefits (e.g., social exclusion, increased pollen, or mosquitoes, etc.) as well, and these dual effects were reflected in the reviewed studies.¹¹⁹ Co-benefits were reported for 30.2% of studies, while 7.9% also reported potential dis-benefits associated with GBGI implementation for heat mitigation. Street trees had the highest number of publications (n = 11) reporting co-benefits, followed by green roofs (n = 10), wetlands (n = 6), and botanical gardens (n = 5). Other measures such as hedges, green walls, pocket parks, and rain gardens also reported co-benefits beyond heat mitigation, although in fewer instances.

Reported dis-benefits for certain GBGI, such as playgrounds, street trees, and green roofs, included higher maintenance costs, conflicts arising from land use, and unintended environmental consequences. For instance, densely planted trees can limit dispersion, which can increase pollution levels in certain conditions,¹²⁰ while certain flora can induce pollen-related allergic reactions.¹²¹ The volume of publications discussing the dis-benefits was noticeably less than those highlighting the co-benefits, suggesting either that the overarching benefits of using GBGI for heat mitigation significantly outbalance any potential adverse outcomes or that there is a bias in the literature toward focusing on the positive effects of GBGI, while neglecting possible undesired effects.¹¹⁹ Further research on evaluation and monitoring is necessary to quantify the compound and inter-linked co/dis-benefits of GBGI and ensure that any implementation options are evidence-based and adopt a holistic approach to optimize their multifunctional benefits.

Efficacy quantification of GBGI cooling

The effectiveness of different GBGI sub-categories in mitigating urban heating was evaluated in four separate classes of studies: *in situ* monitoring, modeling, remote sensing, and a combination of monitoring and modeling techniques. Their efficiency was assessed in terms of temperature reduction (ΔT) in degrees Celsius, along with 95% lower confidence intervals (LCIs) and upper confidence intervals (UCIs) as a result of GBGI intervention against a reference case (without the GBGI interventions). Throughout the paper, the *in situ* monitoring and modeling studies primarily examine air temperature, while the remote sensing (RS) studies focus on land surface temperature (LST). These terms are consistently used to represent temperature in the paper. In the subsequent texts, day-time temperature is reported in Table S6 and the corresponding night-time temperature differences are presented in Figures S7A–S7C. Night-time temperature reduction efficiency of GBGI sub-categories (Figure S7B) have been sub-classified by the type of methodology (monitoring, modeling, and/or RS with averages) used for the reported cooling efficiency. The attenuation pond (monitored, approximately 6°C cooling) and roof garden (monitored, modeled, and remotely sensed, approximately 17°C cooling) reported the most efficient cooling at night time. The highest cooling was reported by RS methods owing to measuring LST rather than the air temperature, followed by monitoring, modeling, and their combinations. Attenuation pond (monitored, approximately 6°C cooling) and roof garden (monitored, modeled, and RS, approximately 17°C cooling) reported the most efficient cooling at night time. The most effective cooling was observed by RS, followed by monitoring, modeling, and their combinations. The calculation of the 95% LCIs and UCIs is performed using the *t*-distribution, which is appropriate for situations involving relatively small sample sizes.¹²²

In situ monitoring. *In situ* monitoring involves the use of equipment or sensors placed directly in the natural environment to collect air temperature data continuously or periodically without causing disturbance to the subjects or surroundings.¹²³ One-half of the studies (50%; n = 101) reported evidence from *in situ*-based monitoring, suggesting the dominance of observation-based heat mitigation assessment of GBGIs. Monitoring studies were evaluated for the efficacy of a wide range of GBGI types (n = 26) compared with

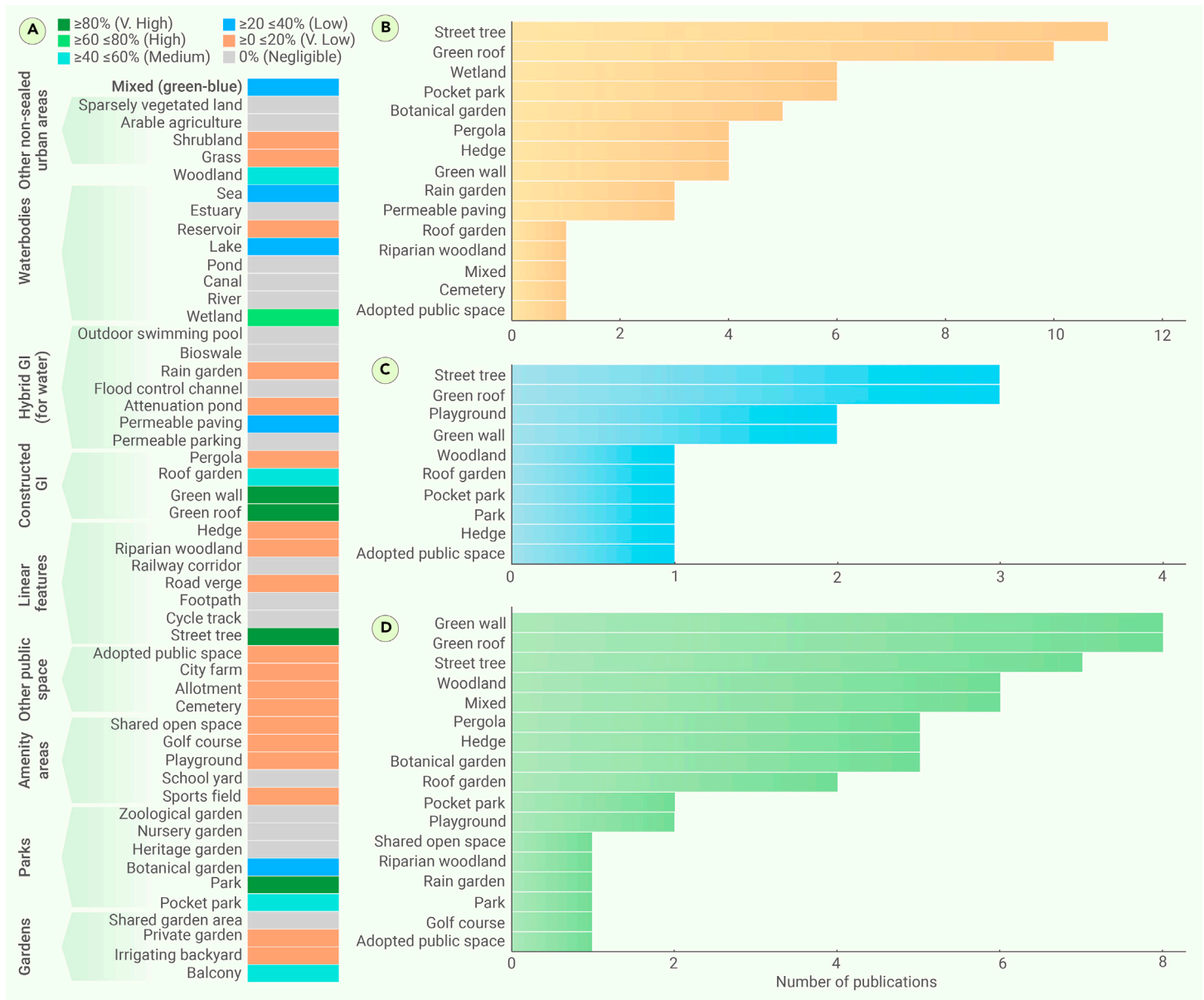


Figure 4. Number of studies under each GBGI category (A) A six-point-scale evidence-based classification of the number of studies under each GBGI category, (B) co-benefits, (C) dis-benefits, and (D) multiple interventions of GBGI within the main category of GBGI for heat mitigation. Gray cells indicate that there was no evidence found in the online database (Table S3).

modeling ($n = 18$), mixed monitoring and modeling ($n = 14$), and RS ($n = 16$) in Figure 5A. Based on the number of publications in each classification scale, green walls, green roofs, wetlands, parks, and street trees showed high to moderate efficiency in reducing the air temperature by up to 4.8°C , 3.9°C , 3.1°C , 3.1°C , and 2.8°C , respectively (Figure 5B). The other GBGI sub-categories, such as pocket parks, vegetated balconies, roof gardens, and woodland, are categorized as medium class, offering significant temperature decreases that range from 1.4°C to 3.07°C . Furthermore, certain GBGI types, such as sea, mixed solutions, road verge, and riparian woodland, provided relatively low (1.4°C) to moderate (3.1°C) cooling efficiency, with relatively high uncertainty (UCI, 2.8°C – 4.8°C). This was presumably due to the small sample size and the consequent low level of confidence in these results. Conversely, GBGI types like rain gardens and attenuation ponds offered the highest temperature reduction (6.1°C – 7°C). However, they are associated with high uncertainty due to the very limited information found within categories with low data availability. Overall monitoring-based data provided a moderate level of confidence (CI, 0.017 – 6.6°C).

In summary, green walls, green roofs, wetlands, parks, and street trees were found to be the most effective in mitigating heat as opposed to those showing lower efficiency such as mixed solutions, and road verges. However, the perfor-

mance results exhibit considerable variability, as reflected by their CIs (Figure 5B) and the number of available publications (Figure 4A). This variability depends on numerous study-specific factors, such as local climatic conditions, the types of GBGI and their design, and upkeep, as well as the uneven distribution of studies for each GBGI type. Therefore, a cautious interpretation is needed when making any direct comparisons.¹²⁴

Modeling. Approximately 24% ($n = 48$) of the reviewed literature used a modeling approach to evaluate the efficiency of different GBGIs against heat. Tree planting along streets was the most effective GBGI category, modeling results showed a temperature decrease of 4.3°C with very relatively low uncertainty (CI, 1.8°C – 6.7°C). Similarly, pocket parks, hedges, irrigated backyards, wetlands, adopted public spaces, shared open spaces, road verges, green walls, rain gardens, parks, lakes, permeable paving's, and green roofs exhibit a range of modeled air temperature reduction, spanning from 0.5°C to 2.9°C (Figure 5C). The other GBGI categories, such as roof gardens, sea, green roofs, permeable paving, parks, lakes, rain gardens, and green walls, exhibited lower temperature reduction, ranging from 0.3°C to 1.48°C . Vegetated balconies demonstrated the most significant decrease in air temperature, with a decrease of 6.1°C . However, only a limited number of publications was available ($n = 7$) for this conclusion.

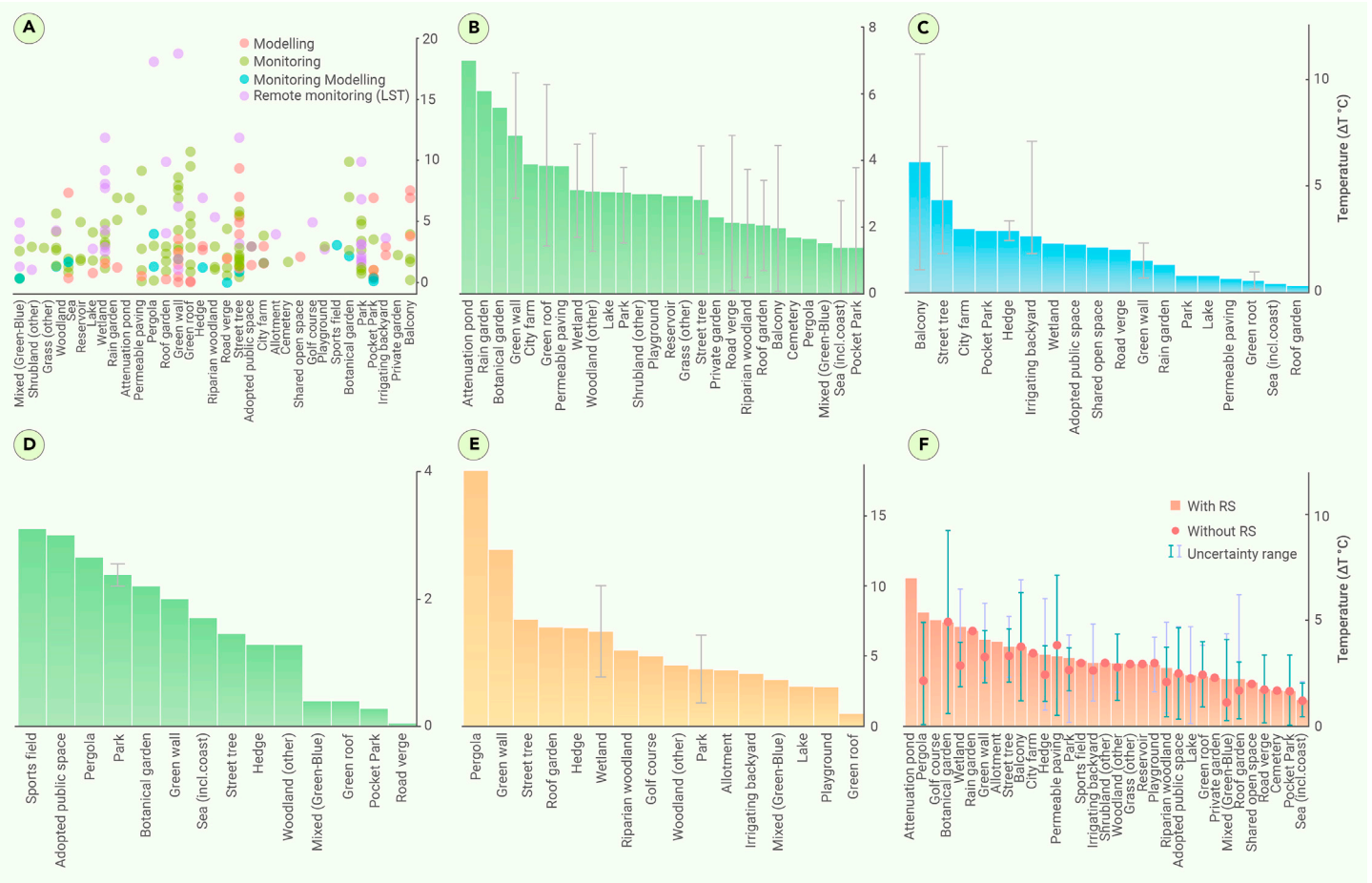


Figure 5. Performance of all GBGI sub-categories (A) Scatter representation showing the performance of all GBGI sub-categories assessed from 202 papers through the following methodologies in the reviewed publications: (B) *in situ* monitoring, (C) numerical modeling, (D) monitoring and numerical modeling (MM), (E) RS, and (F) the overall performance with and without RS (average of a-d) for each of the GBGI categories. The error bars in all plots represent 95% LCIs and UCIs as computed using the t-test. The CI is not applicable for GBGI sub-categories with very low publication availability. The data presented above from individual studies are summarized in Table S3.

Model-based data provide a reasonably narrow level of confidence (CI, approximately 0 to 0.5°C–6.4°C) when assessing the effectiveness of GBGI measures in decreasing air temperatures. This might be attributed to the use of models that work with extrapolated datasets for heat evaluation, which compensate for the limitations arising from limited coverage and the uneven distribution of data from weather stations and monitoring networks. However, it is essential to validate and calibrate these models using observational data to ensure accuracy, identify biases, and account for uncertainty. By combining model-based data with monitoring data, a more comprehensive and robust assessment of heat mitigation can be achieved.¹²⁵

RS. RS-based temperature monitoring entails the use of satellite or airborne sensors to measure and observe temperature fluctuations over extensive regions. Approximately 16% (n = 32) of the total reviewed literature reported varying levels of efficiencies of different GBGI in reducing the LST during very hot days using RS techniques. Among the 16 types of GBGI studied through RS, green walls demonstrated the greatest efficiency, with an LST decrease of 12.6°C (Figures 5A and 5E); however, the uncertainty is very high because only two papers monitored green walls using RS-based techniques. Similarly, street trees, hedges, roof gardens, and wetlands showed relatively high LST decreases of 6.8°C and 7.6°C, respectively. The greatest variability in the reported LST is influenced by spatial resolution because RS platforms (especially satellites) capture data over larger spatial scales, which may include a mix of different land cover types.¹²⁶ Consequently, the integration of temperature values from various surfaces, including hot urban areas or exposed surfaces, can lead to higher average temperature readings.¹²⁷ Therefore, while RS-based measurements offer extensive coverage and the ability to provide spatially detailed information, their accuracy should be validated and calibrated with ground-based measurements.³⁴

Interestingly, mixed initiatives (green-blue), irrigated backyards, allotments, parks, woodland, golf courses, and riparian woodland showed varying levels of

efficiencies in surface and air cooling, ranging from 2.8°C to 5.4°C (Figures 5A and 5E). Conversely, some GBGIs such as green roofs demonstrated lower efficiencies with temperature decrease values of 0.9°C due to factors such as soil moisture and vegetation density.^{41,128,129} These factors, including shallow soil depths, limited water availability, and high evaporation rates,^{36,130} can limit the cooling potential of green roofs.

RS-based monitoring demonstrated that pergolas and green walls exhibited relatively greater temperature reduction efficiencies with high uncertainty emerging from the small number of available publications (n = 2) as opposed to green roofs demonstrating relatively lower efficiencies (n = 20) (Figure 5E). In general, RS studies showed the greatest decreases as compared with the monitoring, modeling, or their combination, and they presented higher uncertainties (as indicated by the CI in Figure 5E). This outcome was expected, as RS studies mostly report LST as opposed to the air temperature used in other cases. To decrease the uncertainty in GBGI performance, it is essential to validate RS-based efficiency assessments against *in situ* measurements.

Combined (in situ, modeling, and RS) studies. Combined temperature monitoring encompasses the use of more than one method (*in situ* measurements, temperature modeling, or RS) to monitor and analyze temperature fluctuations across various scales, ranging from local to global levels.¹³¹ It provides a comprehensive and accurate evaluation of the efficiency of GBGI for heat mitigation, offering spatial and temporal coverage, multi-dimensional insights, and cost-effective data collection. Approximately 9.5% (n = 19) of the reviewed publications covered mixed monitoring and modeling approaches for evaluating the efficiency of different GBGIs in decreasing the temperature (Figures 5A and 5D). Among the 14 types of GBGI assessed through this method, sports fields exhibited greatest highest efficiency of 3°C–3.1°C with high uncertainty/CI, representing a very low publication availability. Other GBGI sub-categories that show a very robust temperature decrease with low uncertainty including woodland,

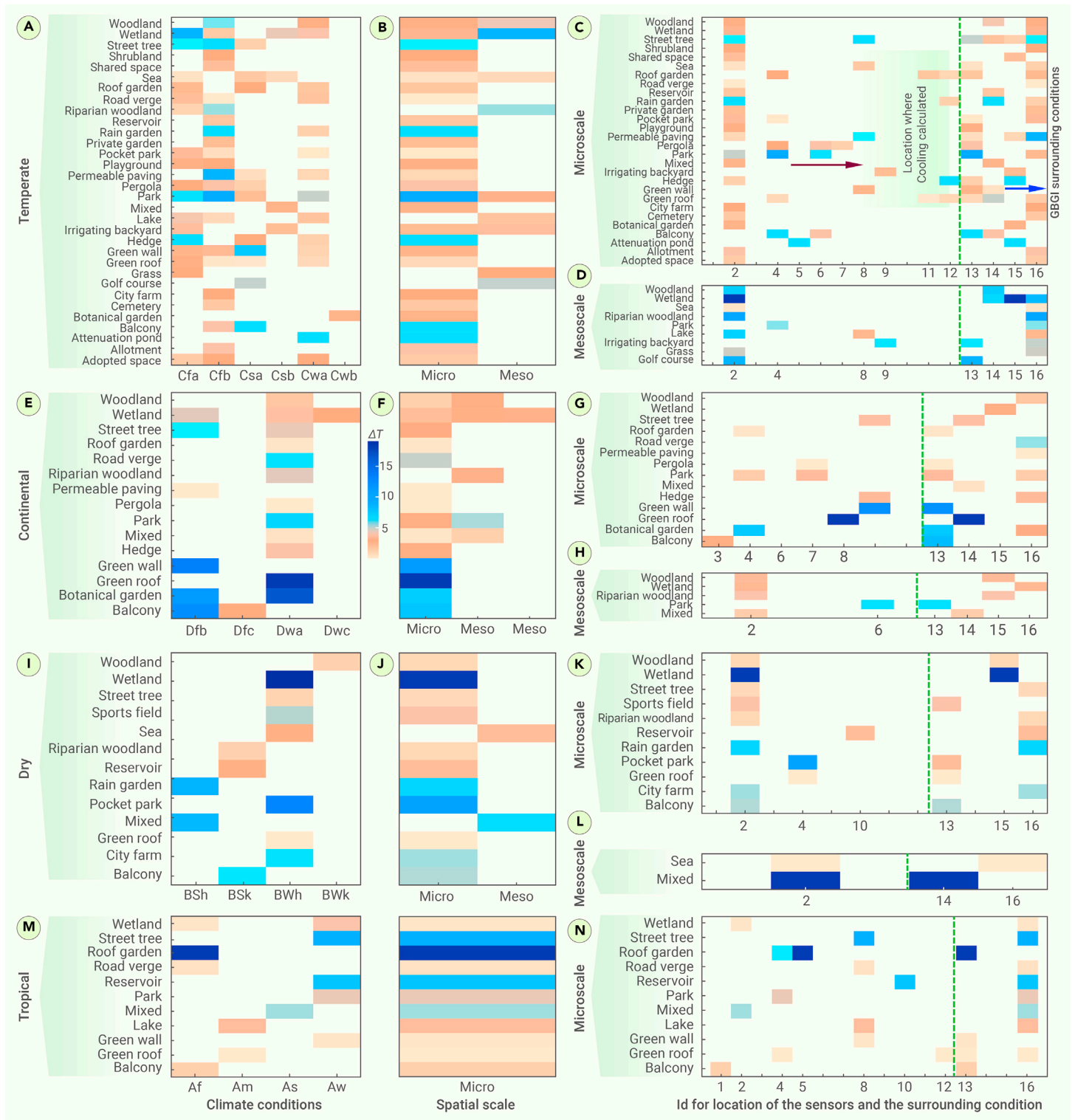


Figure 6. Köppen-Geiger climate conditions Each GBGI's performance is classified into Köppen-Geiger climate conditions (A, E, I), followed by categorization into spatial scales (B, F, J). Cooling performance in the same climate zone at three spatial scales is linked to the location (left: C, D, G, H, K, L, N) and surroundings (right: C, D, G, H, K, L, N) of the GBGIs. The location IDs (1: front, 2: inside, 3: inside and near, 4: inside and outside, 5: inside and top, 6: inside, outside, and near, 7: inside, outside, and top, 8: near, 9: not reported, 10: outside, 11: outside and top, and 12: top) represent where the cooling performance was calculated. The surrounding conditions (13: built-up area, 14: mixed [built-up with nature], 15: nature, and 16: not reported) describe the environment around the GBGIs.

hedges, street trees, seas, green walls, botanical gardens, and parks (with temperature reductions of $\Delta T = 1.3^\circ\text{C}$, 1.3°C , 1.5°C , 1.7°C , 2°C , 2.2°C , and 2.4°C , respectively) (Figure 5F). Green roofs, mixed initiatives (green-blue), and road verges showed relatively lower temperature reduction efficiencies of 0.4°C , 0.4°C , and 0.05°C , respectively (Figure 5F). Furthermore, to analyze the impact of uncertainties arising from RS-based measurements, the performance was evaluated both with and without RS studies. Generally, RS-based measurements

give higher mean performances with relatively high uncertainty, when compared with other approaches (combined monitoring and modeling) (Figure 5F).

Spatial scale. While meso-scale and macro-scale approaches are vital for comprehensive urban planning, the dominance of micro-scale GBGI implementation (approximately 85%) underscores its pragmatic, community-centric, immediate, and cost-effective impactful role in mitigating heatwaves in specific urban areas (Figure 6). For instance, constructed GBGI on built infrastructure (28%)

such as green roofs, green walls, and roof gardens are the most common features implemented at the micro-scale. Other dominant GBGI categories at the micro-scale are parks (16%), and linear features and routes (e.g., street trees, 16%). GBGI such as street trees, parks, and green roofs offer highly localized, direct, and immediate benefits, including shade provision, lower surface temperatures, localized cooling effects, green spaces, and improved air quality, contributing to a healthier and more livable environment in densely populated urban zones where the heat island effect is most pronounced.^{132,133} Compared with meso-scale and micro-scale interventions, these micro-scale interventions can be easier to implement and more cost effective, making them an attractive option for municipalities with budget constraints, facilitating widespread implementation.¹³⁴ Micro-scale interventions also foster community engagement and acceptance, as they are more visible and immediately beneficial to local residents.¹³⁵ The limited adoption of GBGI at the meso-scale (14%) and macro-scale (0.5%) might be influenced by challenges related to macro-scale implementation, such as land availability, funding, lack of best practices that demonstrate their effectiveness at a larger scale, and complex urban planning considerations. For instance, approximately 11% of the reviewed GBGI (waterbodies: wetlands and lakes [8%]; and linear features and routes: riparian woodland [3%]) were implemented at combined meso-scale and/or macro-scale.

Location and surroundings. The location of measurements is crucial to accurately determine the cooling potential of GBGI. The location where GBGI cooling efficiency is calculated is divided into five main categories (front, inside, near, outside, and top of GBGI intervention). Furthermore, these locations are grouped into six subdivisions based on combinations of the five categories (e.g., inside and near, inside and outside). The first five categories are defined as follows: (a) front: measures temperature differences within a few meters (e.g., 1–5 m) from the front of the GBGI; (b) inside: evaluates temperature reduction and other micro-climate changes within the GBGI; (c) near: assesses micro-climate parameters in the area surrounding the infrastructure, extending to approximately 10–20 m from the intervention; (d) outside: evaluates the impact on temperature in areas just outside the intervention, within a radius of 20–50 m; and (e) top: measures temperatures and assesses cooling effects on the top surfaces of GBG interventions. In this analysis, most studies (47%) measured the cooling potential inside the boundary (i.e., core center of GBGI) followed by outside (i.e., close proximity within a distance of 20–50 m to the GBGI boundary [21%]), both inside and outside (15%), a combination of inside, outside, and nearby (3%), and varied locations such as top and near (12%). Approximately 2% of studies did not report the location of the temperature measurements (Figure 6). As expected, cooling effects (average 3.4°C) measured inside GBGI areas were higher compared with those measured outside or on top (2.2°C) of GBGI areas. This can be attributed to the influence of GBGI on the micro-climate of the surroundings. This influence primarily operates through the regulation of the local energy budget, involving two key mechanisms: evapotranspiration and the absorption and reflection of shortwave radiation. Evapotranspiration, a significant cooling mechanism,^{136,137} involves the conversion of vegetational transpired water into water vapor by extracting energy from the local environment. This process contributes to a cooler environment, as evidenced in measurements taken within GBGI. Additionally, at the top canopy, the absorption and reflection of incoming shortwave radiation prevent the shaded areas below from warming up, further enhancing the cooling effect.¹³⁸ As one moves away from GBGI, the cooling efficiency decreases in alignment with the temperature-heat gradient concept. This decrease is attributed to the reduced exposure to GBGI's cooling mechanisms, such as shading and evapotranspiration, as observed in measurements taken outside and on top of the infrastructure.

The cooling efficiency of GBGI depends on the surrounding environments, including built-up areas, natural features (such as lakes and parks), and mixed environments that combine built and natural elements.¹³⁹ Of the analyzed studies, approximately 42% of GBGI are implemented in built-up areas, approximately 7% in natural areas, and 9% in mixed environmental conditions. However, a notable 42% of the papers did not report any characteristics of the vicinity of the studied GBGI. GBGI implemented in built-up environmental conditions, characterized by high-density infrastructure, presents both challenges and opportunities for GBGI in reducing heatwaves. The prevalence of impervious surfaces contributes to heat retention, exacerbating the UHI effect and decreasing the overall efficiency of the GBGI in place.¹⁴⁰ Conversely, GBGI implemented within natural surroundings, including lakes, parks, and tree-covered spaces,

plays a crucial role in enhancing GBGI efficiency for heatwave mitigation. For example, additional trees in parks may aid in the decrease of ambient temperatures.¹⁴¹

Overall performance. Figure 7A shows the mean reduction and CIs for both cases, with and without RS studies, while the mean temperature reduction by each GBGI sub-category for the same scenario is depicted in Figure 7C. The overall mean performance of GBGI based on RS studies showed a relatively greater temperature decrease ($5.8^{\circ}\text{C} \pm 4.4^{\circ}\text{C}$) with moderate uncertainty (CI, 4.3°C – 7.4°C), followed by monitoring ($3.2^{\circ}\text{C} \pm 2.4^{\circ}\text{C}$) with a very narrow CI (2.7°C – 3.7°C), modeling ($2.4^{\circ}\text{C} \pm 2.2^{\circ}\text{C}$; CI, 1.7°C – 3.0°C), and mixed ($1.7^{\circ}\text{C} \pm 1.1^{\circ}\text{C}$; CI, 1.1°C – 2.2°C) studies (Figure 7A). The overall performance with RS measurements indicates that integrating RS introduced an error of 15.6% compared with monitoring, modeling, and combined studies (Table S7). The pronounced temperature reduction evident in RS studies might be partially attributed to their focus on measuring LST, as opposed to air temperatures measured by *in situ* and numerical modeling studies. Additionally, variations between studies within the same category that impact the outcomes of these three types of research could stem from several factors. These include differences in the deployed instrumentation, the methodologies adopted, the materials used in various global regions, and prevailing climatological conditions.

Figures 7B and 7C present the heatmaps and overall mean performances for each GBGI category, respectively. The results show that several sub-categories, such as green walls, green roofs, street trees, parks, and others, show significant temperature reduction (Figure 7B). However, some sub-categories, including attenuation ponds, pocket parks, cemeteries, shared open spaces, and others showed temperature reduction efficiency with high uncertainty. Certain sub-categories have no values for CIs, indicating an insufficient number of publications to calculate them.

The combined results from all types of efficiency assessments discussed above indicate that the most efficient GBGIs for temperature reduction are attenuation ponds and pergolas, with overall temperature reduction efficiencies of 7.0°C and 5.4°C , respectively. However, no confidence intervals are available for the attenuation pond (Figure 7A), and their efficiencies are associated with high uncertainty because that they are categorized under very low and low publication availability categories. Other GBGI sub-categories that demonstrated relatively greater temperature decrease efficiencies are botanical gardens (4.9°C), wetlands (4.7°C), green walls (4.1°C), street trees (3.8°C), vegetated balconies (3.7°C), hedges (3.4°C), permeable paving (3.3°C), and parks (3.2°C). These GBGI types had a diverse range of publication availability, ranging from low to very high.

Furthermore, botanical gardens, wetlands, and permeable paving have relatively large uncertainty, shown by a wide range of CIs; in contrast, parks, wetlands, green walls, and street trees have a narrow CI range, suggesting low uncertainty with high heat mitigation performance (Figures 7B and 7C). Conversely, sub-categories such as sea and road verge showed lower mean temperature reductions ranging from 1.3°C to 1.8°C with relatively narrow CIs, suggesting more reliable heat mitigation performance.

Considerations for GBGI efficiency assessment

The assessment of GBGI for its cooling benefits involves diverse methodologies, each with unique strengths, implications, and limitations. *In-situ* monitoring captures on-site high-resolution and accurate data for real-time, site-specific insights, but may be limited in scope and sample sizes.³⁴ Even if the *in situ* approach captures local nuances, enabling real-time responses to change conditions, its limitations include restricted spatial coverage, resource intensity, and potential temporal constraints, as it may not effectively capture long-term trends.¹⁴² Modeling provides cost-effective scenarios for larger scale understanding but might oversimplify complex interactions.¹²⁵ Modeling-based assessments contribute predictive capabilities and scenario analyses, allowing for the simulation of future GBGI configurations and their impact on urban heat. These models can operate at different scales, integrating variables like land use and building density. Despite their scalability and policy guidance potential, modeling-based assessments require reliable input data, can be complex, and may introduce uncertainties in their outcomes that necessitate validation efforts. Models may also struggle to capture the full complexity of weather systems and the dynamic nature of heatwaves, leading to potential inaccuracies in predictions.¹⁴³

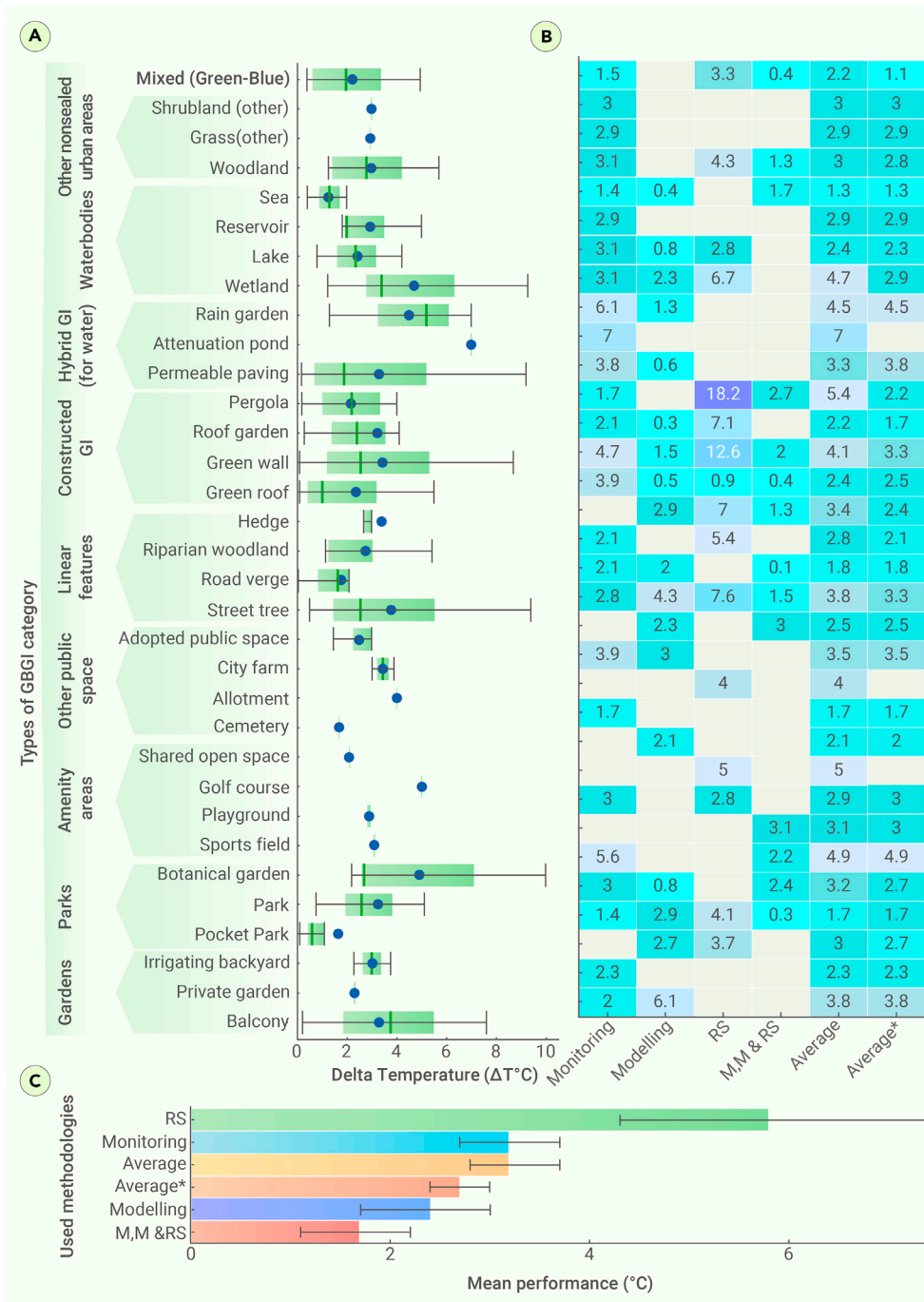


Figure 7. Efficiency of various GBGI types for urban heat mitigation (A) A summary of the overall performance of different GBGI types from all studies, (B) heatmap showing GBGI performances from for different methods and the average values, and (C) overall average of GBGI efficiency for urban heat mitigation. The error bars in all plots represent 95% LCIs and UCIs as computed using the t-test. The Average and Average* values represent the average of all study types with and without RS data, respectively. M&M denotes combined monitoring and modeling studies. The color gradient represents the performance, with gray cells representing studies that did not consider either monitoring, modeling, M&M, or RS. The figure uses a boxplot representation with the median indicated by a thick vertical black line, the mean represented by blue dots, and the upper and lower quartiles indicated by the box boundaries. The circle with a vertical line represents the GBGI categories with only one publication. All numerical data presented is provided in Table S6.

large-scale coverage complements the site-specific insights gained from *in situ* monitoring. Modeling offers a forward-looking perspective with its predictive capabilities, informing policymakers about the potential impacts of different GBGI interventions. These approaches together create a robust framework for urban planning, climate resilience, and sustainable development.

URBAN GBGI AND CLIMATE CHANGE

Climate change is significantly impacting global populations and ecosystems, leading to shifts in temperature and precipitation patterns across various continents that govern the climate types of the region. These changes necessitate a re-evaluation of GBGI to enhance their efficiency in mitigating and adapting to climate variations.^{145–147} Nearly all (98%) of the papers focused on the current climate; only 2% specifically examined future GBGI cooling efficiency.

Table S8 outlines the projected influence of future climate change on the choice of GBGI in various climate zones. Figure 8 shows the Köppen-Geiger climate classification and the location of ten GBGI categories for present and the future under the RCP8.5 scenario. Wetlands and green wall and street trees will be ideal prospective GBGI solutions to counteract changing climate patterns, where cooler and wetter continental sub-climates (Dfb and BSk) are projected from

current warm summer continental or hemiboreal climates (Dfa and Dfb), respectively. The current emphasis on street trees and permeable paving may need to evolve toward more temperature-regulating structures like green walls under the projected Dfb climate.⁹⁸ Wetlands play a pivotal role in climate resilience, particularly in regions transitioning from a humid continental (Dfa) to a fully continental (Dfb) climate. These areas are likely to experience altered precipitation patterns and increased risk of extreme weather events. Wetlands act as natural buffers, absorbing excess water during heavy rainfall and preventing floods. Moreover, they contribute to water purification, biodiversity conservation, and carbon sequestration, enhancing overall ecosystem health.¹⁴⁸ Green walls provide numerous benefits, including temperature regulation, air quality improvement, and aesthetic enhancement. By integrating vegetation vertically onto building structures, green walls contribute to cooling effects, mitigating the UHI effect that can be exacerbated by a shift to a more continental climate.¹⁴⁹ Street trees can provide shade, decrease ambient temperatures, and enhance overall urban micro-climates in regions transitioning from a temperate continental (Dfb) to a cold semi-arid (BSk) climate. They also contribute to carbon

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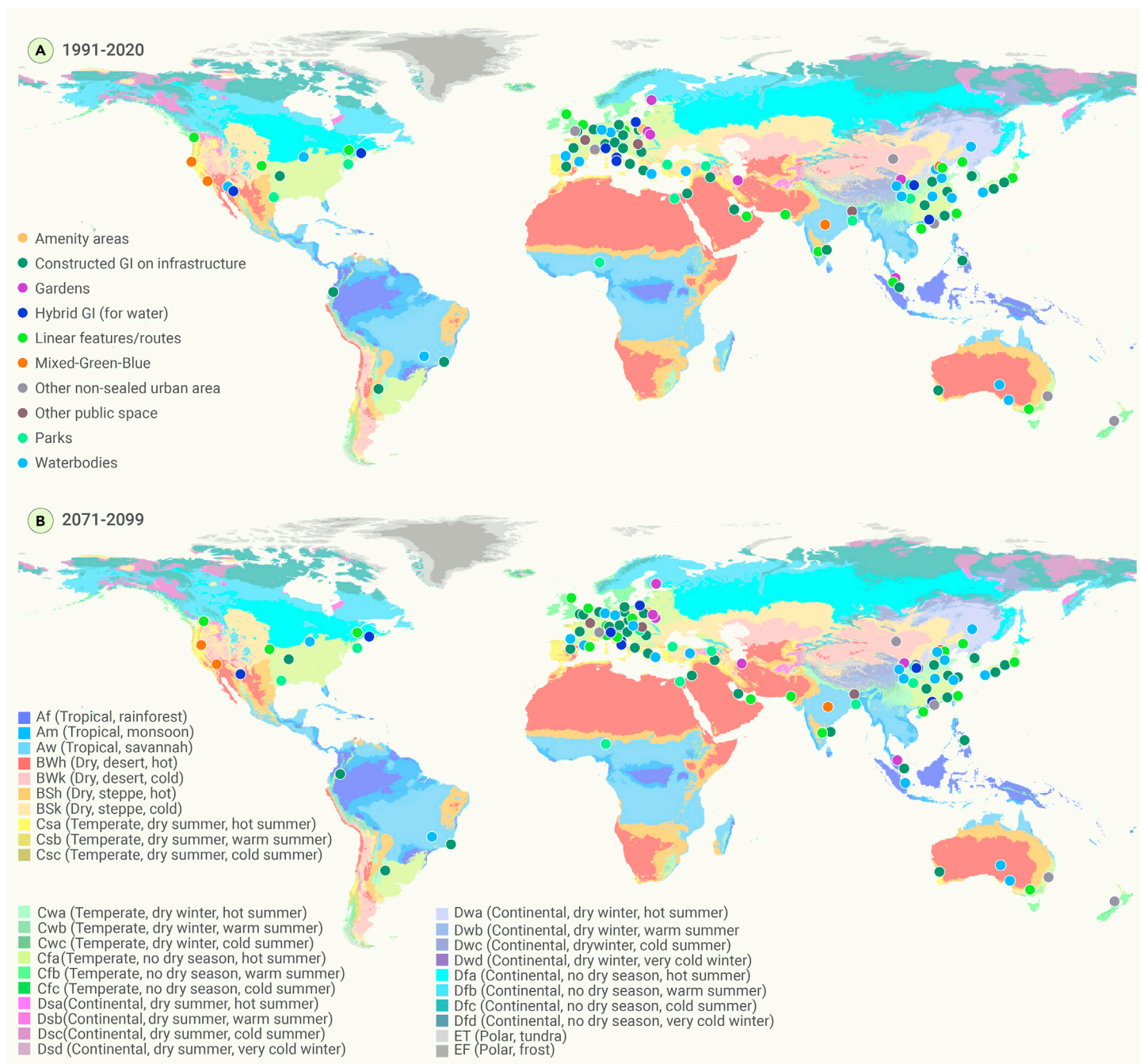


Figure 8. Base maps are Köppen-Geiger classifications, and the point are location of ten GBGI categories (A) The present-day map (1991–2020) and (B) the future map (2071–2100) under the RCP8.5 scenario.

sequestration and improve air quality, addressing multiple aspects of environmental sustainability.¹³³

In the dry climate zone (BSk), the future projection suggests a potential transition toward the BSh and BWk sub-climate, requiring more adaptive GBGI measures. That means the current best GBGI solutions of balcony and wetlands need to be updated to green walls and street trees, for future BSh climate, and current wetlands to woodlands to tackle the evolving climate scenarios (BSk to BWk) for improved urban cooling and biodiversity. In dry climates shifting from semi-arid (BSk) to dry arid climate (BWk), woodlands can act as buffers against extreme weather events, enhancing the overall resilience of the ecosystem.¹⁵⁰ However, the tropical climate zone (Af, Aw, and As) is expected to remain relatively stable, indicating limited changes in the potential cooling effects of GBGI in this area.

For temperate zones in Europe (Cfb, Dfb), expected changes may prompt the implementation of parks, pocket parks, green walls, green roofs, lakes, and grass,

offering adaptive solutions in response to projected shifts in climate (Cfa). These features contribute to temperature regulation and enhanced water management.¹⁵¹ Parks and pocket parks contribute to enhanced green spaces, while green walls and roofs provide urban cooling and reduce heat island effects in the future in Europe.¹⁵² Furthermore, lakes and wetlands expanses can aid in temperature regulation, water management, and biodiversity conservation in Europe under ongoing climate change.¹⁵³ Green roofs with supportive policies have great potential from niche to mainstream in the near future in temperate European cities for climate change mitigation.¹⁵⁴ However, these roofs encounter adoption challenges linked to incentive structures. Building owners bear the risks, while the public reaps the benefits.

A similar study by Zhou et al.¹⁵⁵ found that, in the temperate regions of China, most urban parks in (Northeast China and the North China Plain) are located in the Dwa climate zone at present, but roughly 71% of these parks would be in the Cwa climate zone in future under the RCP8.5 emission scenario between 2071

and 2100. GBGI measures should evolve from current urban parks to prioritize larger water bodies such as lakes and road verge developments to address water retention needs aligning with the principles of sustainable water management and green roofs, repurposing urban space and wetlands for the Cwa sub-climate shift in the changing climate.^{156,157} Additionally, shifts were observed from Aw to tropical monsoon (Am) in both the northern and southern regions, as well as from tropical without a dry season (Af) to Am in the central and southwestern parts of Southeast Asia.¹⁵⁸ This transition could lead to decreased cooling effects due to limitations in the largest park cooling distance and the largest park cooling intensity in the new climate zone. Additionally, urban parks currently situated outside the monsoon climate (Am) and warm semi-arid climate (BSh) zones will undergo changes, with 44% and 20% moving into BSh and Am zones, respectively. This suggests reduced cooling effects due to projected increases in rainfall and higher temperatures. The increase in minimum temperature emerged as a crucial factor driving the climate shift from Cwa to Aw in the north, while increased rainfall was a reason for Aw to Am transition in the north and south. The findings from this study on future climate zones can aid in pinpointing ecologically vulnerable hotspots worldwide affected by climate change. They also contribute to identifying optimal GBGI measures that effectively mitigate adverse impacts such as heatwaves under changing climatic conditions. Collaboration with environmental experts and ongoing community engagement are essential components of successful GBGI implementation under present-day and future climate conditions. In areas transitioning from a humid continental climate (Dwa) to a warm temperate climate (Cwa), adapting GBGI involves prioritizing green roofs and constructed wetlands for temperature control and effective water management, respectively.¹⁵⁹ Thus, considering the expected alterations in climate conditions, these prospective GBGI can aim to provide more sustainable and climate-resilient urban landscapes. Hence, policymakers should consider these projected climate shifts and tailor GBGI strategies to align with these changes, prioritizing features such as green walls, lakes, woodlands, and constructed wetlands accordingly.

CONCEPTUAL FRAMEWORKS FOR GBGI IMPLEMENTATION FOR HEAT MITIGATION

Table S9 presents a qualitative synthesis of the literature in the form of a nine-stage framework for implementing GBGI measures to mitigate heat risks, promote urban climate resilience and provide other co-benefits. Meanwhile, Figure 9 depicts the four stages, along with the processes of co-planning, design, and management, full-scale development, and nine sub-processes in the conceptual framework for GBGI implementation for heat mitigation. The stages, roughly sorted according to their chronological sequence, always accept that circularity and iteration should be inherent in any design process or application of a theory of change¹⁶⁰ (Figure 9), include the following.

Stakeholder engagement

It is crucial to identify and involve all relevant stakeholders and key players including local communities, government agencies, urban planners, environmental organizations, etc. Their active participation in a GBGI project should be ensured from conception to implementation and beyond to gather their input related to the problem of heat, address concerns, and ensure that their needs are considered.^{161,162}

Feasibility studies

It is important to conduct assessments to determine the feasibility and viability of implementing GBGI measures in heat-vulnerable areas with high heat risk exposure, particularly in densely populated urban areas lacking green spaces, where sensitive populations such as the elderly, economically disadvantaged, and those with pre-existing health issues reside. These assessments should consider technical, economic, and environmental factors. This evaluation should include an analysis of the existing urban infrastructure, the identification of potential GBGI implementation sites, and a detailed estimation of costs and benefits associated with various options.¹⁶³

Co-benefits and dis-benefits

It is essential to assess the potential co-benefits (positive impacts, e.g., reduced temperature along with improved air and water quality, enhanced biodiversity, and increased recreational opportunities) and unintended consequences

(e.g., higher maintenance costs or potential social disruptions, and allergic reactions) associated with GBGI implementation.^{119,164}

Design

The plan and design of heat-reducing GBGI measures based on the feasibility study and stakeholder input could include determining the appropriate mix of GI (e.g., parks, urban forests, and green roofs), BI (e.g., ponds, lakes, and wetlands), and gray infrastructure (e.g., permeable pavements) considering local hot climatic conditions, and available space.^{125,165}

Policy and planning

Developing supportive policies, guidelines, regulations, and incentives to integrate GBGI heatwave management measures into urban planning and retrofitting frameworks to align with the sustainability agenda of climate change adaptation and mitigation goals.^{166,167}

Implementation

During the implementation phase, the designed GBGI measures should be constructed and installed on selected sites or areas with proper project management and coordination.¹⁶⁸

Monitoring

After installation, heat reduction potential and other co-benefits of GBGI can be monitored through various parameters, such as temperature, air quality, water management, and vegetation health, which also help to identify any required maintenance or operational issues.¹⁶⁹

Evaluation

The collected data can be analyzed and evaluated in the context of indicators related to heat performance (e.g., thermal index, reduction in heat stress) or other desired co-benefits aiming to assess the heat managing effectiveness of GBGI measures and urban resilience.¹⁷⁰

Upscaling and replication

After a successful and positive evaluation of the heat mitigation potential of the implemented GBGI measures, efforts can be made to upscale the approach to larger areas or replicate it in other locations.¹⁷¹ Lessons learned from previous heat mitigation projects, including best practices for securing resources for GBGI expansion, should be used to guide and enhance future GBGI projects.¹⁷²

In summary, the process of implementing GBGI for heat mitigation and adaptation should involve a rationally structured approach, from stakeholder engagement and feasibility studies to design, policy development, implementation, monitoring, evaluation, and eventual upscaling and replication to exploit their full potential. However, it is important to adapt these specific measures according to the context and needs of each city or region.

KNOWLEDGE GAPS

While GBGI can mitigate UHI effects and heat in general, numerous specific and general knowledge gaps exist that still need to be addressed before GBGI designs can be optimized to deliver maximum cooling benefits. For instance, GBGI such as green roofs and walls, street trees, hedges, wetlands, and lakes were found to have the potential to decrease heat and improve urban micro-climates, yet systematic studies assessing their cooling effectiveness under different climatic conditions (e.g., warm summer day vs. extreme heat day), management regimes (e.g., irrigation vs. no irrigation), urban settings (e.g., residential vs. industrial), and scales remain sparse. Moreover, our study has indicated a generalized knowledge gap referring to integrated approaches to planning, designing, and implementing GBGI. The potential of synergistic effects between combined green and BI elements remains under research. Therefore, further research evaluating the effectiveness of different combinations of blue (e.g., water bodies, wetlands), green (e.g., urban parks, green roofs, street trees), and engineered elements (e.g., cool pavements, reflective surfaces) can help to optimize the design and configuration of these elements to maximize their synergistic effects in heat mitigation.

An understanding of the ideal size, shape, density, and location of GBGI is required to maximize the cooling and other associated co-benefits.¹⁷³ Numerical and computational modeling techniques can simulate the complex interactions between the GBGI and urban micro-climates to identify their optimal design and

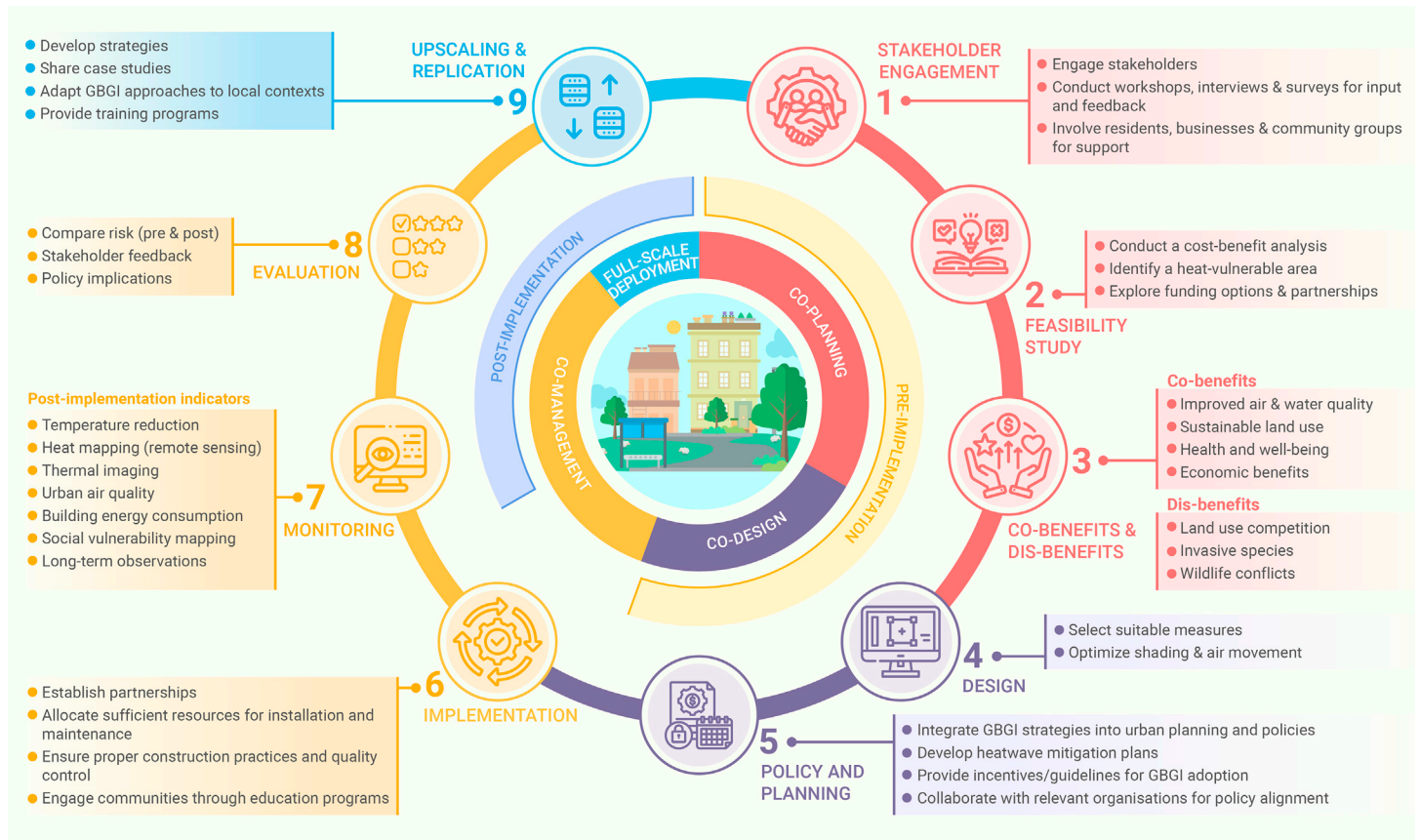


Figure 9. A conceptual framework outlining the implementation of GBGI to mitigate urban overheating A conceptual framework outlining the GBGI implementation for heat mitigation through four stage processes: co-planning, design, and management, full-scale development, and nine sub-processes.

placement.¹²⁵ However, current models often lack the necessary spatial and temporal resolution to capture the fine-scale variations in temperature, relative humidity, and air movement influenced by different infrastructure elements. To address this gap, the development of models that integrate GBGI services, demographic and socio-economic vulnerabilities, and account for the detailed surface characteristics, including vegetation parameters and land use information, is essential, as it will greatly enhance our understanding of the thermal performance of GBGI.

Similarly, the lack of guidelines for GBGI selection and design is another gap that hinders implementation.³⁴ Research is needed to investigate how the elements such as the growth, health, and type of vegetation, degradation of engineered materials, cost effectiveness, and maintenance practices evolve over time. Such information is required for long-term decision-making in urban planning and policy development to support the wider application, replication, and upscaling of GBGI solutions. Knowledge gaps also exist in identifying effective strategies for engaging and educating communities about the benefits of GBGI,^{174,175} as well as promoting sustainable practices, such as water conservation and urban greening, to integrate GBGI into urban design.¹⁷⁶ There is a need for research that explores the governance structures, policy frameworks, stakeholder engagement strategies, and the social, cultural, and economic factors influencing the adoption of GBGI.

The equitable distribution of GBGI and its benefits is an important consideration in complex urban systems.^{177,178} Research should examine the potential disparities in access to and the benefits derived from GBGI measures, particularly in disadvantaged, marginalized, and forgotten communities. Evaluating the environmental justice implications of GBGI implementation will help to ensure that the benefits are distributed fairly and address existing social inequities.

Among the reviewed publications (n = 202), the majority (69.8%) did not report other co-benefits for the used GBGI beyond mitigating and adapting to heat. Therefore, assessing the multi-benefits of different GBGI types emerged as a major research gap. In addition, more studies are required to explore the potential of underrepresented GBGI elements (zoological gardens, sparsely vegetated land, shared garden areas, schoolyards, allotments, rivers, railway corridors, ponds,

permeable parking, outdoor swimming pools, nursery gardens, heritage gardens, footpaths, flood control channels, estuaries, cycle tracks, canals, bioswales, arable agriculture, golf courses, and sports field) and assess their effectiveness beyond heat mitigation and adaptation, for example, in terms of public health and social wellbeing, or biodiversity implications.¹¹⁹ Moreover, significant knowledge gaps exist on concerns related to water availability and management of water-based solutions implementation (e.g., irrigation systems, wetlands, ponds, and rain gardens) during extreme heat. These gaps include sustainable water resources, efficient water storage and management techniques, and the impacts of water scarcity on water-based and water-dependent solutions. Research should explore the effects of improved thermal comfort on physical and mental health outcomes, as well as the social and cultural value of green and blue spaces in enhancing community resilience and social cohesion during increasingly hot summers.

Addressing these knowledge gaps through further research, working with stakeholders, and developing the knowledge-sharing platforms and GBGI database¹⁷⁹ can help to overcome barriers and facilitate the effective implementation of GBGI for heat risk adaptation and mitigation.

SUMMARY AND CONCLUSION

This systematic review fills an important gap in the existing literature by its goal of appraisals of the GBGI efficacy for urban heating by bringing together a complex dataset from various studies. This systematic review builds an evidence base on the benefits of GBGI for heat mitigation, associated co-benefits, knowledge gaps, and recommendations for maximizing its potential. A global mapping of GBGI interventions, specifically aimed at urban heat mitigation, was carried out through a systematic literature review that yielded 202 relevant publications. The meta-analysis provided an evidence-based classification for 51 GBGI types. Both the positive and unintended downsides of GBGI measures were discussed along with the mechanisms by which GBGI regulates temperature and mitigates heat. Knowledge gaps in the implementation of GBGI were identified and the critical synthesis of information was used to propose practical recommendations for effective GBGI implementation. Hence, this review paves the

way for future advancements in the realm of GBGI, offering a comprehensive understanding of its potential and implications.

The most common physical mechanisms by which GI regulates urban heating and creates cooler environments were reported to be shading, evapotranspiration, and thermal insulation. This cooling is also associated with decreasing energy consumption in buildings through subsidizing heat gain and decreasing the cooling load. BI is reported to act as a heat sink, regulating temperature through evaporation, and absorbing heat thereby contributing to the mitigation of UHI effects and the creation of more comfortable urban environments.

The analysis of publications indicates a significant increase in research interest and activity in using GBGI for urban heat mitigation worldwide, with a notable focus in Asia and Europe as opposed to South America or Africa due to urban densification and expansion, coupled with rising temperatures affecting cities worldwide and their populations. There are potential regional preferences and priorities in addressing urban heat and its associated impacts. The most studied GBGI types for urban heat mitigation include constructed GI where plant elements are integrated with existing built structures, but also in the form of street trees, parks or green corridors. For private gardens, sports fields, cemeteries and heritage gardens, the cooling potential was less clear, requiring more studies.

GBGI interventions offer co-benefits such as stormwater management and carbon sequestration, as well as a wide range of ecosystem services. However, unintended consequences also exist, such as increased maintenance costs and potential land use conflicts. Optimizing their multifunctional benefits for any specific context is the key. Street trees were reported to have the highest number of co-benefits in addition to their potential effectiveness in heat mitigation and adaptation, followed by green roofs and botanical gardens. Playgrounds, green walls, green roofs, and street trees had the highest number of reported drawbacks such as pollutants trapped in street canyons and allergic rhinitis. This highlights the importance of considering a balanced approach during their implementation for heat mitigation and adaptation.

Among methods, *in situ* monitoring is the most common approach, followed by modeling, RS, and their combinations for evaluating the urban cooling efficacy of GBGI. Regardless of limited data points, *in situ* monitoring offers high temporal resolution, accurate and reliable real-time ground-based measurements for analyzing (a) short-term trends e.g., heatwave and UHI, and (b) long-term historical climate records for validating RS and model data. Modeling offers spatiotemporal variations, but with uncertainties due to assumptions. RS provides extensive spatial coverage but lacks fine-grained details and requires advanced data processing. While there is no universal approach, combined and customized methods can enhance the spatiotemporal resolution for specific objectives, enhancing our ability to respond to extreme weather events and inform sustainable development and climate resilience policies.

Micro-scale GBGI interventions, focusing on built infrastructure, parks, and linear features, play a vital role in mitigating heatwaves in specific urban areas, providing immediate, cost-effective, and community-centric benefits compared with larger scale interventions. The cooling efficiency of GBGI is influenced by location and surroundings, with measurements inside GBGI areas demonstrating greater cooling effects due to mechanisms like evapotranspiration. However, effectiveness diminishes as we are distancing away from GBGI intervention (e.g., outside of the infrastructure). The type of environment also matters, with GBGI in natural surroundings, like parks, enhancing heatwave mitigation more than those in built-up areas. GBGI effectiveness for urban cooling varies based on climatic zones, population density, city area, altitude, and temporal duration of the study. Region-specific strategies, especially in lower density cities and tropical regions, highlight scalability and enhanced effectiveness. Challenges in denser urban settings and decreased effectiveness over longer temporal scales suggest areas for future research in implementing GBGI for urban cooling. Projected climate shifts require tailored GBGI strategies, emphasizing the adaptation of solutions like green walls, lakes, woodlands, and constructed wetlands to enhance urban cooling and resilience locally and at greater scale.

Addressing the existing knowledge gaps through comprehensive research, stakeholder collaboration, and the development of knowledge-sharing platforms and databases is crucial to optimizing the design, implementation, and benefits of GBGI for effective heat risk adaptation and mitigation. More understanding of the synergistic effects of combining green and BI elements is needed to enhance cooling and reduce urban heating. Additionally, gaps exist in water availability and management, GBGI optimal design and placement strategies, long-term performance and maintenance requirements, community engagement and behavior

change, equitable distribution of benefits, and supportive policy and governance frameworks.

RECOMMENDATIONS

Ten broader, evidence-based recommendations can be drawn from this study.

- Tailored GBGI typology based on geographical location can aid urban heat mitigation. The GBGI cover in any city should be maximized to decrease UHI effects and the risk of urban overheating. All GBGI types provide cooling benefits, many of them also important co-benefits. Nature needs to be brought back into densifying and expanding cities and any opportunity to expand plant cover on the ground, podiums, walls, and roofs must be taken. All urban development must be nature positive to make our cities and their populations resilient against anticipated stresses and shocks from global climate change. Project-specific optimization of GBGI types is recommended to generate maximum cooling and co-benefits.
- Identifying heat-vulnerable regions can inform targeted GBGI selection to provide heat mitigation solutions. This necessitates a comprehensive evaluation of the heat threat, considering its spatial distribution and severity, the vulnerability of the population, which includes demographic and socio-economic factors, like age and income, and the adaptive capacity, such as education and access to healthcare services. Heat-vulnerable areas might necessitate the creation of communal open green spaces and the adoption of other GBGI types, such as street trees, green roofs, permeable paving, rain gardens, bioswales, and wetlands as appropriate. Where financially feasible, increasing the number of community cooling shelters will be a critical investment to keep the most vulnerable members of an urban population safe.
- A monitoring and evaluation framework is crucial for assessing GBGI's performance in heat mitigation and identifying improvements. Our analyses have shown that the cooling capacity of individual GBGI types varies according to the geographical setting. Hence, it will be important that frameworks are established that will quantify cooling benefits and how these benefits can be optimized through improvements in design and management specific to a geographic region. This will allow decision-makers and operators to make informed decisions, and update projects to deliver the most effective GBGI solution.
- For effective climate-resilient urban heat mitigation, it is crucial to comprehend the characteristics, functionality and constraints of GBGI. This includes understanding the potential uses and benefits of different GBGI, such as recreational parks that can improve air quality and mitigate UHI effects, green roofs, roof gardens, and green walls that enhance biodiversity, reduce energy consumption, manage stormwater, improve air quality, decrease noise pollution and improve aesthetics. Additionally, permeable materials used on sidewalks, parking lots, and roads can facilitate water infiltration, reduce stormwater runoff, and recharge groundwater. However, while implementing GBGI, site-specific factors and local climate conditions should be considered to avoid selecting incompatible GBGI. For example, rain gardens, wetlands, or green roofs with shallow soil depths may not be suitable in areas where water availability is limited and evaporation rates are high.
- The impact of GBGI on urban heat mitigation is largely contingent on spatial scales. These scales can range from individual buildings, where green roofs or walls are used, to entire neighborhoods, where parks and urban forests might be more appropriate, and even city-wide initiatives like green corridors, and extensive tree planting. The existing body of literature indicates a positive, nonlinear (saturating) correlation between the size of GBGIs, especially parks, and their cooling potential. Therefore, customizing GBGI strategies to cater for specific heat risk zones and taking into account distinct location characteristics is imperative for achieving the best results.
- Exploring the potential for integrating various GBGI measures may present unique possibilities for enhancing socio-ecological benefits. Making use of multiple GBGIs, coupled with the inclusion of green or blue elements like irrigation systems and green roofs equipped with rainwater harvesting systems, can amplify cooling benefits. Additionally, this also encourages a range of other co-benefits, including biodiversity

enhancement, habitat connectivity improvement, and bolstering ecosystem resilience.

- It is essential to carefully evaluate potential negative consequences to prevent any unintended side effects when implementing GBGI. For instance, dense trees in narrow or deep street canyons may inadvertently increase exposure to trapped pollutants. In addition, biogenic volatile organic carbons can trigger ozone as a secondary pollutant that can produce respiratory and summer smog issues in hot summers. High maintenance requirements, such as those for botanical, zoological, and heritage gardens must also be considered. Limited access to water for irrigation can decrease the cooling capacity of GBGI. Care must also be taken when implementing new GBGI elements that the integrity of the built infrastructure is not compromised. Being mindful of the potential for unintended ecological impacts and displacement of vulnerable communities is also important. Therefore, before selecting suitable GBGI interventions, it is necessary to assess the local context, environmental conditions, available resources and the budget to ensure their long-term effectiveness and avoid possible drawbacks.
- Comprehensive heat mitigation strategies with straightforward-to-implement practical guidelines are required. Policy frameworks should provide guidance on design standards including building codes and zoning regulations, as well as land use policies. They should provide financial mechanisms to incentivize the adoption of GBGI, particularly in areas with high heat vulnerability, with a special focus on schools, social housing and facilities providing aged care.
- Climate literacy programs and public information campaigns are crucial in promoting positive action on urban heat and GBGI interventions. Incorporating climate-related education into the school curriculum is important for developing a deeper understanding of the causes and consequences of environmental heat, as well as the potential solutions offered by GBGI for urban cooling. In addition to the school curriculum, it is crucial to acknowledge that individuals, both professionals and laypeople, have various levels of awareness, knowledge, attitudes, and behaviors. It is necessary to facilitate progress for all individuals along this spectrum, from left to right. This presents a distinct educational challenge.
- Stakeholder participation plays a pivotal role in promoting the adoption of GBGI solutions in regions susceptible to heat. It is vital to actively involve all stakeholders, including researchers, communities, urban planners, engineers, government bodies, non-profit organizations, and businesses, in the co-creation of GBGI initiatives. A collaborative process to combat the effects of urban heat hotspots not only integrates diverse perspectives but also fosters a sense of shared ownership and collective responsibility. This approach ultimately enhances the effectiveness and acceptance of interventions.

To effectively mitigate urban overheating and harness the co-benefits of GBGI, it is crucial to conduct additional research on the less-studied GBGI types and also in less investigated countries to fill the knowledge gaps. A comprehensive understanding of GBGI's potential in heat mitigation can inform urban planning and design strategies aimed at creating sustainable and resilient cities.

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The authors declare no competing interests.

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